



**HAL**  
open science

## Fast fabrication process of low environmental impact MEMS

Etienne Lemaire, Damien Thuau, Benjamin Caillard, Isabelle Dufour

► **To cite this version:**

Etienne Lemaire, Damien Thuau, Benjamin Caillard, Isabelle Dufour. Fast fabrication process of low environmental impact MEMS. *Journal of Cleaner Production*, 2015, 108, pp.207-216. 10.1016/j.jclepro.2015.05.111 . hal-01159175

**HAL Id: hal-01159175**

**<https://hal.science/hal-01159175>**

Submitted on 4 Nov 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Fast-fabrication process for low environmental impact microsystems

<sup>1,2</sup>Etienne Lemaire, <sup>1</sup>Damien Thuau, <sup>1</sup>Benjamin Caillard, <sup>1</sup>Isabelle Dufour

<sup>1</sup>Univ. Bordeaux, IMS, UMR 5218, F-33400 Talence, France

<sup>2</sup>École Polytechnique Fédérale de Lausanne (EPFL), IMT-LMTS, Neuchâtel, Switzerland

Email: etienne.lemaire@epfl.ch

### ABSTRACT

In the context of building a sustainable future by reducing fossil energy consumption with the objective of minimizing detrimental climate change, particular attention was given to minimizing the complexity, energy consumption and environmental impact of microstructures manufacturing. In this work a new fast-fabrication process for microelectromechanical systems is presented. The name of this new fabrication process is KISSES for *Keep It Short, Simple and Environmentally Sustainable*. Combining classical deposition techniques (with common metals and polymers and with less common materials such as tree resins, paper and glue), release techniques and a computer numerical control cutting machine, a two-dimensional fabrication process has been developed and the first steps of three-dimensional microfabrication have also been initiated. In order to test this new process, various test structures have been fabricated and tested. These include resonant structures with electronic actuation and electronic measurement, having good quality factors for plastic-based devices, and high-resolution masks (~10  $\mu\text{m}$ ) which can be used, for example, for screen-printing techniques. Finally, a temperature sensor and a viscosity sensor have been designed, fabricated with the KISSES process and characterized. These devices exhibit, respectively, a limit of detection of 0.112°C and a viscosity estimation error of less than 10% for viscous silicone oils from 5cP to 50cP. These characterizations of the microdevices show that the proposed process provides a simple method that is capable of fabricating devices that function with high performance. The aim of developing a rapid, simple and environmentally sustainable process has therefore been demonstrated.

**Keywords:** microelectromechanical system, fabrication, prototyping, low cost, environmental impact, cleantech

### 1. INTRODUCTION

One of the interests of soft electronics is the reduction of the energy cost which is sometimes related to improved environmental compatibility. In recent years organic electronics have emerged as a viable means of replacing expensive inorganic materials with soft polymers. For instance, organic LED, flat screen displays and electronics paper are now efficient, stable and currently available, already representing in its infancy a 3 billion dollar market (Opera project, 2009). In the near future, organic transistors, solar cells and microelectromechanical systems (MEMS) are expected to follow a similar trend of growth (Opera project, 2009). The fabrication of organic electronics requires less energy than silicon technology (Sheats, 2004). For instance, in the field of organic solar cell technology, the Energy Pay-Back Time (EPBT) can be reduced to less than one

year (Espinosa et al., 2011). Such technological progression ultimately decreases the energetic and environmental impacts of technology manufacturing.

In the context of building a sustainable future with a reduction of fossil energy (Hallock et al., 2004) and minimizing climate change (Rogelj et al., 2011 and Hoffert et al., 2002), a *very long-term sustainable technology* for electronics might be required. The development of *low-impact technology* has already started (Liow, 2009; Hocheng et al., 2012; Kunnari et al., 2009).

Recently in the MEMS field, fast-prototyping technologies have also emerged, some of which may be classified as *low-impact technology*. For example, paper-based MEMS have been developed recently (Liu et al., 2011; Martinez et al., 2010; Ferrer-Vidal et al., 2006). Other groups have explored the use of more broadly biodegradable MEMS (Tran et al., 2011; Suresha et al., 2008; Park et al., 2003). All of these cases furnish examples of *low-impact MEMS*. Thus, the complete life cycle of the system allows for minimizing the energetic and environmental impacts.

In this work a KISSES fabrication process is presented: *Keep It Short, Simple and Environmentally Sustainable*. The features of the proposed KISSES MEMS fabrication technology are presented below:

- ✓ No cleanroom facility required
- ✓ A water-soluble resin or paper-based sacrificial layer, easy to remove, thus facilitating the fabrication of moving structures
- ✓ A vegetal resin-based glue used as a structural or packaging component, thus presenting recycling opportunities
- ✓ Conducting layers using commercially available aluminum foils
- ✓ Insulating layers using commercially available plastic sheets and paper
- ✓ A manual layer deposition utilizing masks or simple spin-coating with annealing
- ✓ Multi-layer assembly involving vegetal resin glue or solvent-free industrial glue
- ✓ Only low cost, highly bio-degradable or recyclable and abundant materials are used (e.g., vegetal resin, water, paper, commercial plastic sheets, commercial aluminum foils, steel strings)
- ✓ Only low-tech<sup>1</sup> machines are required: a vinyl cutting machine, a spin-coater, a simple hot plate
- ✓ Possible compatibility with other processes that are more polluting, expensive or energy consuming and use other materials like epoxy-based resin or carbon nanotubes and other deposition techniques like Electron Beam (ebeam) evaporation of metals or spin-coating with UV exposure.
- ✓ Future features will permit the development of active components fabrication using greener materials (*low-impact* semiconductors, metal-oxides, piezoelectric materials, etc.) to develop circuit capabilities and/or circuit integration which are compatible with greener or cleaner technology (Dangelico et al., 2010, Jørgensen, 2008, Liu and Muller, 2012).

The successful implementation of the new technology required the development of a new process for the fabrication of metallic and organic structures, one which has been motivated by probing the

---

<sup>1</sup> Low technology means simple technology, the opposite of high technology

limits of a computer numerical control (CNC) cutting machine. Fast prototyping of microfluidic systems has already been developed using a digital craft cutter (Yuen and Goral, 2009). The CNC cutting machine that has been used is a Craft RoboPro CE6000 (Graftec Craft ROBO Pro), which has a resolution of up to 20 microns and can cut plastic, paper and other material layers up to 250 microns thick. Velocity, acceleration and force applied by the blade during the cutting process are adjustable parameters. By adjusting these parameters, a layer of material can be completely or partially cut (etched). By combining complete and partial cutting the fabrication of complex structures can be realized. This idea is summarized in Figure 1. Many types of materials can be processed, such as paper, polymers, or thin layers of metal. In fact almost all of the structures presented in this work have been fabricated from materials commonly found in our direct environment such as garden, kitchen, and supermarket.

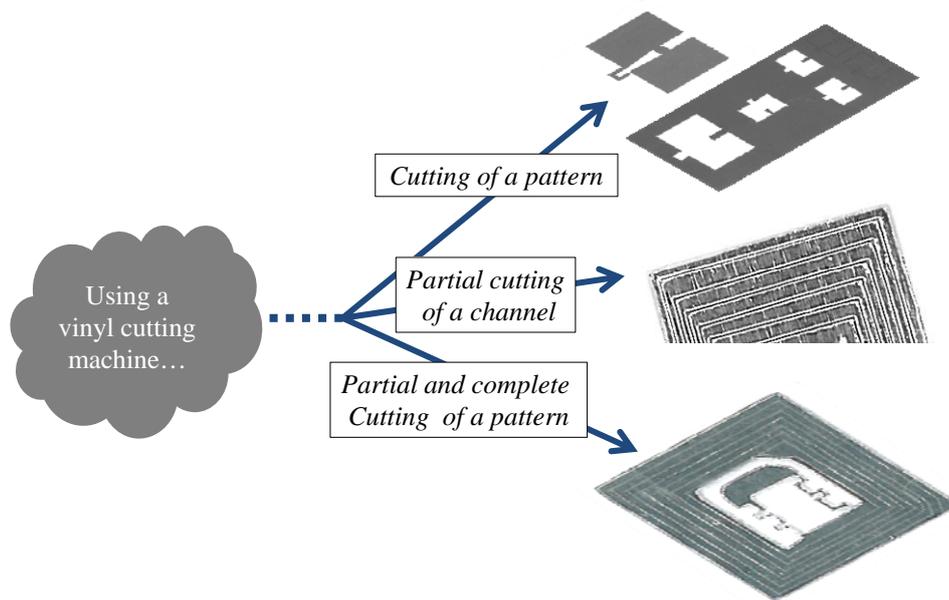


Figure 1 – Some of the opportunities offered by a vinyl cutting machine along with optical images of realized structures.

