SURFACE MICROMACHINED SHOCK SENSOR FOR IMPACT DETECTION

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ABSTRACT

A set of copper micromachined impact sensors has been fabricated. The devices consist of a combination of suspension spring and plunger mass that impacts a stop closing an electrical circuit when subject to accelerations of 100-10,000 G's. The devices are fabricated with a three mask process using a silicon dioxide sacrificial layer and copper as the structural material. The stress in the copper films was about 20 MPa in the tensile state which makes it suitable for micromechanical devices that require a low resistance. Device length ranges from 0.2-1.5 mm. The process flow and special fabrication techniques for copper films are described. Initial experiments indicate a closing on resistance below 2 Ω.

INTRODUCTION

Many electromechanical devices are micromachined with polysilicon or highly doped silicon because of the low stress and excellent mechanical properties of this material [1, 2]. However, silicon structures are unsuitable for devices that require the closing of an electrical contact because of the formation of a thin layer of insulating native oxide on its surface and their relatively high resistivity. Metals are ideal candidates for electromechanical switching applications where the cost of electronic controls is an important consideration. This paper presents a surface micromachined shock sensor fabricated with copper. Shock sensing devices are needed for air bag systems and in portable notebook computers to prevent writing on their disk drives under impact. For drive failure, this threshold is between 100-200 G. Up to six shock sensors are required per disk drive; hence active devices are prohibitively expensive.

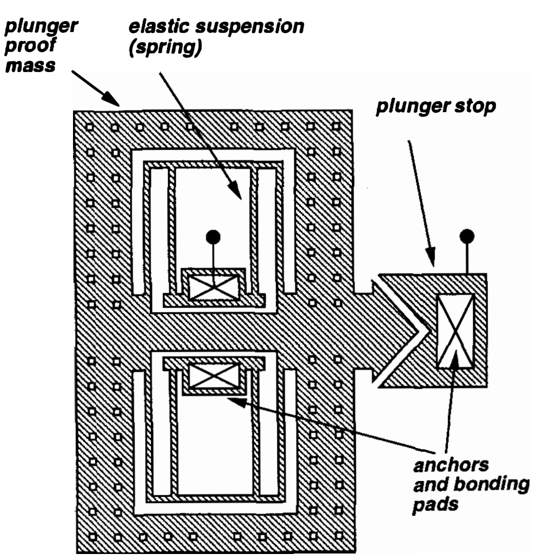

Fig. 1: top view of a shock sensor

The device fabricated here is a passive mass-spring switch which closes when the impact acceleration exceeds a threshold level. Fig. 1 shows the structure of one type of shock sensor. The device consist of a plunger that is suspended by elastic folded beams [1]. The plunger is separated from an stationary electrode a short distance apart. When the device is subject to a strong acceleration, the plunger impacts the stationary contact hence closing the switch. In order to obtain a good contact with low resistance, the device is completely micromachined in copper.

Copper is an excellent candidate material for electromechanical switching because of its low resistivity ($2\ \mu\Omega - cm$), high current capability, and low residual stress [3–5]. The copper plunger is a symmetrically shaped, conductive proof mass, and supported 4 μm above the substrate by folded beams 4μm wide anchored near the proof mass center. The folded-beam suspension design makes the device sensitive only to the translational acceleration component along the axis The gap between the plunger and the stationary contact is 5-10 μm. The length of the switch structures ranges from 0.2 to 2 mm. Devices with single, double folded, and simpler single beam suspensions were fabricated.

SHOCK SENSOR CHARACTERISTICS

The device has a simple mechanical model of spring and proof mass as shown in Fig. 2. Upon the application of a positive acceleration to the structure, the plunger mass displaces in the positive direction. The threshold acceleration a_c needed for closing the switch is

$$a_c = \frac{k\,d}{m} \qquad (1)$$

where d is the electromechanical contact gap, k the spring constant and m the plunger mass. In the device structure, the springs are folded beams with spring constant [6]

$$k = \frac{E\,t\,w^3}{N\,l^3} \qquad (2)$$

where E is the young modulus of the beam material t, its thickness, w its width, and l its length, and N the number of folds. The plunger mass is distributed around the beams with an approximate mass

$$m \approx \rho\,t\,l^2 \qquad (3)$$

Therefore the approximate device area A is

$$A \approx \left(\frac{w^3\,d\,E}{N\,a_c\,\rho}\right)^{2/5} = c\,v^{4/5} \qquad (4)$$

