Polymer-Based Cantilevers With Integrated Electrodes

Schahrazede Mouaziz, Giovanni Boero, Radivoje S. Popovic, *Member, IEEE*, and Jürgen Brugger

***Abstract*—An innovative release method of polymer cantilevers with embedded integrated metal electrodes is presented. The fabrication is based on the lithographic patterning of the electrode layout on a wafer surface, covered by two layers of SU-8 polymer: a 10-μm-thick photo-structured layer for the cantilever, and a 200-μm-thick layer for the chip body. The releasing method is based on dry etching of a 2-μm-thick sacrificial polysilicon layer. Devices with complex electrode layout embedded in free-standing 500-μm-long and 100-μm-wide SU-8 cantilever were fabricated and tested. We have optimized major fabrication steps such as the optimization of the SU-8 chip geometry for reduced residual stress and for enhanced underetching, and by defining multiple metal layers [titanium (Ti), aluminum (Al), bismuth (Bi)] for improved adhesion between metallic electrodes and polymer. The process was validated for a miniature 2×2 μm^2 Hall-sensor integrated at the apex of a polymer microcantilever for scanning magnetic field sensing. The cantilever has a spring constant of $\cong$1 N/m and a resonance frequency of $\cong$17 kHz. Galvanometric characterization of the Hall sensor showed an input/output resistance of 200 Ω, a device sensitivity of 0.05 V/AT and a minimum detectable magnetic flux density of 9 μT/Hz$^{1/2}$ at frequencies above 1 kHz at room temperature. Quantitative magnetic field measurements of a microcoil were performed. The generic method allows for a stable integration of electrodes into polymers MEMS and it can readily be used for other types of microsensors where conducting metal electrodes are integrated in cantilevers for advanced scanning probe sensing applications. [1573]**

***Index Terms*—Dry etch, Hall sensor, integrated electrodes, polysilicon sacrificial layer, stress-reducing geometries, SU-8 cantilever, thin film metal deposition and lift off.**

I. INTRODUCTION

SENSORS based on cantilevers have seen a rapid growth recently as their relative simple mechanical behavior allows straightforward translation of mechanical forces into displacement. Cantilevers have the additional advantage that micro and nanosensors placed on their distal can be approached to surfaces for investigation of material properties. Microcantilevers were originally made for surface probing in atomic force microscopes (AFM) where typically silicon and silicon nitride is used as cantilever material. Polymer-based devices are interesting alternatives to silicon for selected applications in micro/nano-electro-mechancial-systems (MEMS/NEMS), particularly when the polymer materials can be functionalized for enhanced specific material properties (e.g, optical, electrical, and mechanical). Possible applications include scanning probe instruments, accelerometers, pressure sensors, but also biomedical microinstruments and microfluidic devices. Many polymer-based materials can be rendered photosensitive which allows the realization of microstructures using lithography and moulding techniques to form quasi-three-dimensional (3-D) devices. For instance, SU-8 [1], [2] is an epoxy-type negative tone photoresist with a low optical absorption in the near UV range spectrum. This allows the micropatterning of thick coatings with vertical sidewalls and high-aspect ratio. Once SU-8 is cross-linked it is chemically stable and resistant to most solvents and acids. It has a very high thermal resistance and good mechanical properties as well. Due to the high-aspect ratio capability it has been used, at the beginning, as mold for electroplating for metallic-microgears [3], microcoils [4], and wheels [5] and as a basic material for fabrication of microfluidic channels [6], [7] and microgears [4], [8]. Later, SU-8 was used also as structural material for micromechanical devices such as AFM cantilevers with integrated moulded nanoscale tips [9]. The fact that SU-8 has about 30 times smaller Young's modulus E than silicon (E_{SU8} =4−5 GPa and E_{Si} = 167 GPa [10]) makes SU-8 extremely interesting as cantilever probes. Another interesting concept incorporated SU-8 pillars on the top of silicon cantilevers as additional mass to alter their resonance frequency [11].