Classical deposition techniques such as screen-printing, spin-coating or spray-coating used in conjunction with high-resolution computer numerical control (CNC) cutting substantially extend the fabrication capabilities of this technique. This concept is summarized in Figure 2: (1) the CNC cutting machine allows the production of masks and the cutting of monolayer structures; (2) by combining deposition steps with a mask and cut by the machine, multilayer structures can be achieved.

The main advantages of the presented fabrication technique are rapidity, simplicity and low cost. In addition, by choosing appropriate types of materials and processes, the energetic and environmental impacts of the final device can be minimized.

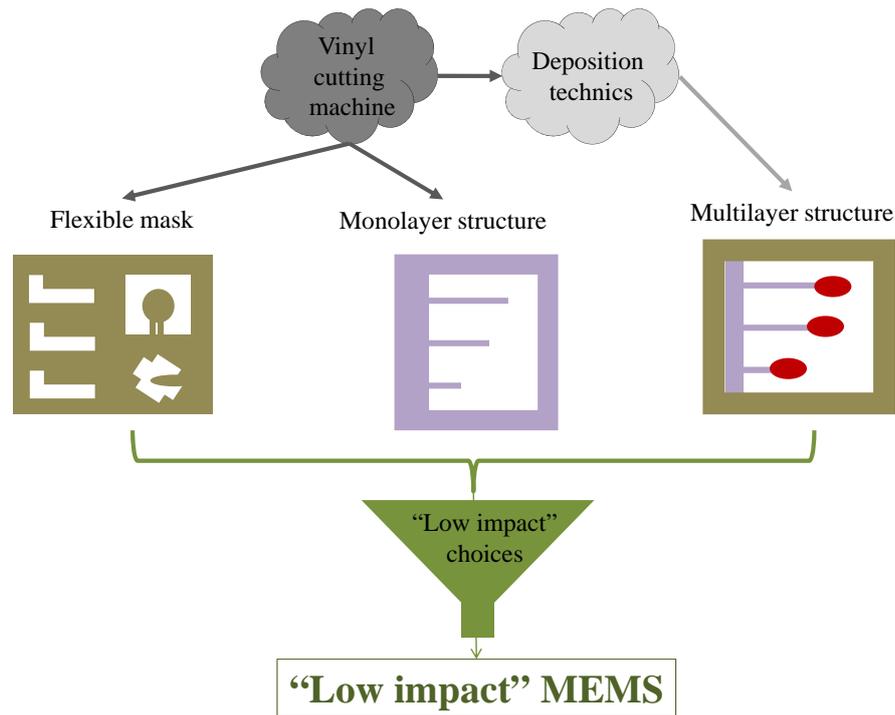


Figure 2 – Overview of the fabrication capabilities of cutting techniques and classical deposition techniques.

The fabrication process (energy involved, machine and process complexity, resources and products used) and the device itself (biodegradability or recyclability) can be labeled as *low-impact*, meaning that the complete life cycle of the product tends to be as clean as possible regarding environmental considerations. For example, masks and MEMS structural materials can be made of paper instead of silicon, glass, or plastic. Furthermore, a sacrificial layer can be composed of vegetal resin in order to replace classical SU8 resin, and chemical etching can be replaced by a cutting process.

In this work, various “low-impact” microstructures made of a wide range of environmentally friendly materials have been developed. With the aim to further underline the potential of the proposed innovative fabrication process and its potential applications, several designs have been fabricated (section 2), characterized (section 3) and tested (section 4).

## 2. FABRICATION METHODS

Figure 3 shows four different structures that have been patterned using the high-resolution CNC cutting machine. Each one illustrates a specific fabrication capability that can be achieved using unconventional materials and some well-known techniques of fabrication. In Figure 3a, a U-shaped structure has been designed, proving the ability of patterning different types of materials coated on paper and commercially available aluminum foil. In Figure 3b, a platelet resonator made of commercial aluminum foil and suspended by four arms has been patterned. In this case, a sacrificial layer has been used to release the suspended structure. In Figure 3c, a bimorph cantilever-based actuator made of commercial plastic sheet and aluminum has been fabricated. The

aluminum layer has been etched in order to pattern actuation paths and electrodes. Finally, Figure 3d shows the design of a mask made of commercial aluminum foil. Other masks presented later have also been made with cellulose acetate sheet (21x29.7cm<sup>2</sup>). However, this type of mask can be made with *any* polymeric thin foil.

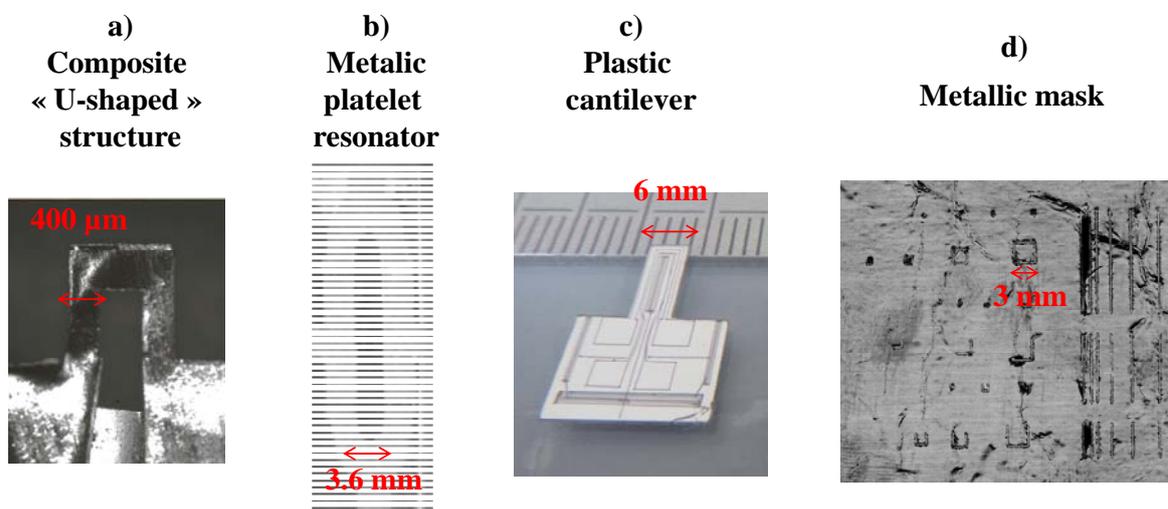


Figure 3 – Images of the four types of structures considered in the present paper.

The structures have been fabricated using both solid- and liquid-based materials. The preparation of viscous glue as well as deposition techniques used in this work are detailed in the present section, including the different materials used, the cutting process, parameters and methods.

## 2.1 Glue preparation using vegetal resin

Solid cherry tree resin (composed of several polyterpenes described by Langenheim, 1990) is dissolved into a solution containing 2% acetic or citric acid. After one day of dissolution, liquid viscous glue is obtained. Filtration is then performed using a commercial coffee filter. The process is illustrated in Figure 4. The viscosity of the filtered resin (used as glue) depends on the concentration of water in the solution. The obtained glue can be used as an alternative to commercial glue<sup>2</sup> which has also been used in this work. Both glues are soluble in water and have been used as sacrificial layers in the fabrication of the MEMS devices.

<sup>2</sup> Commercial glue used : Liquid UHU glue, labelled « without solvent », <http://www.uhu.fr/produits/colles-multi-materiaux/detail/uhu-colle-toutflex-clean-sans-solvant.html?cHash=2828c2bd8cd9eb7f31b5f8055668582&step=49>

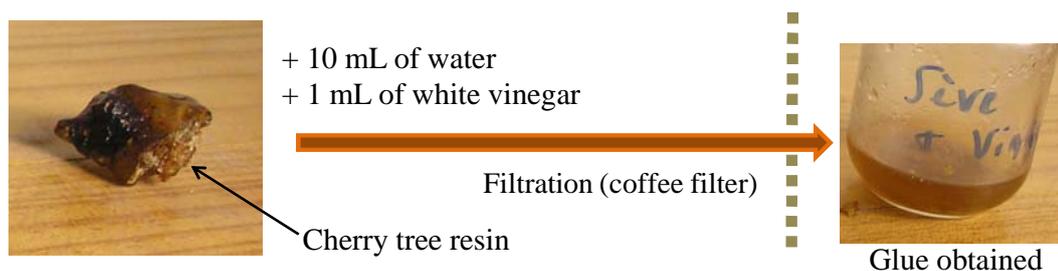


Figure 4 – A diagram depicting the fabrication of the glue using vegetal resin.

