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A DUAL-EDM REVERSE DAMASCENE PROCESS FOR RF SWITCHES AND OTHER BULK METAL DEVICES

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ABSTRACT
This paper reports a manufacturing process suitable for lithography-compatible fabrication of suspended micro-structures from any conductive material (including bulk metal) that is available in sheet form. It uses two aligned steps of batch mode micro-electro-discharge machining followed by a series of filling and lapping steps similar to a damascene process. The process is demonstrated by the fabrication of a bi-stable RF switch from #302 stainless steel foil. The fabricated devices have a footprint of 5 × 5 mm², with 25 µm thickness, and a minimum feature size of 5 µm.

I. INTRODUCTION
A majority of physical microfabricated devices currently use silicon and its compounds as a structural material [1]. The use of silicon is partly attributed to the well-established microelectronics industry, which provides mature technology and supports research that proved the feasibility and benefits of using microsystems in commercial applications and scientific discovery. Many microsystems either substantially benefit from or require the use of the broader material base being widely used at the macro-scale. The need for materials becomes even more pronounced when bio-compatibility or operation in air is desired, as oxidation resistance is essential [2]. Further, the use of specialized materials can potentially eliminate the need for vacuum packaging or facilitate operation in extreme environments, thus broadening the application space and leading to substantial packaging related cost savings.

Here, we report a reverse damascene process sequence to fabricate in-plane released structures from a bulk conductive material. This process is applicable to most conductive materials available in sheet form, including alloys like stainless steel, Pt-Rh [3] and SiC [4]. The development of this process for in-plane structures allows the fabrication of a wide range of devices as demonstrated by other in-plane fabrication technologies like deep reactive ion etching (DRIE) and LIGA [5]. In particular, the process is demonstrated by using #302 type stainless steel to fabricate bi-stable RF switches. This is a category of devices on which the choice of structural material can have a profound impact [6].

II. PROCESS FLOW
The process flow, shown in Fig.1, uses batch-mode electro-discharge machining (EDM) [7] to pattern the conductive structural material from a stainless steel sample (workpiece) using high aspect ratio patterned electrodes that are used as cutting tools. These tools are fabricated using a single mask UV-LIGA process (which is essentially the LIGA process, except that instead of X-ray lithography, ultraviolet lithography is used to fabricate the electroplating mold).

Step 1 The structural conductive material is chosen to be about 50 - 200 µm thicker than the final thickness of the device

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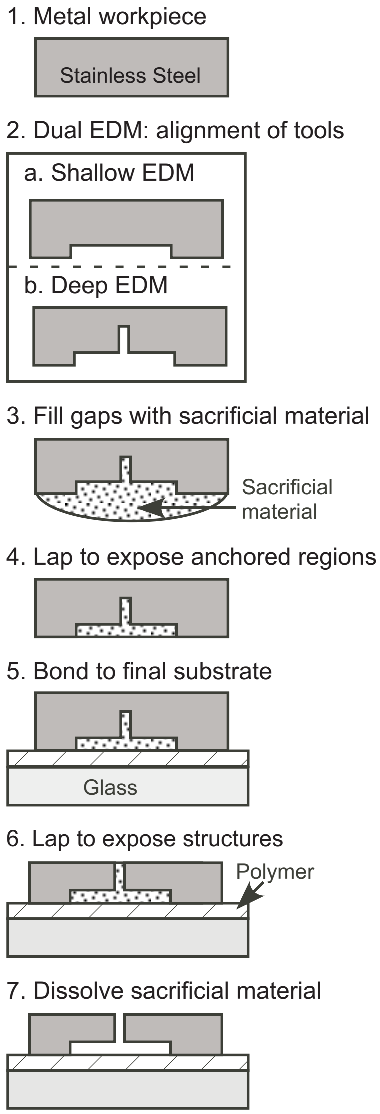

Figure 1. The reverse damascene process flow.

to minimize the amount of material to be removed during subsequent lapping. The important consideration is that the stiffness of the material is sufficient to allow handing and clamping while carrying out EDM. In this case the sample is obtained by cutting a 250 µm thick stainless steel #302 shim stock into 1 cm × 1.2 cm pieces. The thickness tolerance of the sheet is ±5 % and all burrs on the sample are removed by polishing with sandpaper.