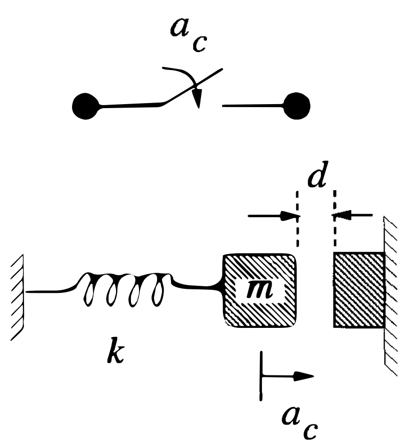

Fig. 2: shock sensor model

Where $v = \sqrt{E/\rho}$ is the wave velocity of the material [7]. Copper has a Young modulus of approximately 110 GPa, and a density of 8.9 g cm^{-3} [8] yielding a wave velocity roughly 4.4 times smaller than that of silicon and a corresponding reduction on device area. The dynamics of the spring-mass system are determined by the second order differential equation

$$m\ddot{x} + \mu\dot{x} + kx = ma_c \tag{5}$$

Where μ is the damping coefficient. For laterally driven structures the damping coefficient is very low [9, 10]; hence the solutions are nearly sinusoidal. Therefore the time required for switch closure is approximately

$$t_c \approx \frac{\pi}{2}\sqrt{\frac{d}{a_c}} \tag{6}$$

which for a 10 μm gap is approximately 150 μs at 100 G's. The very short closing time is a consequence of the small travel of the plunger. After the plunger impinges onto the contact, the structure will go through a series of rebounds due to the low damping coefficient; thus a latching type of circuit is needed to detect the first contact closing.

STRESS IN COPPER FILMS

The material used for our device is sputtered copper. Copper films have been under intense investigation as an interconnect layer for VLSI circuits [11]. As a mechanical layer, copper films have in general a very low intrinsic stress [5]. Because the yield stress of copper is very low (55 MPa) [8], any stress higher than this value is essentially relaxed by plastic deformations. The ability of copper to relax its internal stress [3] is one of its most desirable features for micromechanical applications. The Young modulus of copper is 110 GPa, comparable to that of silicon, but its ultimate stress is substantially lower (230 MPa).

A set of 1 μm-thick copper films were sputtered on silicon substrates in an RF magnetron (Enerjet) system at a power of 800 W at various argon pressures. The stress of the copper film was then measured using an optical stress gague. Figure 3 shows the stress in the copper samples deposited at various pressures. The lowest stress samples were sputtered at 16 mT with a tensile residual stress of 50 MPa. The stress in the samples relaxed to even lower values at room temperature after the samples were left for a period of time. The samples shown in the figure were given a short 20 min anneal at 300 °C in a rapid thermal anneal system (Peak Systems ALP 3000). During this thermal cycle,

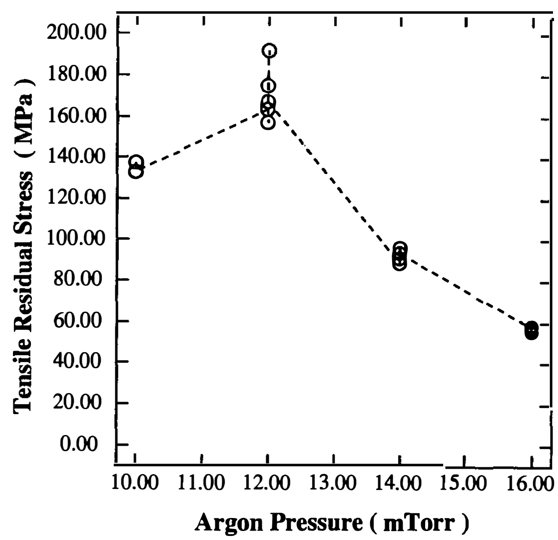

Fig. 3: copper stress

its residual stress is relaxed due to recrystallization [12,3]. The stress on the annealed samples was 10-20 MPa, low enough for most micromachining applications.