## 2.2 Deposition techniques

The “U-shaped” structure shown in Figure 3a is composed of either an SU8 layer or an epoxy (CV59) layer spin-coated on an aluminum sheet. The aluminum sheet is placed on a silicon wafer used as handling support. Both resins (SU8 or CV59) are spin-coated at 1000rpm for 60 seconds. The resin is subsequently soft-baked at 95°C for 90 seconds and at 110°C for 5 minutes. In fact the SU8 resin is not entirely cross-linked in order to avoid fracture during the cutting process step. Instead, a post-cutting UV exposure and hard bake are performed to fully cross-link the resin. The resulting thickness of the SU8 and epoxy CV59 layers are 90µm and 70µm, respectively.

The metallic platelet resonator and mask shown in Figures 3b and 3d have been fabricated using a sacrificial layer of glue (either the vegetal resin or the commercial UHU). The soluble resin is manually screen-printed on a 150µm-thick paper sheet. The aluminum sheet is then rolled down on the paper sheet, followed by polymerization of the glue lasting one hour. Subsequently, the structure is patterned.

The hybrid cantilevers (Figure 3c) are the only structures fabricated from an expensive fabrication step consisting of the deposition of a 700nm metal layer by Electron Beam onto a plastic cellulose acetate transparent sheet of 100µm thickness. The cantilever beam is patterned by choosing any desired geometry (triangular, rectangular or U-shaped) by the cutting design.

## 2.3 Cutting process

The high-resolution CNC machine can be used to cut a single or multilayer material. A rotating blade is able to cut the material as defined by the designed layout<sup>3</sup>. The blade moves in the X-direction and the support, where any materials<sup>4</sup> desired to be patterned are placed, moves in the Y-direction. Therefore, the cutting is performed into a planar surface (two dimensions). Nevertheless, the depth of the cutting can also be monitored by adjusting the applied force and the offset of the blade resulting in material cutting in a third dimension. In fact, four parameters can be adjusted at each cutting procedure: the force applied on the blade, the velocity of the cutting, the acceleration of the blade and the offset of the blade. As illustrated in Figure 5, a complete or partial cutting of the structural layer may be performed. It is worth emphasizing the significance of the aforementioned options for patterning the top layer of a bimorph structure. For instance, if a thin metallic layer has been deposited onto the initial plastic layer sheet before cutting, the separation between metallic areas is possible on the surface of the bimorph sheet by cutting only the metallic

<sup>3</sup> A dedicated software package is sold with the Graphtec machine, but the pattern can be made using any 2D drawing software able to export into SVG format (like the open source software Inkscape, [www.inkscape.org](http://www.inkscape.org))

<sup>4</sup> Paper, cardboard, plastic or thin layers of metal (up to 10µm) and more generally layers of soft materials (up to 250µm) like polymers and biopolymers.

layer. Additional steps can then be employed to pattern the plastic foil by releasing some parts. By combining partial and complete cutting, complex structures can be fabricated.

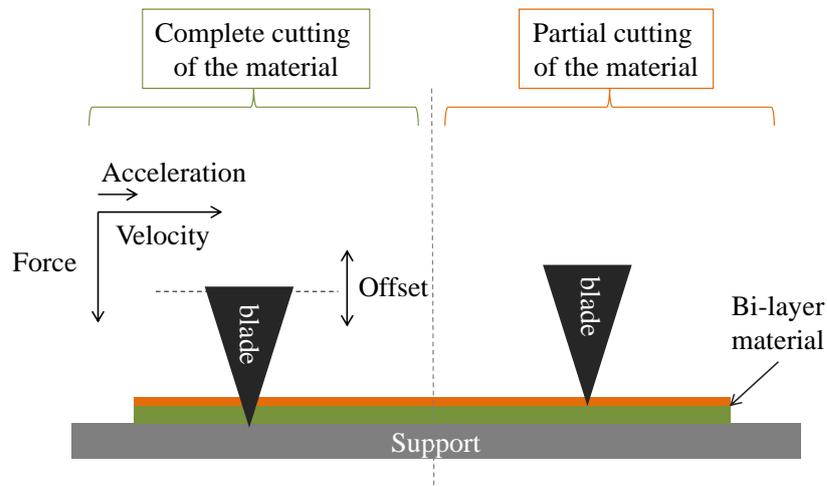


Figure 5 – Schematic of the cutting process using the Graphtec Craft RoboPro, including the cutting process type (complete or partial) and process parameters (force, velocity, acceleration, offset).

Different patterns have been cut using the CNC machine and various combinations of materials. Table 1 presents the cutting parameters used to obtain the structures presented in this work based on different layer stacks:

- The “U-shaped” structure has been cut into a 10µm-thick aluminum foil on which has been deposited a layer of epoxy CV59 or SU8.
- The aluminum platelet resonator has been cut into a stack of paper, sacrificial layer of glue and aluminum foil.
- The paths of the multilayer microcantilever have been first partially cut into the metalized transparent plastic sheet. Then the microcantilever pattern has been obtained with the complete cutting of the foil.
- The aluminum mask was based on the same procedure as for the platelet resonator. For the plastic masks the same parameters were used as for the previously mentioned plastic foil, complete cutting being used.

	Force	Velocity	Acceleration	Offset
<b>Epoxy/Al</b>	6/31	2/60	1	0
<b>SU8/Al</b>				
<b>Al/Glue/Paper</b>	4/31	5/60	1	0
<b>Al/Plastic foil</b>				
<b>Partial cutting</b>	4/31	2/60	1	-1
<b>Complete cutting</b>	27/31	12/60	1	0

Table 1 – Cutting parameter values (arbitrary units of the machine software) used with the Graphtec machine for the three types of materials systems.

## 2.4 Summary and opportunities

More generally a complete procedure can be extracted from the four structures fabricated in this work. The combination of ink or glue deposition, cutting procedure, and another technique such as the liberation of the structure with or without the use of sacrificial layers are summarized in Figure 6.

Presently, this fabrication process permits the fabrication of two-dimensional microstructures using a wide range of materials. One of the main advantages of this technique is a very short fabrication time. Hundreds of structures can be designed and fabricated per day.

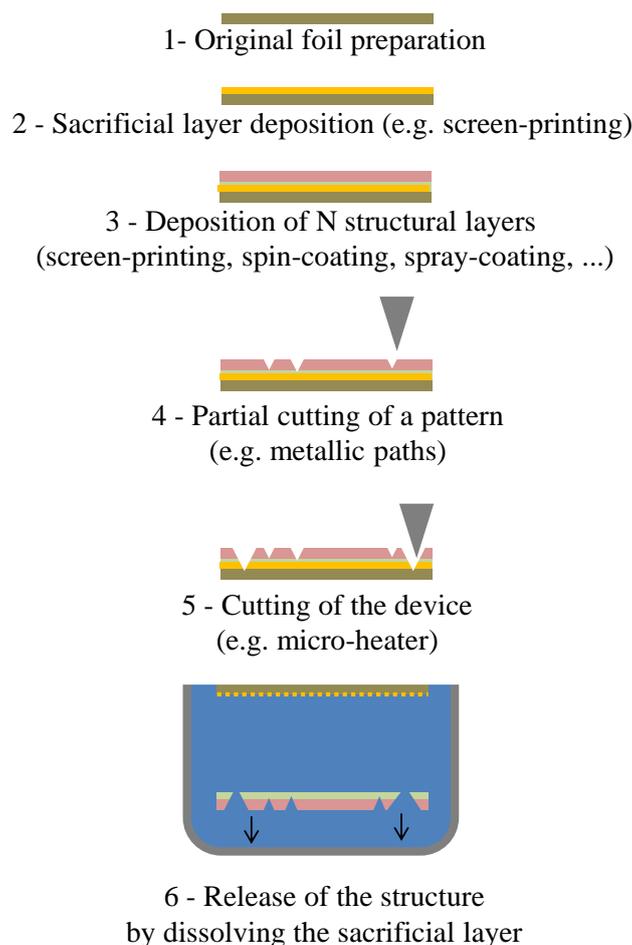


Figure 6 – Diagram providing a general overview of the steps involved in the proposed fabrication process with specific examples of applications listed parenthetically.