Step 2 While carrying out the EDM, the sample is attached on the mandrel of the Panasonic MGD-2625 EDM machine and the tool is placed on the stage as shown in Fig. 2a. This arrangement allows a small sample to be conveniently attached and electrically connected using conductive silver epoxy, while larger EDM tools are placed on the table and electrically connected through metal clamps. The EDM tools typically have dimensions of 2 cm × 2 cm and cannot be electrically connected through their Si substrate.

The flatness of the mandrel with respect to the stage of the EDM machine is maintained by machining its bottom surface

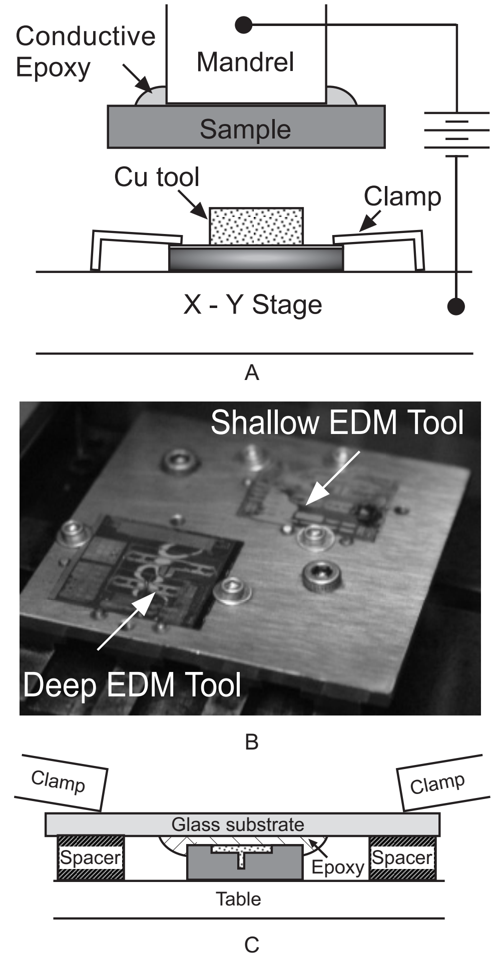

Figure 2. A) Setup for attaching sample (workpiece) to carry out EDM. B) Custom jig for alignment of the dual EDM steps. C) Setup to minimize wedge error while bonding to substrate.

using a wire EDM operation [8]. Also, applying a uniform pressure on the sample during the curing process minimizes any angle between the sample and the mandrel. Once machining is completed, the silver epoxy can be softened in acetone to release the sample.

The attached metal sample is subjected to a pair of consecutive batch-mode EDM [7] steps. A deep EDM step defines structures, and a shallow EDM step recesses these structures from the anchored regions. The shallow EDM is carried out first to a depth of about 8 µm. A larger recess accounts for any wedge error during EDM as well as lapping steps. The sample is cleaned to remove the debris generated and then followed by deep EDM to a depth of about 30 µm. The machining depth is limited by the efficiency of debris removal and electrode wear.

In order to carry out the two-step EDM process, alignment must be carried out. The procedure developed is to fabricate the EDM tools for the two steps on separate wafers and align the individual dice using a custom jig shown in Fig. 2b. The fabrication on separate wafers allows a quicker processing with less care for the shallow EDM tool, as it has large feature dimensions, as opposed to the high aspect ratio deep EDM tool. An alternate approach may be to fabricate the dice adjacent to each other on a single wafer and avoid alignment.

