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TECHNICAL NOTE

Uncrosslinked SU-8 as a sacrificial material

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Abstract
SU-8 has gained wide popularity as a surface micromachining material, mostly due to characteristics of the epoxy in the crosslinked state. However, uncrosslinked SU-8 also has interesting properties, particularly as a planar sacrificial layer in surface micromachined processes. Uncrosslinked SU-8 can maintain a flat, stable surface for subsequent surface micromachining; it is chemically resistant to subsequent surface micromachining; and uncrosslinked SU-8 can be removed selectively in the presence of a wide range of materials, including metals, semiconductors, oxides, ceramics and many polymers. The processing of uncrosslinked SU-8 as a sacrificial layer is mostly unchanged from the conventional method. However, care must be taken to not to expose the SU-8 to UV radiation when patterning and avoid significant movement of the uncrosslinked SU-8 when taken above the glass transition temperature (∼65 °C). In this paper, uncrosslinked SU-8 as a sacrificial layer is demonstrated, the fabrication details are described, and an application is shown.

1. Introduction

Surface micromachined, mechanically free microstructures often utilize a sacrificial layer to release the mechanically free part. Sacrificial layers have several necessary characteristics. They must provide a stable, planar platform for subsequent surface micromachining. They must be chemically resistant to subsequent processing. Finally, they must remove easily, cleanly and selectively to release the mechanically free structure. Only a few materials fulfill these requirements, the most widely used in the MEMS field being SiO_2 (Howe 1988, Monk *et al* 1992) and copper (Kim *et al* 1992).

The introduction of high aspect ratio microfabrication technologies, such as SU-8 epoxy (Lorentz *et al* 1997), has greatly expanded the accessible design space for micrometer scale systems. These micromachining technologies extend MEMS designs into the third dimension by tens or even hundreds of micrometers. However, neither SiO_2 nor copper scales well with the increasing thicknesses allowed by SU-8. The deposition of SiO_2 in layers thicker than a few micrometers is prone to severe internal stress. Copper sacrificial layers, on the other hand, may be deposited to thicknesses on the order of hundreds of micrometers, however the selective deposition and removal of the copper sacrificial layer becomes more time intensive with increasing thickness of the layer. Additionally, both of these materials impose significant fabrication constraints, e.g. SiO_2 requires elevated temperatures for deposition, and copper is often selectively removed with strong basic or acidic etchants for appreciable etch rates. Moreover, electrodeposited copper requires significant additional fabrication complexity, which entails deposition of an insulating layer, deposition of a seed layer, deposition and patterning of the electrodeposition mold, establishment of electrical contact to the seed layer, uniform and stress-free deposition of copper, and finally selective removal of all of the above materials.

An alternative sacrificial material may be found upon closer examination of SU-8. Crosslinked SU-8 is a negative resist and has a density of 1 190 kg m^{-3}. Its Young's modulus varies with its processing, with a typical range of

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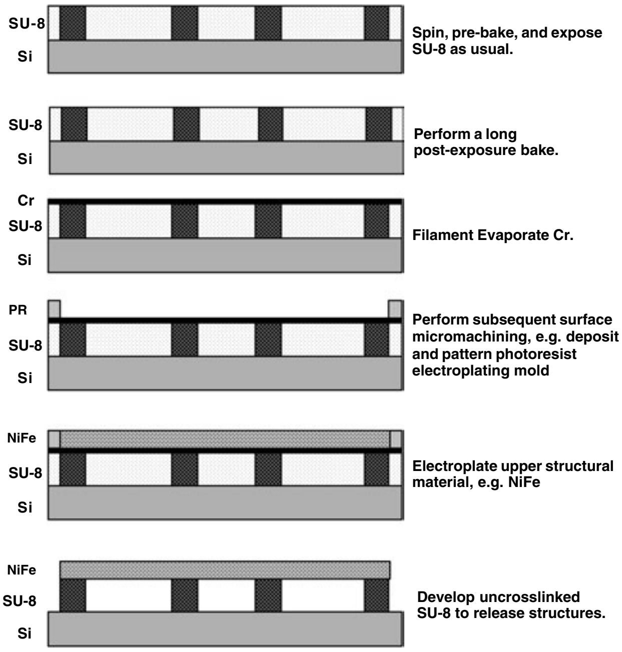

Figure 1. General process flow for using uncrosslinked SU-8 as a sacrificial layer.