An extension of the present work to a three-dimensional fabrication process is currently in progress. Using an optical or a mechanical alignment (Brugger et al., 1999; Dubourg et al., 2011), multiple layers of a final complex structure can be fabricated separately and then assembled. Each layer can be bonded or glued to the others. A final cutting step can then be used to create the global structure.

The structures fabricated and characterized in this work are the cornerstone of a future complete alternative fabrication method to manufacture complex organic or inorganic MEMS devices.

### 3. CHARACTERIZATION

The four different types of structures have been characterized optically. All types of structures have been actuated electromagnetically in air by the Lorentz force by means of a neodymium magnet being placed near the microstructures. The electrical current passing through the structures interacts with the magnetic field and causes the occurrence of a Lorentz force which actuates the structures (Fadel et al., 2004). An optical vibrometer<sup>5</sup> has been used to measure the dynamic vibrations of the actuated microstructures. Images and measurements of each type of structure are presented in this section.

#### 3.1 “U-shaped” structure

The “U-shaped” design is a convenient design for several types of applications (see section 4). A bimorph “U-shaped” structure (70 $\mu\text{m}$  of epoxy on 10 $\mu\text{m}$  of aluminum) has been characterized in Figure 7. The low  $Q$  factor measured in air suggests that non-negligible internal losses appear due to the presence of epoxy. Moreover, the non-ideal clamping also produces an important part of the mechanical losses. Nevertheless, when operated in a liquid medium the hydrodynamic losses dominate (Dufour et al., 2014). Consequently this sensor is useful for liquid medium measurements as shown later in section 4.1.

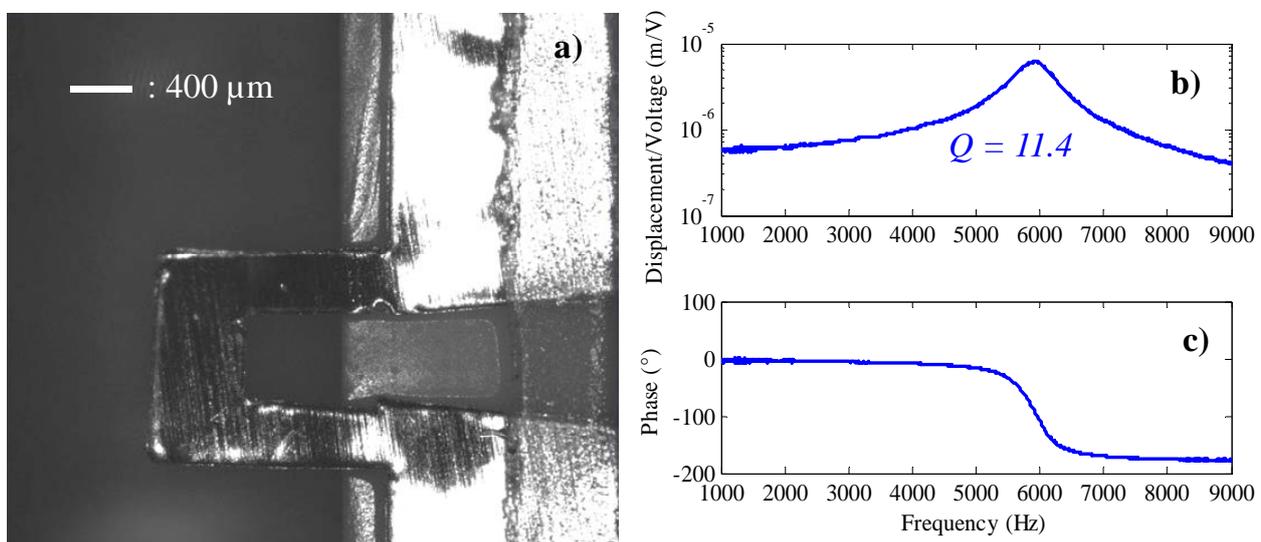


Figure 7 – a) Optical image of a “U-shaped” bimorph structure (epoxy/aluminum), b) Amplitude and c) Phase of the first out-of-plane resonance mode of the structure measured in air. The quality factor is calculated to be 11.4.

<sup>5</sup> MicroSystem Analyser, MSA-500 from Polytec, [www.polytec.com](http://www.polytec.com)

### 3.2 Platelet resonator

In order to improve the previous device's performance in air, a metallic monolayer platelet resonator has been fabricated. Depending on the current and magnetic field directions, the motion of the platelet resonator can be in-plane (longitudinal or lateral) or out-of-plane (transverse) (Heinisch et al., 2011). In this experiment the magnetic field was not controlled, so the three spatial components of the magnetic field in the environment of the structure are present. Therefore, in-plane and out-of-planes modes can occur in the same experiment. In Figure 8, three vibration modes can clearly be observed. Furthermore, two additional modes can be identified in the phase spectrum. The combination of in-plane and out-of-plane modes has been characterized. In fact, this experiment provides proof of concept that a metallic platelet resonator with appropriately designed mechanical properties can be manufactured using a commercial foil of aluminum and a vinyl cutting machine. The quality factor has been more than doubled compared to the previous structure (U-shaped device).

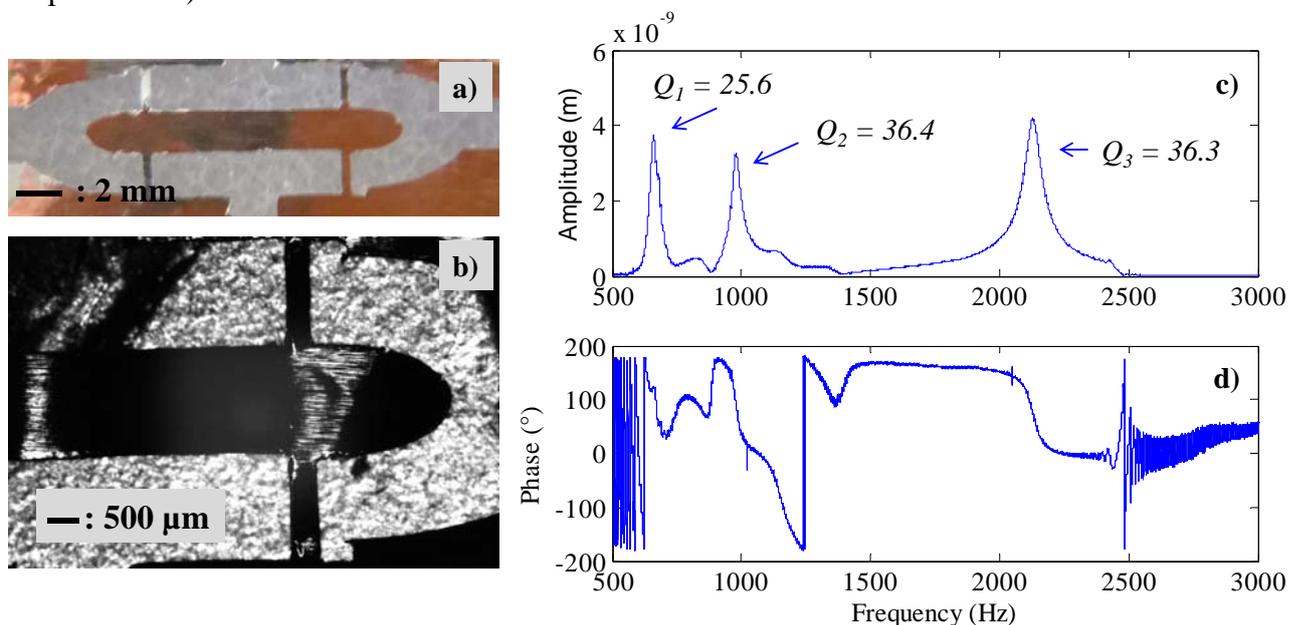


Figure 8 – a) Optical image of the aluminum platelet resonator, b) Zoomed-in view of two arms of the structure. c) Amplitude and d) Phase of the electromagnetically actuated microstructure measured in air. The quality factors of the three modes are indicated.