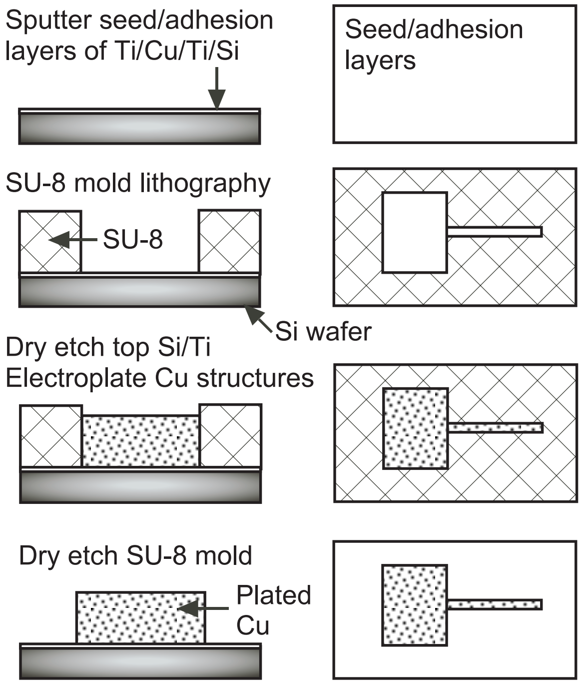

Figure 3. UV-LIGA process used to fabricate copper tools for batch-mode EDM of the steel foil.

The electroplated Cu electrodes are about 100 µm thick, fabricated with SU-8™ as a mold on a Si substrate. The process flow (Fig. 3) starts with sputtering of 500 Å thick layers of Ti/Cu/Ti/Si. The Ti is for adhesion, Cu is the seed layer for electroplating and Si is for adhesion of SU-8. Sputtering is followed by SU-8 lithography to make a 100-µm thick mold with 10 µm wide trenches. The top Ti/Si layers are etched away in a CF_4/O_2 plasma exposing the underlying seed layer of Cu. This is followed by Cu electroplating with agitation to form the copper structures with an aspect ratio of 10:1. The wafer is then lapped to planarize the top surface to account of variations in plating rate with position and feature size. The SU-8 mold is stripped in a CF_4/O_2 plasma at high power with the Cu seed layer serving as an etch stop. The wafer is coated with a thick layer of photoresist and then diced using a dicing saw. The photoresist that protects the structures during dicing and is then removed in Baker PRS-2000™.

Step 3 The trenches formed are filled with a removable filler material, in this case ethyl cynoacrylate and allowed to cure for about four hours. An alternative for the filler could be electroplated copper. The filler serves to cover the released structures during subsequent bonding to glass substrate with epoxy and provide mechanical support while lapping. In the absence of the filler, the epoxy would adhere to the released structures as well as the anchor regions.

Step 4 The wafer is then lapped to remove the excess cynoacrylate and expose the anchor regions. During lapping the sample is attached to a holder wafer using paraffin wax.

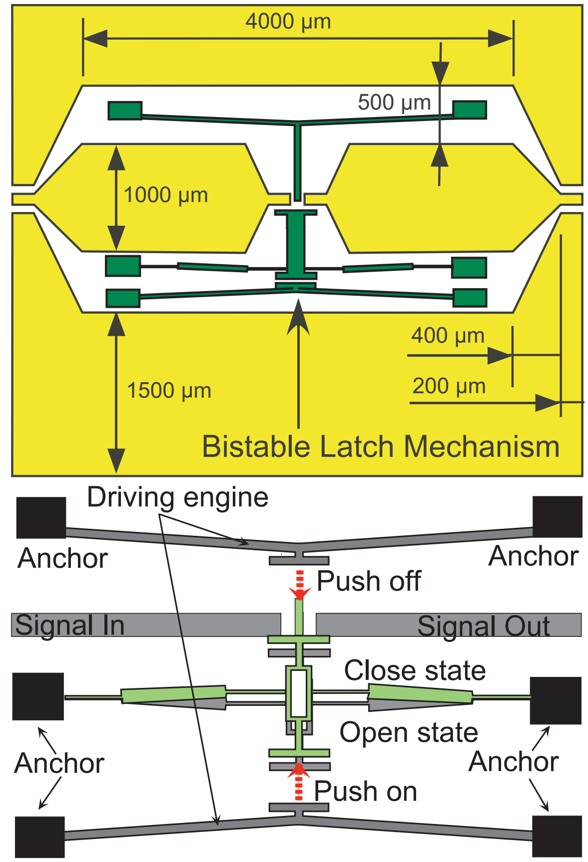

Figure 4. Schematic of the RF-switch and bi-stable mechanism with dimension of the coplanar waveguide (CPW) .