Unfortunately, unlike silicon with its semiconducting and piezoresistive properties, SU-8 is a passive material, i.e., it has no inherent properties that can be exploited for sensing applications. To overcome this limitation, two distinct approaches have been proposed recently.

- The first method is to modify the SU-8 itself by incorporating micro and nanoparticles into the polymer. Jiguet *et al.* added Ag particles (mean size of the particles is about 1.1 μm) to make SU-8 conducting [12]. Gammelgaard *et al.* developed an SU-8/carbon composite by mixing carbon-black particles into SU-8 [13]. In both cases the composite material could still be structured by standard UV lithography although the resolution was deteriorated because of the particle induced scattering of the UV light used to expose the resin.
- The second possibility is to embed electrode structures on the surface of SU-8. This was first shown by Kim *et al.* where a self-assembled monolayer (SAM) was used as anti-adhesion coating for a dry mechanical release [14]. Thaysen *et al.* showed recently a first generation of SU-8 cantilevers with integrated metallic strain gauge for use in AFM or chemomechanical transducers [15].

In this paper, we present a microfabrication method for polymer-based cantilevers with integrated electrodes suitable for the realization of cantilever sensing systems technique.

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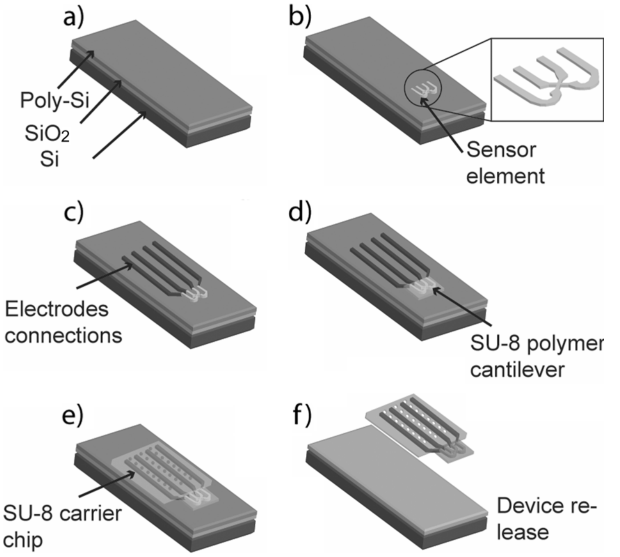

Fig. 1. Schematic illustration of the process for SU-8 cantilever with integrated electrodes. (a) Silicon wafer with 0.5 μm of thermal oxide on which 2 μm of polysilicon sacrificial layer is deposited. (b) Electrodes (e.g., micro Bi-Hall sensor) realized with lift off. (c) Thin metallic film structured with lift off to pattern the electrodes. (d) and (e) Thin and thick SU-8 photoresist layers spin-coated on the patterned thin metal films and treated with the suitable, low stress process.(f) Release the devices by plasma etching of the polysilicon.

The novelty in this microfabrication technology is the use of polysilicon as a sacrificial layer removed by a dry-etching technique. As demonstrator we present a new micron-scale magnetic field sensor based on a bismuth (Bi) Hall-probe integrated at the distal end of a SU-8 cantilever. The highly sensitive Bi Hall-probe can be scanned across the sample and measure the magnetic stray field with high spatial resolution. In view of our application, Bi is the appropriated material for the micro-Hall sensors.

However the method is compatible with a variety of other metallic thin films.