### 3.3 Multilayer microcantilever with metallic paths

A multilayer MEMS has been fabricated showing another capability of the vinyl cutting machine, namely metal etching. Firstly, a thin layer of aluminum (700nm) has been deposited by Electron Beam on a commercial plastic foil. Etching of the aluminum layer was performed resulting in metal actuation paths. Finally, without requiring any alignment, the complete pattern of the cantilever has been achieved. Optimization of the quality of aluminum thin-film cutting on polyethylene terephthalate (PET) is illustrated in section 8. (See Figure 14 in the supplementary data.)

This multilayer cantilever has also been actuated electromagnetically using one of the two metallic paths available (Figure 9). The mechanical spectra obtained optically are shown in Figures 9c and 9d. The cantilever is 5mm long and has an out-of-plane displacement on the order of 10nm

for the first mode of vibration and 1nm for the second mode of vibration. However, it can be noticed that the measured quality factors are extremely good for a plastic-based structure. This promising design could have sensing or actuating applications.

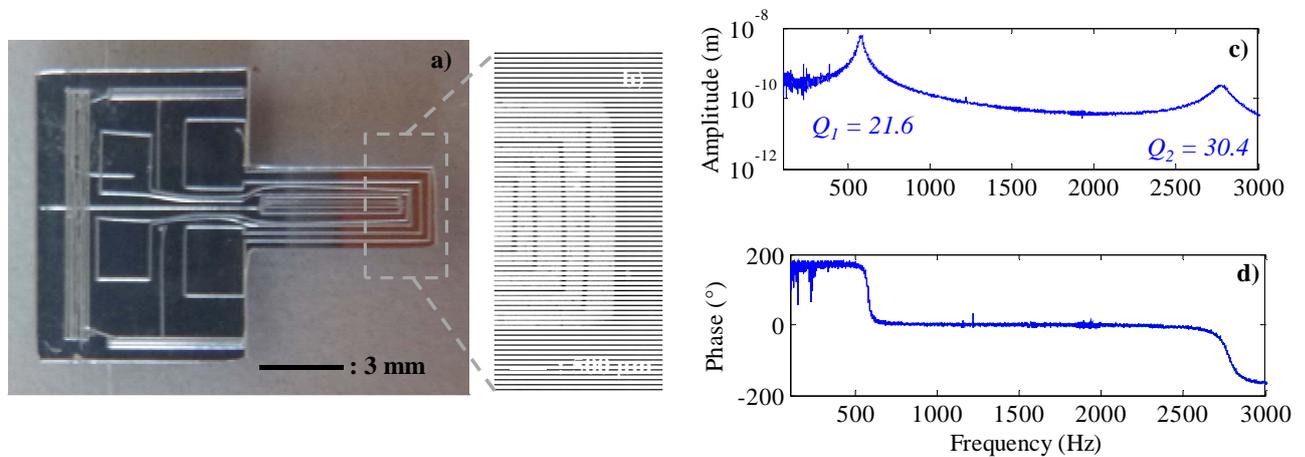


Figure 9 - a) Optical Image of the entire bimorph cantilever (aluminum/plastic), b) Zoomed-in view of the free-end of the cantilever. c) Amplitude and d) Phase of the electromagnetically actuated microstructure measured in air. The quality factors of the two modes are indicated.

Similar structures could be obtained using a plastic mask also cut with the machine; in this case ebeam-evaporation has to be performed through the mask before a final cut of the structure.

### 3.4 Mask fabrication

The main use of a vinyl cutting machine in the future could be for low-cost mask fabrication. Indeed, plastic or metallic masks can easily be fabricated by evaporation, spray-coating, spin-coating or screen-printing deposition processes.

In order to define the limits of resolution of the cutting, a test-pattern including lines, squares and holes has been cut on aluminum and cellulose acetate foils (both commercial products available at supermarkets for contact with food). Figure 10 illustrates the main results obtained with both materials. The layout drawn with the dedicated software is shown in Figure 10a. Firstly, one can observe that a good reproducibility and success rate is difficult to obtain on aluminum foil. Nevertheless, an aluminum mask can be compatible with a high-temperature deposition technique and it can be washable or reusable in many cases. Secondly, the plastic sheet offers an excellent reproducibility. Despite this, plastic masks are not compatible with all types of deposition techniques. Figures 10d and 10e illustrate the possibilities of the cutting and define the best resolution that can be achieved.

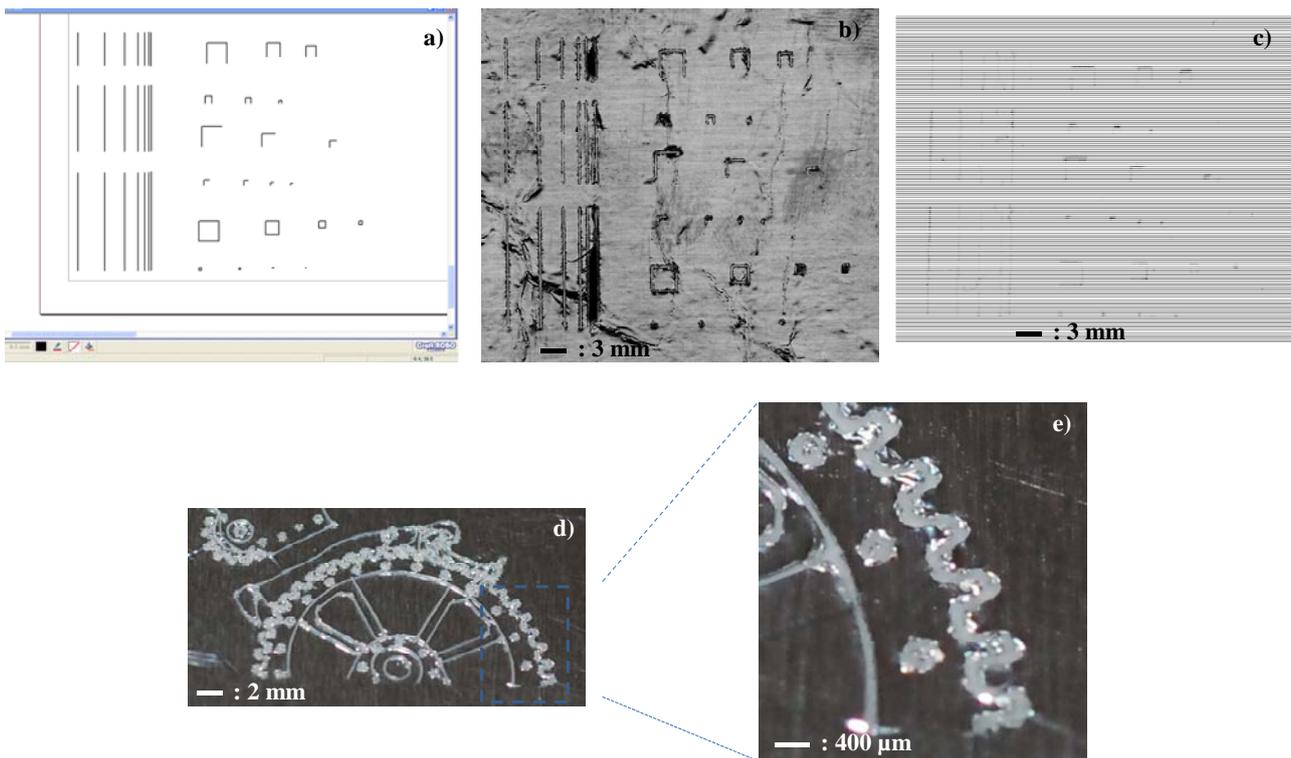


Figure 10 – a) Design of a test mask on the dedicated software, b) Image of an aluminum mask, c) Image of a transparent plastic mask, d) Resolution test on a bimorph support (aluminum over plastic), e) Zoomed-in view of the same image to appreciate the cutting resolution.

The cutting resolution limits for aluminum and plastic are detailed in Table 2.

<b>Cutting resolution (<math>\mu\text{m}</math>):</b>	<b>On aluminum foil</b>	<b>On plastic foil</b>
<b>Minimum line width</b>	180	50
<b>Minimum space between two lines</b>	500 - 1000	200 - 500
<b>Minimum width of a hole</b>	800	200

Table 2 – Estimated resolutions of the fabrication technique on aluminum and plastic foil.

The cutting resolutions obtained are of the same order of magnitude as the resolution of screen-printing techniques (Liang et al., 1996). Therefore, typically expensive screen-printing or stencil-printing masks can be manufactured using the proposed fabrication method at a lower cost. As an illustration, stencil printing of conductive paste is presented as an example in section 8. (See Figure 15 in the supplementary data.) More generally, low-cost masks can be used for any deposition, etching or exposure methods which require a shadow mask.