4–5 GPa (SU-8 1999). Its characteristics in the crosslinked state make it highly suitable for a number of structural purposes that have been widely discussed in the literature, such as cantilever probes, pH sensors and waveguides (Microchem 2002). However, uncrosslinked SU-8 also has a number of interesting properties. Below the glass transition temperature, $T_g \sim 65$ °C, SU-8 is highly chemically resistant, maintains a flat stable surface for subsequent photolithography, and because uncrosslinked SU-8 is developed with solvents, it may be easily and selectively removed in the presence of a wide range of materials, such as semiconductors, metals, ceramics and certain polymers. Since uncrosslinked SU-8 is deposited simultaneously with the crosslinked SU-8, a significant amount of fabrication complexity may be avoided, such as deposition of the insulating layer/seed layer/electroplating mold or deposition of thick layers (>10 μm) of SiO_2. Moreover, unlike SiO_2 or copper, the uncrosslinked SU-8 sacrificial layer is naturally co-planar with the final structural material, insuring a flat, planar surface for subsequent layers of micromachining. Finally, a wide range of sacrificial layer thicknesses from 5 μm to 250 μm have been demonstrated by simply varying spin speed and pre-soft baked SU-8 viscosity.

2. Fabrication process

The typical method to process SU-8 is to spin, pre-bake, expose, post-bake and immediately develop. However, if the development step is postponed, then the uncrosslinked SU-8 remains and may be used as a sacrificial layer. The general process flow for using uncrosslinked SU-8 as a sacrificial material is shown in figure 1. For the most part, the SU-8 process remains unaltered, however the key changes are the long post-exposure bake and the chromium deposition.

The long post-exposure bake minimizes the amount of reflow that the uncrosslinked SU-8 undergoes, if taken above the glass transition temperature, $T_g \sim 65$ °C. Without this step, if the uncrosslinked SU-8 is taken to a high enough temperature, e.g. to soft-bake photoresist, then it reflows, which may move or deform structures above the uncrosslinked SU-8. A long post-exposure bake, on the order of several hours, depending on the thickness of the sacrificial layer, suppresses this flow. The displacement due to reflow may also be mitigated by having small areas of uncrosslinked SU-8, since large continuous areas allow greater displacements in the uncrosslinked SU-8.

Chromium must be deposited on top of the SU-8 to prevent exposure of the uncrosslinked SU-8 sacrificial layer from subsequent lithography. At least 250 Å of chromium must be deposited for a sufficiently opaque layer. It should be noted that this thin film of Cr may also conveniently serve as an excellent adhesion layer for the next layer. SU-8 is crosslinked by the release of protons from exposure to photons of UV energy or greater. As a result, no metal deposition technologies that expose the uncrosslinked SU-8 to photons of these energies may be used. Both sputtering and electron beam metal deposition technologies emit high energy photons that can crosslink the unexposed SU-8. However, filament evaporators vaporize metal by resistively heating a crucible. If the temperature of the evaporated metal and crucible is low enough such that the emitted blackbody radiation has a sufficiently low amount of energy in the UV or above, then metal may be deposited on uncrosslinked SU-8 without affecting it. Fortunately, at a pressure of 1 μTorr, Cr sublimates at approximately 977 °C. At this temperature, the peak of the blackbody radiation is theoretically calculated to be approximately 4 μm, well in the infrared range, and therefore, virtually no crosslinking photons are generated. Observing the metal and crucible during deposition, the color is a dull orange-red, corroborating low energy photon radiation.

Once the SU-8 has metal deposited on it, subsequent lithography is possible since the crosslinked versus uncrosslinked SU-8 differ in appearance. The Cr on top of the crosslinked SU-8 appears smoother and more reflective. It is easily distinguished both by the naked eye as well as under magnification. Subsequent surface micromachining may then be continued on top of the SU-8.