II. EXPERIMENTAL PROCESS

A. Hall Sensors and Electrodes

A silicon wafer with 0.5 μm of thermally grown silicon dioxide is used as a substrate. A 2-μm-thick layer of polysilicon is deposited by low-pressure chemical vapor deposition (LPCVD) and used at the end of the process as a sacrificial layer to release the devices [Fig. 1(a)]. Standard negative tone resist (MAN 1410) photolithography is used to pattern with lift off the Bi, the material used to produce Hall sensors [see Fig. 1(b)]. Bi is a semimetal with a carrier concentration fifth-order magnitude smaller than metals, low resistivity, and negligible surface charge depletion effects, the usual limiting factor to the miniaturization of semiconductor devices [16]. Hexamethyldisulazane (HMDS) adhesion promoter is used in an oven at 150 °C to enhance the bonding of the photoresist to the polysilicon surface. Then, a 1.35-μm-thick MAN 1410 negative photoresist is spin-coated in Rite Track, an automatic spin coater, at 2000 rpm for 45 s. The resin is baked 90 s at 98 °C, exposed to the UV light during 40 s (corresponding time to an energy of 370 mJ/cm^2) and developed in a beaker in a time of 90 s. Evaporation of Bi is carried out by Joule effect in Alcatel EVA 600 evaporator. The thickness and the rate of deposition are 300 nm and 5 Å/s, respectively. Metal lift off is done first in a bath of EC solvent for 120 min; then, in a second bath of acetone for 60 min. The wafers are cleaned in isopropanol, quick dump rinse (QDR), and ultraclean rinse, consecutively.

The electrodes made with two metallic thin films, Ti-Al are structured by lift off in the same way as Bi. After photolithography of 1.35-μm MAN 1410, Ti and Al are deposited successively by e-beam evaporation with Alcatel EVA 600 [see Fig. 1(c)]. The thickness and rate of deposition are 20 nm at 5 Å/s for Ti and 280 nm at 10 Å/s for Al. Metals lift off is similar to aforementioned Bi thin film. The choice of the bilayer Ti-Al is based on the fact that the SU-8 has a good adhesion on the Al but the direct electrical contact between the Bi and Al is not optimal.

B. SU-8 Polymer Cantilevers and Carrier Chip

After dehydration of the substrate in the oven at 150 °C for 20 min, an initial thin layer of SU-8 (2007 Microchem) is spin-coated in RC8 spin-coater to produce cantilevers of the following dimensions: 500-μm length, 100-μm width, and 10-μm thickness [see Fig. 1(d)]. The spin-coating is done in two ramps: the first at 1000 rpm for 5 s and the second at 1500 rpm for 40 s. Stress control is achieved by a careful adjustment of all thermal treatments during the process. This step is extremely important to reduce the mechanical stress on the cantilevers and to improve the adhesion of the metallic structures on the SU-8 cantilevers. The softbake and the postexposure bake programs are composed of temperature ramps of 1 °C/min with a waiting time of 50 min at 65 °C and then 60 min at 95 °C. This is a relatively longer than usual postbake procedure, but is well optimized to reduce the stress significantly. Because of light reflection from the metal layers below the SU-8 layer, the energy of the UV exposure is reduced to the lowest possible value, which in our case is 100 mJ/cm^2. The photoresist is developed with propyleneglycol monomethyl ether acetate (PGMEA) for 2 min and 30 s, rinsed in isopropanol, and dried carefully in a nitrogen gas stream. An oxygen plasma treatment is necessary to clean the substrate surface, which is carried out using 500 W of 2.45 GHz RF power for 30 s in Tepla 300. This preceded the spin-coating in the RC8 of the thick SU-8 (50 Microchem) photoresist, a layer to build a carrier chip structure of 2.5-mm width, 4.5-mm length and 200-μm thickness [see Fig. 1(e)]. First ramp is at 400 rpm for 5 s and the second is at 600 rpm for 40 s. This layer is prebaked at 65 °C for 60 min and then ramping the temperature at 1 °C/min to 95 °C for 120 min. The layer is exposed with an energy of 600 mJ/cm^2, and post baked in the same way as it is prebaked. Finally, the SU-8 layer is developed in PGMEA during 23 min and rinsed with isopropanol.