FABRICATION

The impact sensor was constructed as shown in Fig. 4. First a uniform layer of low-stress silicon nitride [13] 0.1 μm thick is uniformly deposited in on n-type (100) silicon wafers with a resistivity of 10-30 $\Omega - cm$. The silicon nitride layer provides an insulator surface that isolates the two terminals of the impact switch. The nitride film was deposited on a LPCVD reactor at 835 °C and 320 mT with SiH_2Cl_2 and NH_3 flows of 100 and 25 sccm. The nitride was tensile with a stress of about 150 MPa. Next, a 2.5-4 μm thick layer of plasma-enhanced (PECVD) SiO_x was deposited as a sacrificial layer. The PECVD film was grown on a SEMI group reactor with a SiH_4 flow of 24 sccm and N_2O flow of 20 sccm at 100 mT and a substrate temperature of 200 °C. The power used in the deposition was 80 W, with a deposition rate of 12 nm/min.

The PECVD film was next patterned and etched 1 μm deep using in a plasma etch reactor. These indentations patterned in the sacrificial layer are needed to form "dimples" that reduce the adhesion of the microstructure to its substrate. The photoresist was next stripped, and the samples were cleaned. The PECVD film was next patterned and etched with diluted 5:1 BHF down to the insulating SiN to form the anchors of the structure. Using the same resist, a thin layer 50 nm-thick of evaporated Cr was deposited. The Cr layer is used as an interfacial layer that attaches to the copper [14] film. The Cr was next lifted off, and the samples thoroughly cleaned. Next a 2-3 μm-thick layer of copper was sputtered at a power density of 800 W and at an Ar pressure of 16 mT. The samples were next annealed at 300 °C for 20 min in a N_2 atmosphere to relieve the residual stress of the film.

A 2 μm layer of resist was used as a mask for patterning the copper film. After the copper film is deposited, Special precautions are required to prevent the oxidation of copper [15,16,11,17] during baking and removal of the resist. Samples that were baked at 110 °C for more than 30 min showed signs of copper oxidation. The copper was etched by several two different methods. Copper cannot be etched by plasma chemistry

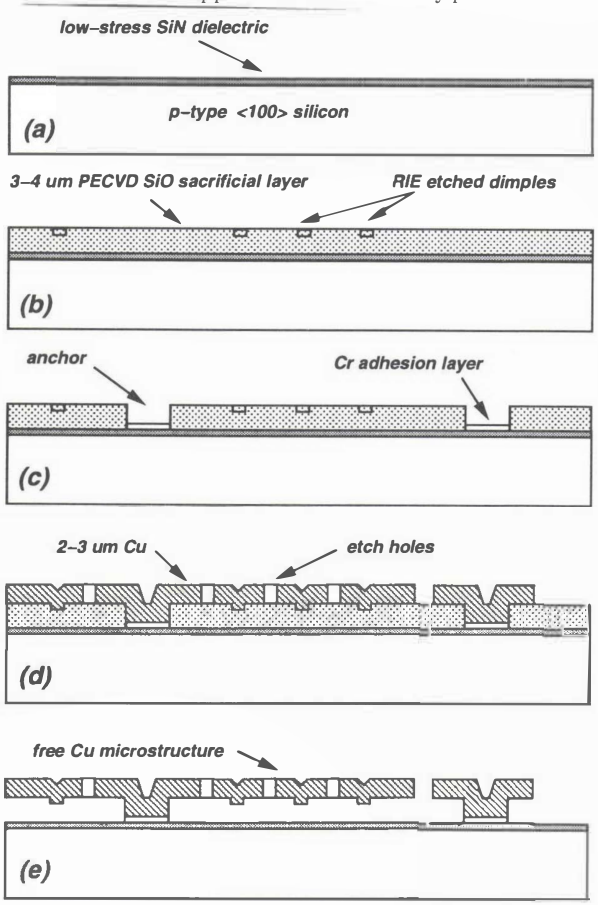

Fig. 4: process flow

easily at room temperature because it does not generate volatile reaction byproducts [18,19]. One set of samples was etched by ion-milling at 300V and 100 mA Ar beam current in a Millatron reactor. The etch rate was approximately 18 nm/min. Higher potentials caused thermal migration [11] of the copper through the PECVD oxide and excessive bombardment of the resist (1822). A second set of samples was etched in a weak 1:2:200 HCl : H_2O_2 : H_2O_2 solution with an etch rate of 0.3 μm/min. The resist was removed by an acetone bath and a short 2 min O_2 plasma descum at 250 mT and 180 W. Resist removal with PRS1000 stripper resulted in chemical attack of the copper, and high power O_2 plasma stripping for long times resulted in excessive copper oxidation. The samples etched by ion milling were thoroughly rinsed and annealed a second time at 300 °C for 20 min in N_2 atmosphere.