Step 5 The exposed regions and the filler are bonded to a glass substrate using epoxy (Araldite 2055). In order to avoid a wedge between the sample and the substrate, it is cured clamped with spacers between the glass substrate and a flat table surface as shown in Fig. 2c.

Step 6 The bonded metal sheet is then lapped back, similar to a damascene process [9], except that the structural material is defined by the negative image (or reverse) of the damascene layer.

Step 7 The final release is carried out by stripping the sacrificial filler in acetone.

III. DEVICE STRUCTURE & FABRICATION RESULTS

The reverse damascene process has been used to fabricate a bi-stable single-pole-single-throw (SPST) RF switch for a coplanar waveguide (CPW) [10], as shown in Fig. 4. The electromagnetic simulations used Sonnet™, while the bi-stable mechanism and electrothermal actuators were designed using ANSYS™ to provide a switch closing force in the milli-Newton range, enabling the potential to have a high RF power efficiency. A bent-beam electrothermal actuator is located on either side of the CPW, and generates in-plane motion that is orthogonal to the CPW. These actuators are used to toggle a bi-stable switch that, in its closed position, serves as a bridge across a small break in the CPW.

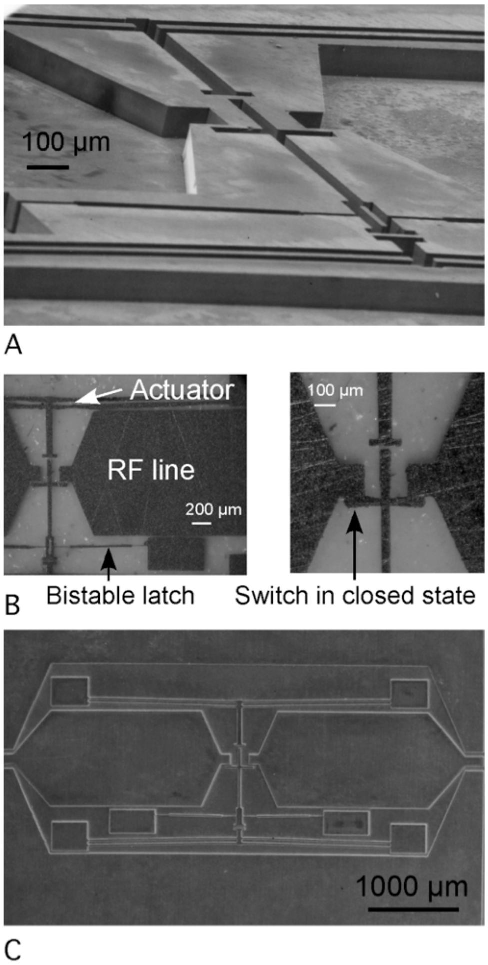

Figure 5. A) SEM of UV-LIGA tool used for EDM. B) Optical micrographs of switch in on and off state. C) SEM of fabricated RF switch.

Figure 5a shows a SEM of 100 µm tall copper structures with a minimum feature size of 10 µm use as a tool for the dual-EDM. The 20 µm wide actuators and the bi-stable mechanism are shown with the switch in the off state (Fig. 5b), as well as the on state of the switch. A SEM image of the overall device is shown in Fig. 5c. The device has 25 µm thick structures separated from the substrate by a gap of 5 µm. The minimum feature generated is a 5 µm wide beam of the bi-stable mechanism.

An important consideration is the minimum feature size achievable with the process, which is determined by the dimensions of the copper electrodes as well as the EDM process itself. For a tool fabricated with UV-LIGA, a height-to-width aspect ratio of 10:1 is achievable; the height of the tool is selected to be about 50 μm taller than the thickness of the final structures desired. This additional height is to account for tool wear, wedge error and gap for debris removal. Due to the viscosity of the SU-8 photoresist electrode heights up to about 250 μm are convenient to process.

For a 100 μm thick copper tool, the minimum feature on the SU-8 mold will be a 10 μm trench. This trench will create a 10 μm wide electroplated structure, which is used to create trenches in the final stainless steel sample material. The width of the EDMed trench on the steel sample created is greater than that of the copper electrode due to an additional discharge gap of about 5 μm, which leads to trenches of about 20 μm width. The length of a trench also limits the width of a trench achievable, as electrode wear increases considerably with length. For structures with dimensions such as the RF switch, using copper electrodes of widths less than 10 μm may be challenging due to excessive electrode wear.