C. Devices Release

A crucial step is to detach the fragile elements from the surface via a sacrificial layer technique without altering their performance. In the past, several releasing methods using wet chemistry have been presented for SU-8 based devices, such as positive tone photoresist or Ti etching by hydrofluoric (HF) acid [5] and by enhanced sacrificial layer etching [17]. It has also been shown that a mechanical dry-release technique based on the anti-adhesion coating of a self-assembled monolayer (SAM) film as sacrificial layer can be used [14]. The advantage of using SAM is that surface features down to the nanometer scale can be replicated into the polymer film due to the extremely thin SAM layer (<2 nm). This enabled the realization of metal-coated photoplastic probes for scanning near-field optical applications (SNOM) with sub-70-nm optical resolution. The disadvantage of the SAM release technique is that the relatively high force needed to detach the photoplastic elements from the surface can only be applied to solid and compact devices, and not to mechanically compliant elements such as elastic flexible cantilevers. Recently, Zou *et al.* presented scanning probe microscopy (SPM) probes made with a metal tip and a polymer handle. The wet etching release was based on a copper sacrificial layer removed by a mixture of acetic acid, hydrogen peroxide, and water [18]. Metz *et al.* showed the technique of anodic dissolution of sacrificial metal layers for the complete or partial detachment of microstructures [19].

In our case, the release of the whole device containing metals integrated to the cantilevers and the carrier chip is performed in an Alcatel 601, a high inductively coupled plasma (ICP) reactor using SF_6 at 20 °C to dry etch the polysilicon sacrificial layer [see Fig. 1(f)]. Due to its high selectivity compared to the polysilicon (>200), the SiO_2 is used as an etching stop layer. The devices are released in about 15 min with a rate of under dry etch of about 3.5 μm/min. The dry-etching time depends strongly on the mask design shape, which is discussed in detail in Section III-A.

III. Results and Discussions

A. Optimized Structural Geometry for Improved Underetching and Stress Release in SU-8 Structure

In order to easily handle the probes, a bulk chip of millimeter size (4.5×2.5 mm^2 in our case) is necessary. In addition, the presence of four electrodes that establish the contact to the electronic part of the setup requires a mechanically stable bulk chip. The release by dry etching of a chip with dimensions in the millimeter range requires more than 60 min when using the aforementioned etching parameters. This has a negative impact on microstructures released after a short time (e.g., Bi is etched with the fluorine reactive etching gas [20]). We investigated new mask designs to find the shape that leads to the shortest under dry-etch time in order to protect the delicate materials (Bi in our case) from a long exposition etching time, a compromise between the stability of the bulk chip and the under etch time. Two decisive points for the mask designs are taken in consideration. First, any large structure needs to contain holes which enable the reactive gases to penetrate and etch the sacrificial layer. Second, the size of the holes has to be as large as possible. Different designs are conceived that help to determine the most efficient structures. In a carrier chip having diamond-shape, features of 270-μm size (see Fig. 2) are underetched, while in honeycomb pattern (see Fig. 3), the structures to release have only 50-μm size. The time to release the carrier chip with small diamond-shaped holes is almost six times longer than for the honeycomb pattern.

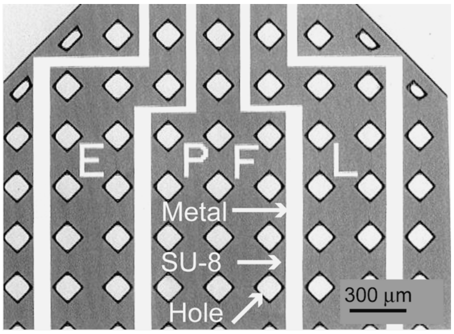

Fig. 2. Optical image of SU-8 chip with diamond shape holes and four embedded metal electrodes. For this design, the time for dry etch of the polysilicon sacrificial layer is 80 min (which is too long for the exposed metal).

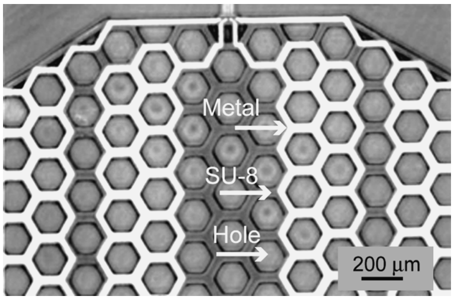

Fig. 3. Optical image of SU-8 structure with embedded metal electrodes. The time for dry etch of this geometry is 15 min (which is an acceptable time for the exposed metal).