The last step in the process is the sacrificial release. The PECVD oxide layer was sacrificially etched in concentrated (49 %) HF which does not attack copper. The structures were released in 1.5 min. Next the samples were rinsed and let dry. San ples

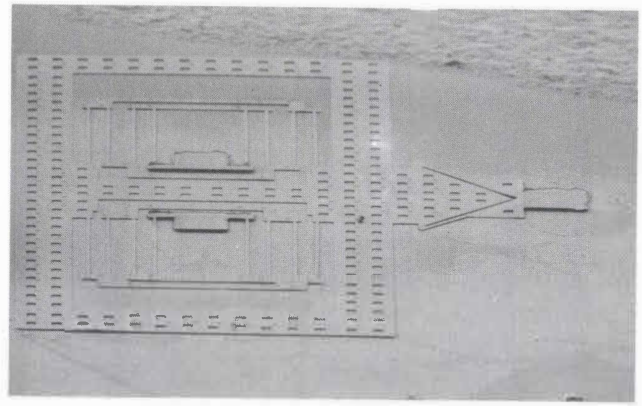

Fig. 5

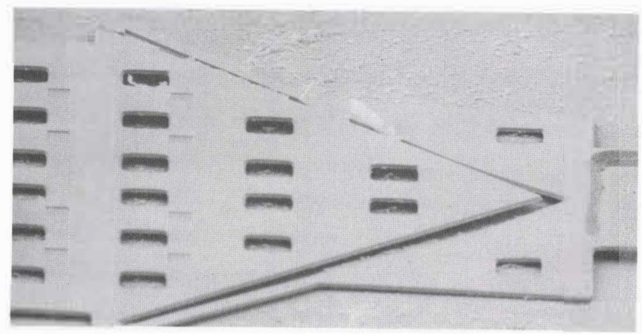

Fig. 6

etched by ion-milling were warped down indicating a change in the copper stress by the ion bombardment. Furthermore, the prolonged exposure to Ar in the ion-milling system substantially degraded the adhesion of the Cr layer yielding structures that lifted off the substrate. The flattest samples were obtained by the wet etch. Fig. 5 shows a SEM of a completed double folded device. Fig. 6 shows the tip of the plunger and copper stopper. Fig. 7 shows a 500 μm-long segment of the structure showing its flatness with some of the support beams adhering to the surface. The structures were probed, and the contact closing resistance was below 2 Ω.

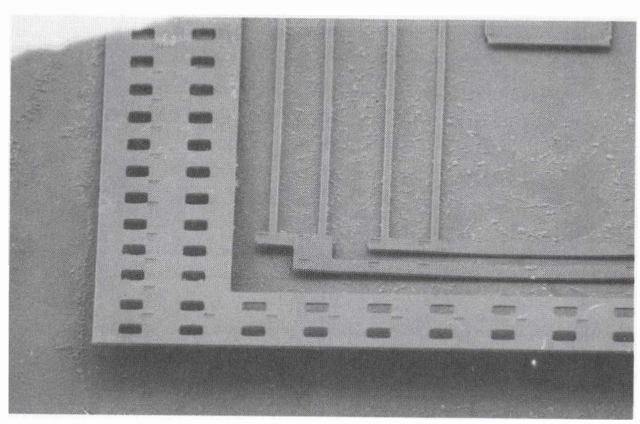

Fig. 7

DROP TEST SETUP

The structure was next mounted on a DIP package and wire bonded. The sensor chip was mounted on a small PC board attached to a flip-flop deglitching circuit. The whole assembly was next mounted on a 0.337 kg aluminum block with a hole in the middle that rides along a vertical guide. At the base of the guide, a spring of constant k_s was inserted into the guide. The block was next dropped at different heights, and the behavior of the switch device was monitored. The impact acceleration for the switch can be determined from the properties of the spring and the height at which it was released. These are related by the equation

$$a = v_o\sqrt{\frac{k_s}{m}} = \sqrt{\frac{2Ghk_s}{m}} \quad (7)$$

Where v_o s the velocity of the block at impact and h is the release height. The copper micromachined devices are currently under testing.

SUMMARY

A simple microelectromechanical impact sensor is described. The device consists of a copper proof mass and a spring that closes a switch when subject to a shock. The device is made of thin film copper, and it is fabricated with three lithographic steps. Procesing details for the copper accelerometer switch are discussed.

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