#### 4. POTENTIAL APPLICATIONS

The quick prototyping of MEMS, especially organic MEMS, is possible using the proposed fabrication method. Two examples of fast MEMS prototyping to test a new concept and/or new materials are illustrated in this section.

#### 4.1 Viscosity sensor

A “U-shaped” structure, shown in Figure 11a, can be used as a physical sensor. Electromagnetically actuated in a liquid medium, the mechanical resonance of the structure can furnish information on the physical behavior of the fluid (Martin et al., 1991; Dufour et al., 2012). The first out-of-plane mode of resonance has been measured in fluids of increasing viscosities. Four different silicone oils provided by Sigma Aldrich have been used. The mass density and viscosity of these Newtonian fluids are precisely established. A first approach is based on the fact that the quality factor of the actuated structure depends on the viscosity of the liquid surrounding the structure. This tendency can be observed in Figure 11b for the mode-1 response.

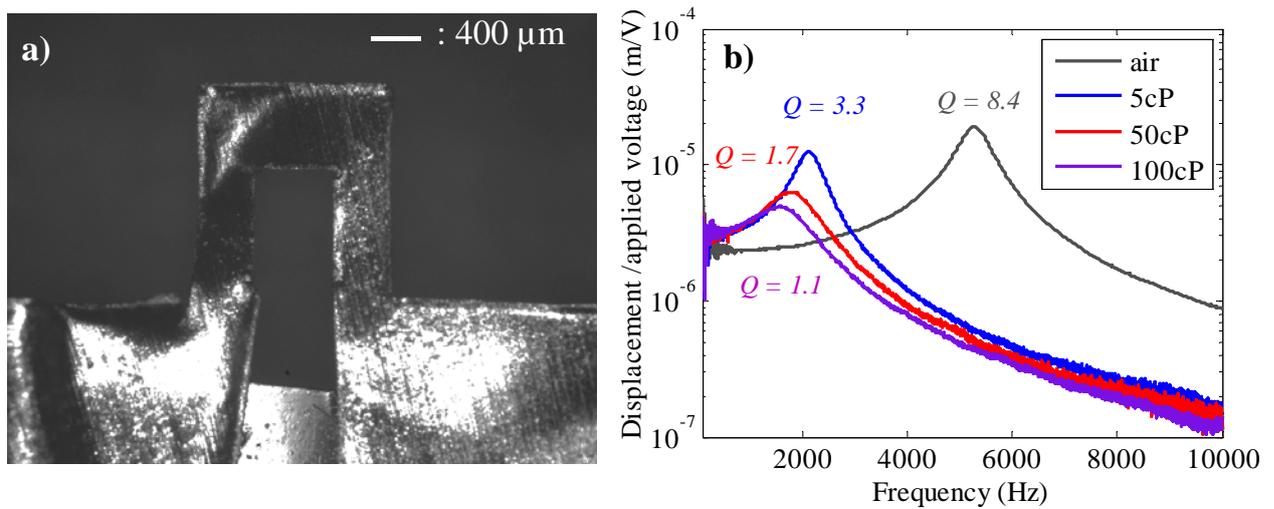


Figure 11 – a) Optical image of a bimorph “U-shaped” structure (Al/SU8); b) Mode-1 resonance of the device measured in air and in calibrated silicone oils having viscosities of 5, 50 and 100cP (or mPa.s).

To be more specific, from the measurements presented in Figure 11 and knowing the structure’s dimensions and properties, the calculation of the mass density and viscosity can be performed. A specific method compatible with a “U-shaped” structure has been developed for this purpose (Belmiloud et al., 2008; Lemaire et al., 2013). After accounting for the internal losses, which are not negligible in this case (the “U-shaped” structure is partially made of plastic), the mass density and viscosity are calculated without calibration. The measured and calculated values are presented in Table 3.

<b>Calibration fluids: silicone oil</b>					
<b>Reference data</b> ( $\rho_k, \eta_k$ )	916.0 kg.m <sup>-3</sup> 5 cP	938.8 kg.m <sup>-3</sup> 10 cP	949.1 kg.m <sup>-3</sup> 20 cP	963.8 kg.m <sup>-3</sup> 50 cP	965.2 kg.m <sup>-3</sup> 100 cP
<b>Measured eigenfrequency</b> ( $f_0$ )	2137.8 Hz	2034.7 Hz	1977.5 Hz	1805.1 Hz	1575.7 Hz
<b>Measured Quality factor</b> ( $Q$ )	4.1844	3.3432	2.5579	1.7399	1.1030
<b>Calculated mass density and viscosity</b> ( $\rho_c, \eta_c$ )	1094 kg.m <sup>-3</sup> 5.030 cP	1144 kg.m <sup>-3</sup> 11.19 cP	1089 kg.m <sup>-3</sup> 19.07 cP	1072 kg.m <sup>-3</sup> 51.76 cP	992.3 kg.m <sup>-3</sup> 155.8 cP

Table 3 – Values of the known physical parameters of the calibrated fluids ( $\rho_k, \eta_k$ ), measured mode-1 response parameters in the medium ( $f_0, Q$ ), and calculated mass density and viscosity values from measurement ( $\rho_c, \eta_c$ ).

The calculated values of mass density might not be considered as sufficiently accurate to evaluate this physical parameter using this “U-shaped” sensor. On the contrary, the calculated values of viscosity show good agreement with the reference values. The measurement error is less than 10% (except for the 100cP oil which is out of the viscosity range of the sensor). The viscosity range of the sensor is a function of the quality factor, i.e., the higher the quality factor, the more accurate the viscosity measurement. In the future a sensor optimized with respect to quality factor may offer even more precise in-situ viscosity measurements. Moreover, using the types of sensors considered in this study (cantilever, “U-shaped”, platelet) actuated electromagnetically, an integrated (non-optical) measurement technique is available and has been used (Heinisch et al., 2012). In summary, the low cost and the low energetic and environmental impacts of the proposed production method offer a real opportunity for the development of a low-cost, low-impact viscosity sensor.

## 4.2 Temperature sensor

A U-shaped piezoresistive organic cantilever-based resonator has been fabricated and used as a temperature sensor. The device has been fabricated as follows. Initially, a piezoresistive solution of CNT/SU8 has been spin-coated on a PET sheet of 100 $\mu$ m thickness. Afterwards, the resonator has been simply patterned using the CNC machine as described previously. The final dimensions of the structure shown in Figure 12 were 2800 $\mu$ m long, 350 $\mu$ m wide (width of an arm) and 118 $\mu$ m thick.

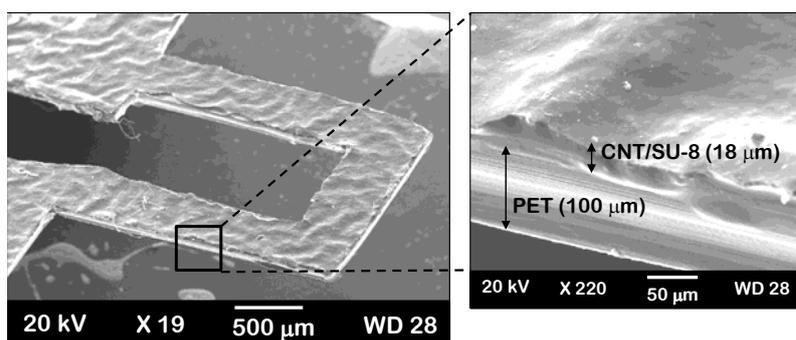


Figure 12 - SEM images of the fabricated resonator.

The electromechanical response of the organic U-shaped microcantilever-based resonator as a function of temperature has been recorded (inset of Figure 13). The resonant frequency of the first out-of-plane flexural mode of vibration has been found to decrease from 3594Hz to 3277Hz as the temperature increases from 23°C to 48°C. Moreover, the quality factor has been calculated at different temperatures without exhibiting significant changes. An average value of  $Q = 20.5 \pm 0.8$  has been measured.