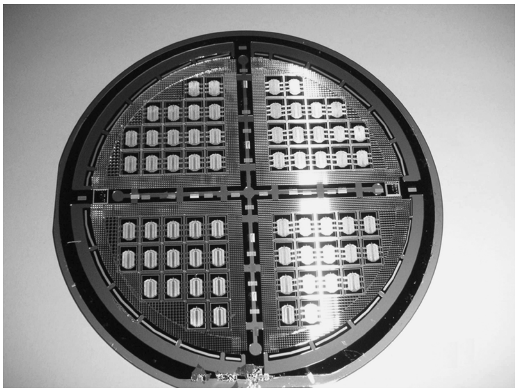

Fig. 4. Photograph of a full wafer (100 mm) that contains 64 chips after the dry-etch release. The devices stay fixed to the wafers by means of six bars that are broken before using the device.

B. Fabricated Devices

An optical image of a 100-mm wafer after the finished process is shown in Fig. 4. The wafer contains 68 cantilever chip devices that are still attached to a rim on the wafer by six tiny SU-8 bars. The devices are handled individually by detaching them from the wafer after breaking off the bars using tweezers. Fig. 5 shows the Al–Ti metallic tracks on the SU-8 carrier chip demonstrating that the metal film adheres very well to the SU-8. This allows electrical connection by

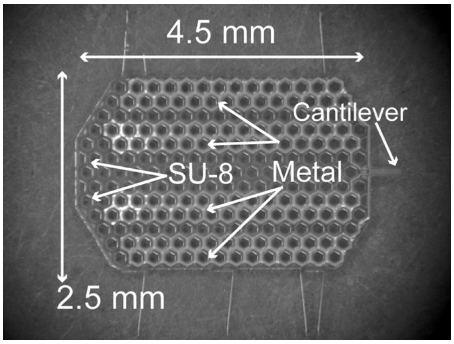

Fig. 5. Photograph of a complete device made with SU-8 thick photoresist for the carrier chip and on the top four metallic electrodes of Ti-Al.

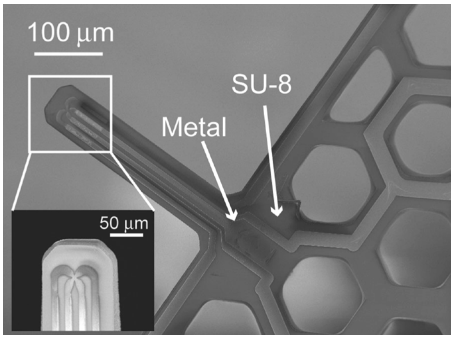

Fig. 6. Scanning electron microscopy image after dry-etch release of the device. The patterned Ti-Al bilayer has a good adhesion to the SU-8 cantilever and carrier chip. A Hall sensor of 2 × 2 μm^2 active area made with 300-nm thickness Bi thin film is integrated at the edge of the SU-8 cantilever.

means of standard miniaturized metallic microprobe needles or other chip-to-chip interconnects using spring-like clamps. The patterned Bi on the cantilever shows excellent adhesion as well; no delamination has been observed. A complete Hall sensor on SU-8 cantilever is shown in Fig. 6.

C. *Mechanical Characteristics of the Cantilevers*

The SU-8 cantilever with the metallic tracks has been mechanically characterized with an interferometer and the results have been confirmed by laser beam deflection in an AFM setup. The SU-8 and the multiple layers of metal (Al–Ti–Bi) are sufficient to reflect the laser light. For a rectangular cantilever of the 500-μm length, 100-μm width, and 10-μm thickness, the resonance frequency is $\cong$17 kHz and the estimated spring constant is $\sim$1 N/m. The measured quality factor in air is about 30. Long-term measurements over several days of continuous operation with a vibration amplitude of 200 nm rms have shown no noticeable deterioration of the mechanical and electrical characteristics of the sensor performance and resonance frequency. It demonstrates the stable integration of metal electrodes in the SU-8 cantilever device.

