TECHNICAL NOTE

Uncrosslinked SU-8 as a sacrificial material

Charles Chung and Mark Allen

Microelectronics Research Center, 791 Atlantic Drive, Georgia Institute of Technology, Atlanta, GA 30332-0269, USA
E-mail: cccatl@hotmail.com and mark.allen@ece.gatech.edu

Received 26 November 2003, in final form 2 June 2004
Published 23 September 2004
Online at stacks.iop.org/JMM/15/N1

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 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 SiO2 (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 SiO2 nor copper scales well with the increasing thicknesses allowed by SU-8. The deposition of SiO2 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. SiO2 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...
The long post-exposure bake minimizes the amount of reflow that the uncrosslinked SU-8 undergoes, if taken above the glass transition temperature, \( T_g \sim 65 \, ^\circ\text{C} \). 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 \( \mu \text{Torr} \), Cr sublimates at approximately 977 \( ^\circ\text{C} \). At this temperature, the peak of the blackbody radiation is theoretically calculated to be approximately 4 \( \mu\text{m} \), 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 \( \mu\text{m} \) 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

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

<table>
<thead>
<tr>
<th>Fabrication of the suspended NiFe electrodes</th>
<th>Processing Cu sacrificial layer</th>
<th>Processing SU-8 sacrificial layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Deposit insulator to separate silicon substrate from electrode</td>
<td>1. Spin, pre-bake, expose and post-bake SU-8</td>
<td></td>
</tr>
<tr>
<td>2. Deposit electroplating seed layer</td>
<td>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)</td>
<td></td>
</tr>
<tr>
<td>3. Deposit photoresist plating mold for Cu sacrificial layer</td>
<td>3. Deposit and define photoresist plating mold</td>
<td></td>
</tr>
<tr>
<td>4. Electroplate copper</td>
<td>4. Electroplate NiFe</td>
<td></td>
</tr>
<tr>
<td>5. Remove photoresist mold</td>
<td>5. Simultaneously remove uncrosslinked SU-8, seed layers and photoresist via lift-off (selective removal of each layer is also possible)</td>
<td></td>
</tr>
<tr>
<td>6. Deposit another photoresist plating mold for NiFe electrode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Electroplate NiFe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Remove photoresist mold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Selectively remove copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Remove electroplating seed layers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Remove insulator</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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 Clarant 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, NH₄OH + CuSO₄ 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 CuSO₄ and NH₄OH. 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
Technical Note

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 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.

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.

References