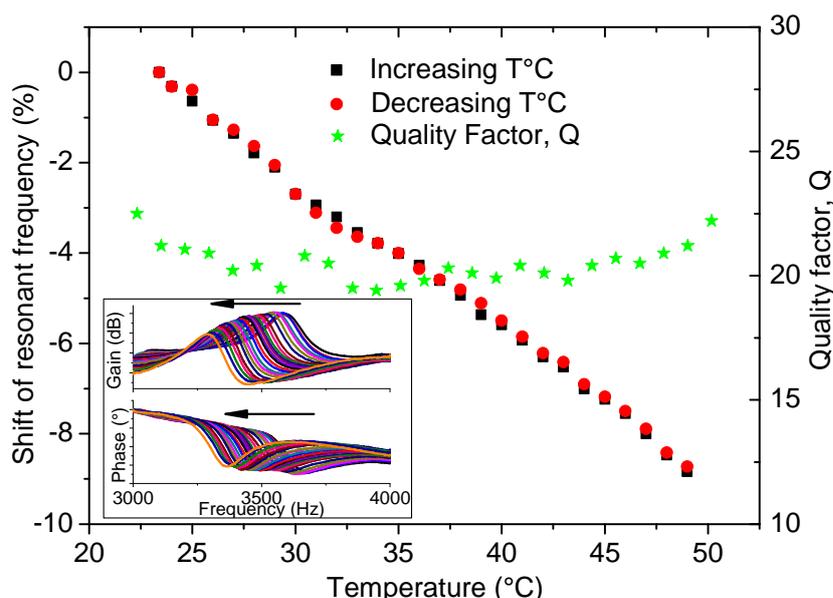


Figure 13 – Measured values of the shift in resonant frequency and the quality factor as functions of temperature.

The relative changes in resonant frequency as well as quality factor versus temperature are plotted in Figure 13. The piezoresistive response to temperature change has shown an excellent linearity with a correlation coefficient ( $R$ ) of 0.9975. The sensitivity of the PET-based resonator has been determined from a linear regression to be  $-0.33\%/^{\circ}\text{C}$  in the range 20-50°C. The limit of detection (LOD) has been calculated to be 0.112°C. These results suggest that organic PET resonators are very sensitive to temperature change and may therefore be considered promising MEMS for applications as temperature sensors for, say, human body temperature measurements or building temperature monitoring. Furthermore, the stability of the fabricated organic resonator to

humidity has been investigated whereby a very small shift of resonant frequency (less than 0.7%) has been observed over the broad relative humidity range of 10 to 90% RH.

## 5. CONCLUSIONS AND FUTURE WORK

A fast prototyping method, named KISSES, has been developed in this work. This original method has three main advantages: (1) low environmental impact, (2) low cost, and (3) extremely fast prototyping. The use of the proposed method can help to make the manufacturing of low-cost, low-impact MEMS a reality. Moreover the fabrication can be achieved completely by reusing common waste materials (aluminum foil, paper, cardboard, etc.), highlighting the concepts of remanufacturing and recycling. As a result, both functioning microstructures as well as prototypes used for elucidating fundamental scientific concepts related to microtechnology can be realized. Moreover, such prototypes can span a broad spectrum of applications and do so at minimal cost while meeting environmental and recycling objectives.

To demonstrate the feasibility of the approach, metal-based MEMS devices have been fabricated using a minimalist process requiring only paper sheet, aluminum foil, an ecological resin-based glue, water and a vinyl cutting machine. The fabricated devices can be recycled along with all the wastes produced during the fabrication: aluminum and paper can be efficiently recycled, while water, which contains the tree resin, can simply be used to water a tree. Therefore, the proposed method (fabrication process and the fabricated system) can be considered to have an extremely low environmental impact.

The materials, tools, and short production time of the process make the proposed fabrication method very attractive for the development of MEMS devices at reduced cost. Indeed, plastic film, aluminum foil and glue can be bought in a supermarket for few dollars. The vinyl cutting machine has an initial cost between \$300 and \$3000 (USD) depending on the brand and resolution. A manual screen-printing tool can be purchased for less than \$100. Consequently, the entire fabrication process can be set up for less than \$2000. Regarding the cost involved, this fabrication technique can also be considered an ideal candidate for scientific educational purposes. Lab sessions on microtechnology and especially MEMS fabrication could be facilitated and realized easily in a short period of time to demonstrate the many concepts involved in microfabrication.

The proposed method should also generate significant interest in application areas involving screen-printing mask fabrication or prototyped organic sensors as illustrated in section 4. In fact, this new fabrication method permits one to bring an idea to reality or to test a new concept in only one day.

Nevertheless, some drawbacks still remain. The optimum resolution of the technique is limited by the cutting machine and is around 50 $\mu$ m. This is not sufficient to manufacture nanoelectronic devices, but once again it can be more than adequate for numerous projects and applications at the micro-scale.

The development of a more general technique which allows for 3-D etching of materials is a future goal, the successful achievement of which would complete the introduction of a new low-cost green-technology for the fabrication of microsystems.

## 6. ACKNOWLEDGEMENTS

The authors would like to thank the University of Bordeaux and the IMS Laboratory which are the major financial and structural contributors to this work. The corresponding author would like to thank Pole Emploi which financed the major part of writing of this paper, written during a period of unemployment.

## 7. REFERENCES

Belmiloud, N., Dufour, I., Colin, A., Nicu, L., 2008. Rheological behavior probed by vibrating microcantilevers. *Appl. Phys. Lett.*, 92, 041907.

Brugger, J., Andreoli, C., Despont, M., 1999. Self-aligned 3D shadow mask technique for patterning deeply recessed surfaces of micro-electro-mechanical systems devices. *Sensor Actuat. A-Phys.*, 76, 329-334.

Dangelico, R.M., Pierpaolo P. 2010. From green product definitions and classifications to the Green Option Matrix. *J. Cleaner Prod.* 18.16, 1608-1628.

Dubourg, G., Fadel-Taris, L., Dufour, I., Pellet, C., Ayela, C. 2011. Collective fabrication of all-organic microcantilever chips based on a hierarchical combination of shadow-masking and wafer-bonding processing methods. *J. Micromech. Microeng.*, 21, 095021.

Dufour, I., Maali, A., Amarouchene, Y., Ayela, C., Caillard, B., Darwiche, A., Guirardel, M., Kellay, H., Lemaire, E., Mathieu, F., Pellet, C., Saya, D., Youssry, M., Nicu, L., Colin, A., 2012. The microcantilever: a versatile tool for measuring the rheological properties of complex fluids. *J. Sensor.*, 2012, 719898.

Dufour, I., Lemaire, E., Caillard, B., Debéda, H., Lucat, C., Heinrich, S.M., Josse, F., Brand, O., 2014. Effect of hydronamic force on microcantilever vibrations: Applications to liquid-phase chemical sensing. *Sensor.Actuat.B-Chem*, 192, 664-672

Espinosa, N., García-Valverde, R., Urbina, A., Krebs, F.C., 2011. A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions. *Sol. Energ. Mat. Sol. C.*, 95, 1293-1302.

Fadel, L., Dufour, I., Lochon, F., Français, O., 2004. Chemical sensing: millimeter size resonant microcantilever performance, *J Micromech. Microeng.*, 14, S23-S30.

Ferrer-Vidal, A., Rida, A., Basat, S., Yang, L., Tentzeris, M.M., 2006. Integration of sensors and RFID's on ultra-low-cost paper-based substrates for wireless sensor networks applications. 2nd IEEE Workshop on Wireless Mesh Networks. 126-128

Graphtec Craft ROBO Pro, <http://www.graphtecamerica.com>

Hallock, J.L., Tharakan, P.J., Hall, C.A., Jefferson, M., Wu, W., 2004. Forecasting the limits to the availability and diversity of global conventional oil supply. *Energy.* 29, 1673-1696.

Heinisch, M., Reichel, E.K., Jakoby, B., 2011. Suspended plate in-plane resonator for rheological measurements at tunable frequencies. *Proceedings SENSOR+Test Conference 2011.* 61-66.

Heinisch, M., Reichel, E.K., Dufour, I., Jakoby, B., 2012. Tunable resonators in the low kHz range for viscosity sensing. *Sensor. Actuat. A-Phys.*, 186, 111–117.