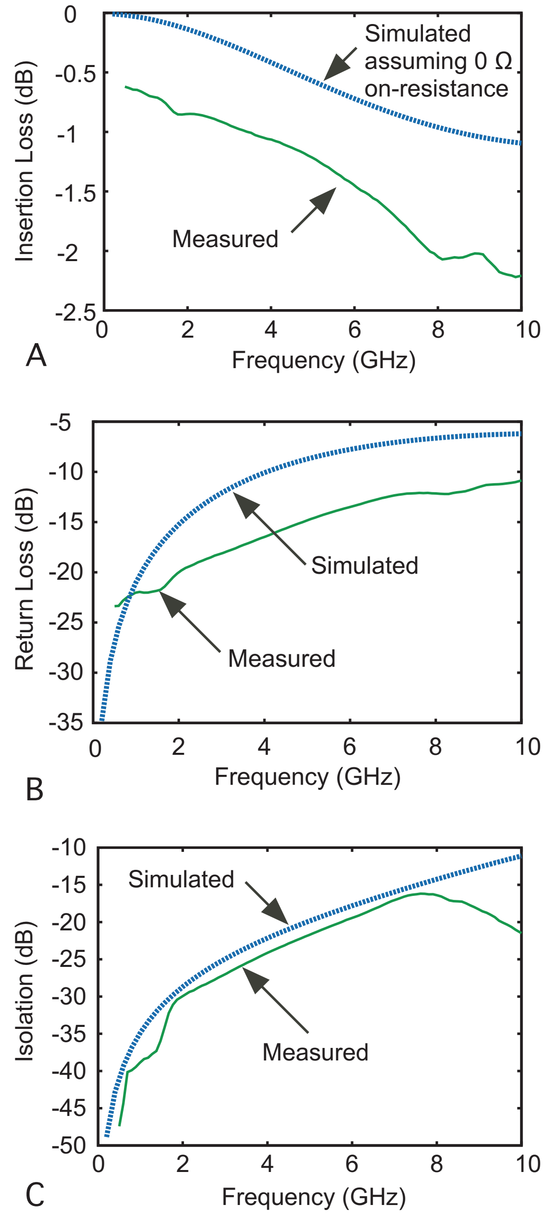

Figure 6. Measured RF test results for insertion loss, return loss and isolation, shown along with idealized simmuations that neglect parasitic resistances

In the case of beams on the final substrate, features of about 5 μm are achievable by accounting for the discharge gap. By placing copper electrodes 15 μm apart, a 5 μm discharge gap on either side, leads to 5 μm beams.

The heights of the final structures are limited by the lapping and wedge errors. Structures less than 25 μm tall (thick) are challenging: at these thicknesses, narrower features (< 10 μm) may be sheared off during the final lapping step. It is convenient to make structures greater than 50 μm in height to simplify the alignment and lapping steps.

IV. RF RESULTS

The switch has been tested in its on and off state and RF characteristics have been determined for insertion loss, return loss and isolation. These characteristics are compared to idealized simulated values in the absence of resistance. Figure 6a shows that the measured insertion loss is 0.7 dB at 2 GHz and could be due to the oxide on the surface of stainless steel. Figure 6b shows that isolation better that -30 dB at 2 GHz, while Fig. 6c shows the return loss in less than -10 dB from DC to 4 GHz.

V. CONCLUSIONS

The reverse damascene process developed can be used to fabricate in-plane released structures from any conductive material available in sheet form. The process expands the range of materials available for microfabricated devices to bulk metals, which offer the ability to operate without packaging in ambient or extreme environments. A number of bulk metals are also well-known to be bio-compatible for applications that need this feature. The process is demonstrated by fabricating a bi-stable RF switch from #302 type stainless steel with 25 μm thick structures with a minimum feature of 5 μm. The RF tests results provided for the switch indicate that the use of noble metal alloys could potentially improve the electrical characteristics of this device. For example, in the future, this fabrication process may be repeated with Pt-Rh alloy.

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