3. Application

The motivation for this exploration was to fabricate capacitive electrodes for a bulk-machined, torsional silicon oscillator. The electrodes function as both sensors and actuators. The requirements are that the electrodes must be conductive, mechanically stiff compared to the motion of the oscillator and electrically insulated from the silicon oscillator.

In addition to these requirements, the performance of the device benefited from a large separation between the silicon and the metal electrode for two reasons. First, the electrode gap needed to be on the order of 125 μm to allow the oscillator sufficient amplitude in its motion. Second, the anchors for the capacitive electrodes should be separated from the silicon substrate as widely as possible to minimize

Table 1. Comparison of the SU-8 sacrificial layer technique and the Cu sacrificial layer technique for the fabrication of suspended electrodes.

Fabrication of the suspended NiFe electrodes	
Processing Cu sacrificial layer	Processing SU-8 sacrificial layer
1. Deposit insulator to separate silicon substrate from electrode 2. Deposit electroplating seed layer 3. Deposit photoresist plating mold for Cu sacrificial layer 4. Electroplate copper 5. Remove photoresist mold 6. Deposit another photoresist plating mold for NiFe electrode 7. Electroplate NiFe 8. Remove photoresist mold 9. Selectively remove copper 10. Remove electroplating seed layers 11. Remove insulator	1. Spin, pre-bake, expose and post-bake SU-8 2. Deposit Cr using filament evaporation to protect uncrosslinked SU-8, and deposit Cu seed layers for NiFe electrodeposition (may be done without breaking vacuum) 3. Deposit and define photoresist plating mold 4. Electroplate NiFe 5. Simultaneously remove uncrosslinked SU-8, seed layers and photoresist via lift-off (selective removal of each layer is also possible)

Table 2. Detailed account of fabrication of the NiFe electrodes.

Clean silicon wafer using RCA clean
Spin Microchem SU-8 2025 (1000 rpm/30 s)
Soft-bake SU-8 on hotplate (ramp from room temperature to 100 °C/hold at 100 °C for 1 h)
Expose (50 s at 20 mW cm^{-2}; i-line)
Post-bake SU-8 on hotplate(100 °C/∼12 h)
Deposit Cr/Cu/Cr electroplating seed layer with filament evaporator (500 Å at the rate of 3 Å s^{-1} for Cr and 2500 Å at the rate of 3 Å s^{-1} for copper)
Spin Clariant AZ4620 photoresist for plating mold (1000 rpm/30 s)
Allow AZ4620 to rest for 5 min
Soft-bake photoresist on hotplate (100 °C/8 min)
Expose photoresist (8 min/5 mW cm^{-2} at 365 nm)
Develop photoresist in AZ400 (diluted 3:1) for ∼3 min
Dip wafer in dilute HCl to remove protective layer of Cr
Electroplate NiFe (35 μm)
Simultaneously remove SU-8, photoresist and seed layers using Shipley 1112 photoresist stripper for about 25 min (10 min with agitation). At the beginning, do a quick dip in an ultrasound bath to break up the seed layer. (Each layer may be removed individually with acetone/methanol for photoresist, NH_4OH + $CuSO_4$ for copper, dilute HCl for Cr and PGMEA for the uncrosslinked SU-8)

parasitic capacitance between the upper electrode and the silicon substrate.

A mechanically stiff, yet conductive upper electrode was fabricated using electroplated metal. The electrodeposition process enables a thick, relatively stress-free conductive layer to be deposited. Given the dimensions of the electrode, 3 mm long and 250 μm wide, a 25 μm thick layer was sufficiently stiff to be an order of magnitude stiffer than the torsional springs that supported the oscillating silicon body.

A typical method to fabricate these electrodes would be to use a Cu sacrificial layer. However, using our SU-8 sacrificial layer can reduce the process time and process complexity significantly. A comparison of the two methods is detailed in table 1, and a detailed account of how the electrodes were fabricated is summarized in table 2.