D. *Galvanomagnetic Characteristics of Hall Sensor*

The Bi Hall sensor shown in Fig. 6 has been electrically and magnetically characterized. The input/output resistance of the sensor is 200 Ω. The maximum current applied is 4 mA. Up to this current value the voltage measured stays constant and then fluctuations appears due to the increase of the resistance.

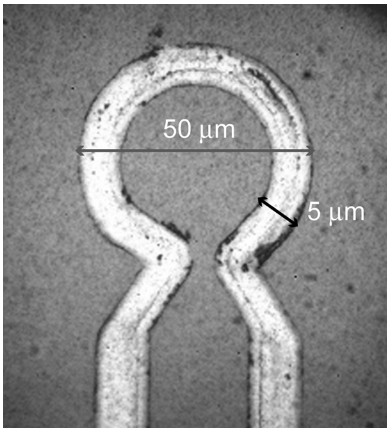

Fig. 7. Optical image of microcoil used to calibrate the Hall sensors. The diameter of the microcoil is 50 μm and the width is 5 μm.

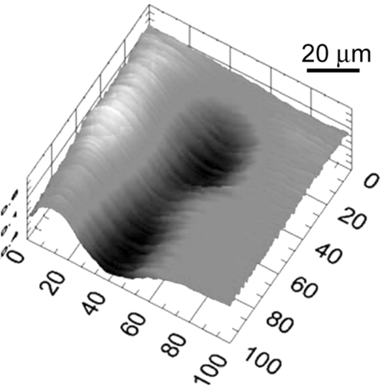

Fig. 8. Magnetic field image of the microcoil shown in Fig. 7 measured with the Hall sensor represented in Fig. 6.

The sensor sensitivity is 0.05 V/AT whereas the minimum magnetic flux density detectable is 9 $\mu T/Hz^{1/2}$ above 1 kHz at room temperature. A preliminary magnetic imaging experiment has been carried out over a microcoil of 50 μm diameter made with Al (300 nm) deposited on SiO_2 on a Si substrate as shown in Fig. 7. With a coil current of 20 mA, the magnetic field at the coil center is about 500 μT. A scanning Hall probe microscope image of the microcoil (shown in Fig. 8) proves the feasibility of magnetic imaging with Bi Hall probes integrated on SU-8 cantilever. The scanning range $(100 \times 100\ \mu m^2)$ is in XY plan and the separating distance (1 μm in our case) between the sample and the sensor is in Z-axis, the direction of the detected magnetic field coming from the microcoil.

IV. CONCLUSION

Our experiments show that a dry-etching technique of a sacrificial polysilicon layer is feasible and reproducible to release polymer cantilever devices, formed with integrated electrodes on SU-8 support. The releasing technique is clean, fast, and reliable, and can be used for many applications as long as the materials involved are compatible with the ICP etch gases. The releasing time depends on the mask design that has to be adapted to the shapes of the devices and the materials used in the process. We have proven that the cross-linked SU-8 is a suitable material to integrate patterned metals as it shows a high resistance to the etch gas SF_6. The thermal treatment of SU-8 has been optimized in order to reduce the mechanical stress and improve the adhesion of the electrodes. There is no apparent mechanical stress on the SU-8 structures nor damage in general to the SU-8 cantilevers or on the carrier chip, even after a long etch times. The method has been developed and validated for the fabrication of a micro-Hall sensor on cantilever for scanning magnetic microscopy. A microstructured Bi cross is connected with four conducting wires Ti/Al to contact pads leading to the external readout electronics.

Due to its interesting chemical, mechanical, and optical properties, SU-8 is a very promising material for MEMS/NEMS applications. The generic technology described in this paper can be considered as a window for new opportunities. It can readily be applied to the fabrication of microcoils, similar to those shown in Fig. 7, for electron spin resonance microscopy and integrated four-point microprobes for electrical characterization of metallic thin films, etc., [21]. The described technology opens the way to further advances in the field of functional polymer sensors combined with surface microfabrication techniques. The devices are constructed layer by layer (metal and photoplastic polymer) on a planar surface offering all advantages of microfabrication methods, including low-cost mass-fabrication potential.

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