- Hocheng, H., Chang, J.H., Jaddav, U.U., 2012. Micromachining of various metals by using *Acidithiobacillus ferrooxidans* 13820 culture supernatant experiments. *J. Cleaner Prod.*, 20, 180-185.
- Hoffert, M.I., Caldeira, K., Benford, G., Criswell, D.R., Green, C., Herzog, H., Wigley, T.M. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science.*, 298, 981-987.
- Jørgensen, T.H. 2008. Towards more sustainable management systems: through life cycle management and integration. *J. of Cleaner Prod.*, 16, 1071-1080.
- Kunnari, E., Valkama, J., Keskinen, M., Mansikkamäki, P. 2009. Environmental evaluation of new technology: printed electronics case study. *J. Cleaner Prod.*, 17, 791-799.
- Langenheim, J.H., 1990. Plant resins. *Am. Sci.*, 78, 16-24.
- Lemaire, E., Heinisch, M., Caillard, B., Jakoby, B., Dufour, I., 2013. Comparison and experimental validation of two potential resonant viscosity sensors in the kilohertz range. *Meas. Sci. Technol.*, 24, 084005.
- Liang, T.X., Sun, W.Z., Wang, L.D., Wang, Y.H., Li, H.D., 1996. Effect of surface energies on screen printing resolution. *IEEE T. Compon. Pack. B.*, 19, 423-426.
- Liow, J.L., 2009. Mechanical micromachining: a sustainable micro-device manufacturing approach? *J. Cleaner Prod.*, 17, 662-667.
- Liu, X., Mwangi, M., Li, X., O'Brien, M., Whitesides, G.M., 2011. Paper-based piezoresistive MEMS sensors. *Lab. Chip.*, 11, 2189-2196.
- Liu, G., Müller, D.B., 2012. Addressing sustainability in the aluminum industry: a critical review of life cycle assessments, *J. Cleaner Prod.*, 35 108-117.
- Martin, S.J., Granstaff, V.E., Frye, G.C., 1991. Characterization of a quartz crystal microbalance with simultaneous mass and liquid loading, *Anal. Chem.*, 63, 2272-2281.
- Martinez, A.W., Phillips, S.T., Whitesides, G.M., Carrilho, E., 2010. Diagnostics for the developing world: microfluidic paper-based analytical devices. *Anal. Chem.*, 82, 3-10.
- Opera Project, 2009. Towards Green Electronics in Europe - Strategic Research Agenda – Organic & large area electronics.
- Park, J.H., Davis, S., Yoon, Y.K., Prausnitz, M.R., Allen, M.G., 2003. Micromachined biodegradable microstructures. *IEEE The Sixteenth Annual International Conference on Micro Electro Mechanical Systems 2003*, Kyoto, 371-374.
- Rathore, P., Srinivas K., and Amaresh C. 2011. Sustainability through remanufacturing in India: a case study on mobile handsets. *J. Cleaner Prod.* 19.15, 1709-1722.

Rogelj, J., Hare, W., Lowe, J., Van Vuuren, D.P., Riahi, K., Matthews, B., Meinshausen, M., 2011. Emission pathways consistent with a 2°C global temperature limit. *Nat. Clim. Change.* 1, 413-418.

Sheats, J.R., 2004. Manufacturing and commercialization issues in organic electronics. *J. Mater. Res.*, 19, 1974-1989.

Suresha, K.M., Yang, S.Y., Lee, M.H., Kim, J.H., Kim, J., 2008. Actuator, sensor and MEMS devices based on regenerated cellulose. *Compos. Interface.*, 15, 679-685.

Tran, R., Dey, J., Gyawali, D., Zhang, Y., Yang, J., 2011. Biodegradable elastomeric polymers and MEMS in tissue engineering. In: Chio, M., Chiao, J.C. (Eds.), *Biomaterials for MEMS*. Pan Stanford Publishing Pte. Ltd. Chapter 3.

Yuen, P.K., Goral, V.N., 2010. Low-cost rapid prototyping of flexible microfluidic devices using a desktop digital craft cutter. *Lab. Chip.*, 10, 384-387.

## 8. SUPPLEMENTARY DATA

- Thin film cutting (Figure 14): PET foil (125 $\mu\text{m}$  thick) coated with aluminum (150nm thick), cutting of an interdigitated pattern. Line width = 50 $\mu\text{m}$ .

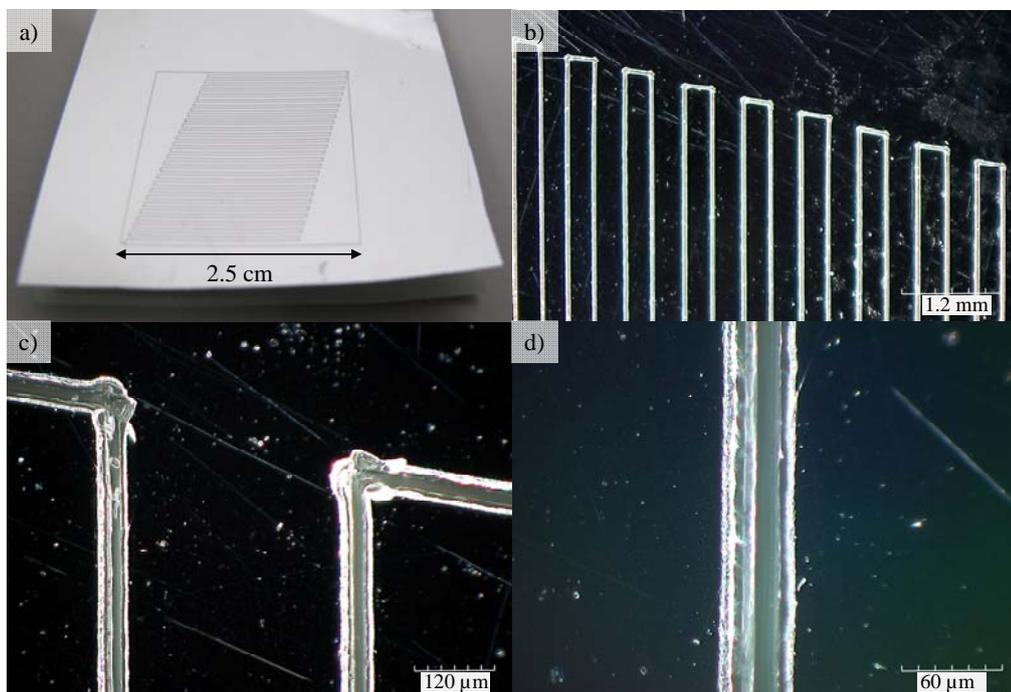


Figure 14 – Interdigitated aluminum electrodes patterned using a vinyl cutting machine: a) Zoomed-out view; b), c), d) Microscopy images of the line cut.

- Stencil printing (Figure 15): low-temperature conductive paste deposition on a printed circuit board (PCB) using a stencil cut with the vinyl cutting machine

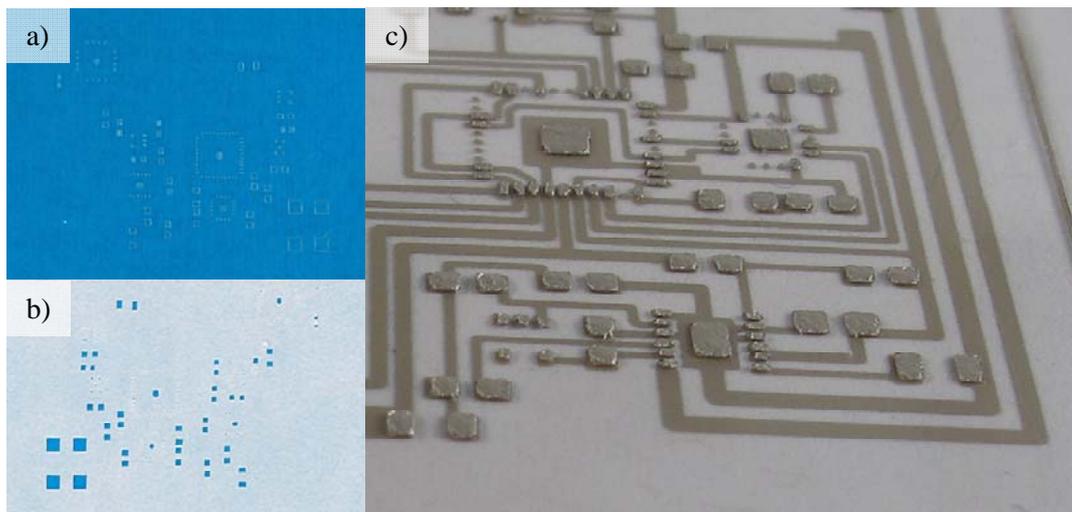


Figure 15 – a) Transparent and b) Opaque stencils cut with the vinyl cutting machine. c) Printed circuit board with conductive paste deposited using stencil printing.