A fabrication flow is illustrated in figure 1. First, SU-8 is spun, soft-baked and exposed. Then the SU-8 undergoes a longer than usual, typically a few hours, post-exposure bake to relax stress in the uncrosslinked SU-8. Next, a layer of Cr at least 250 Å is filament evaporated to protect the uncrosslinked SU-8 from subsequent lithography. For electroplating, the seed layer may also be deposited at this step without breaking the vacuum. Photoresist for the electrodeposition mold is then spun, baked, exposed and developed as usual. NiFe is then electroplated.

Removal of the unneeded materials may be done in two ways. The first method is to remove each material one-by-one sequentially. The photoresist mold may be removed with acetone. The copper seed layer may be removed with a saturated solution of $CuSO_4$ and NH_4OH. The protective Cr layer may be removed with a solution of sodium hydroxide and potassium permanganate. And, finally, the SU-8 sacrificial layer may be removed by finally developing the SU-8 using the usual developers, e.g. PGMEA.

The second method uses lift-off and is faster and easier than the first method. After the NiFe is electroplated, the photoresist mold is removed using acetone. Removal of the uncrosslinked SU-8 also simultaneously removes the seed layers. The unneeded seed layer material is lifted off with the removal of the uncrosslinked SU-8. In this method, ultrasonic

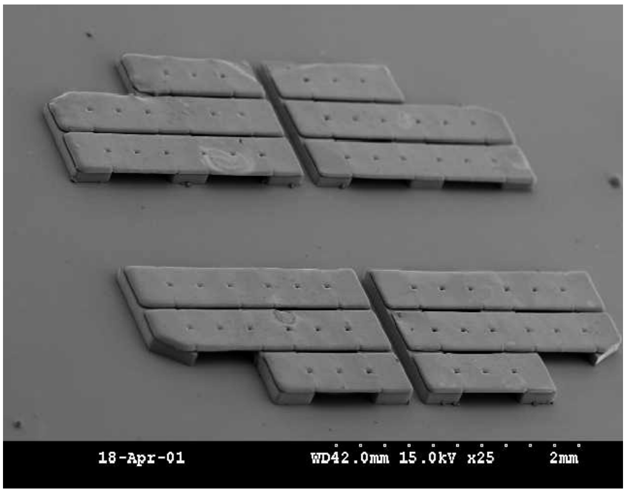

Figure 2. Overview of upper NiFe electrodes for silicon oscillator. The uncrosslinked SU-8 has been removed. Multiple electrodes are fabricated so that some may serve as actuators and others as capacitors. The process flow from figure 1 was used in the fabrication.

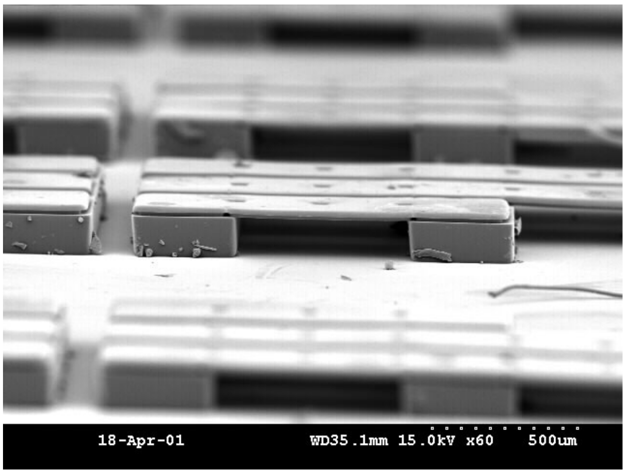

Figure 4. Close-up of the SU-8 stand-off that insulates the upper electrode from the silicon substrate. The SU-8 structure is 125 μm thick and the electroplated NiFe is approximately 35 μm thick. The thickness of the SU-8 layer allows for a minimum parasitic capacitance and a maximum actuation voltage.

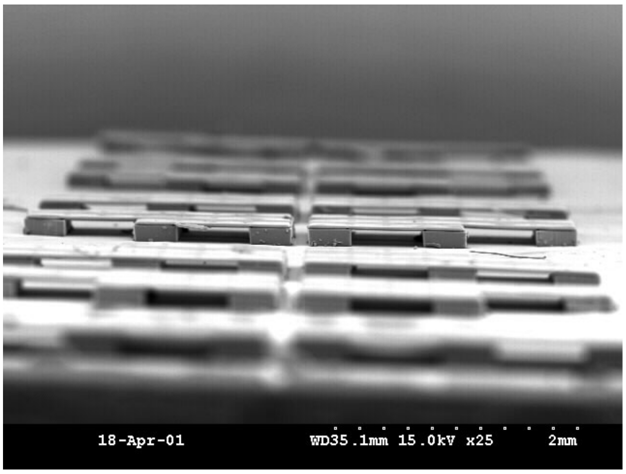

Figure 3. Side view of the electrodes. The uncrosslinked SU-8 is clearly removed, since it is possible to see through, underneath the NiFe electrodes.

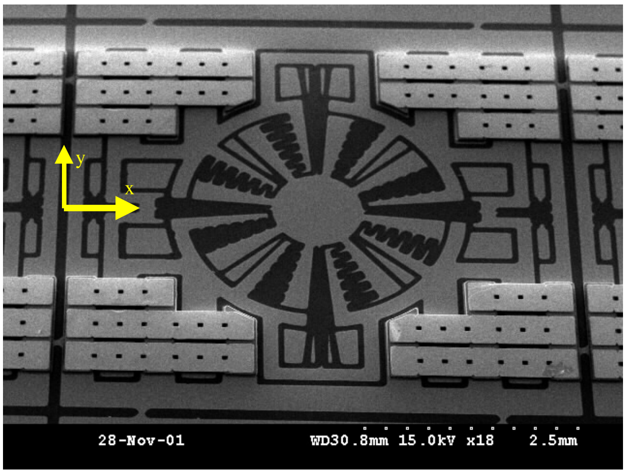

Figure 5. The silicon oscillator is etched out of the bulk silicon using deep reactive ion etching. The center is electrostatically actuated by the comb drives arranged radially about the center. The center body rotates about an axis perpendicular to the surface, and when the chip is rotated about the *y*-axis, the center body's movement gyroscopically induces oscillations in the outer oscillator, which rotates about the *x*-axis. The motion of the outer member is allowed by the removal of the uncrosslinked SU-8 underneath the electrodes (Kaiser *et al* 2000). The NiFe electrodes serve as both capacitive sensors and electrostatic actuators, and they are insulated from the Si substrate by 125 μm of crosslinked SU-8.

agitation to disrupt the seed layer is helpful to allow chemical contact between the uncrosslinked SU-8 and the developer.

A view of the electrodes from overhead is shown in figure 2. Figure 3 shows that the uncrosslinked SU-8 is completely removed from underneath the electrode. Figure 4 shows a close-up of one of the electrodes from the side. The height of the SU-8 is approximately 125 μm and the thickness of the NiFe is approximately 35 μm.

This fabrication technique may be additionally used in conjunction with deep reactive ion etching. Once the electrodes were fabricated and the uncrosslinked SU-8 was removed, a photoresist mask for the oscillator was patterned on the back side of the wafer. The silicon was then etched from the back side through the wafer using deep reactive ion etching. A picture of the electrodes with the bulk-machined silicon is shown in figure 5.

4. Conclusion

Uncrosslinked SU-8 as a sacrificial material has been demonstrated. The process is mostly unchanged from the typical SU-8 process, however there are a few changes to which attention must be paid, i.e. a long post-exposure bake and filament evaporation of chromium. Also, this sacrificial layer cannot be exposed to radiation intense environments or temperatures above 120 °C, since these conditions will cause the sacrificial SU-8 layer to crosslink. When applicable, uncrosslinked SU-8 sacrificial layers may reduce fabrication time and complexity. This technique seems particularly well suited for applications that require sacrificial layers on the order of tens or hundreds of micrometers thick. This technique has been demonstrated to work at thicknesses ranging from 5 μm to 250 μm. Finally, an application of this technique was illustrated and its compatibility with deep reactive ion etching of silicon is demonstrated.

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