J. Micromech. Microeng. **1** (1991) 30–33. Printed in the UK

A mechanical surface adhesive using micromachined silicon structures

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Received 16 September 1990, accepted for publication 3 December 1990

Abstract. We have developed a velcro-like mechanical fastening system, capable of joining two surfaces together without chemical bonding, using silicon micromachining techniques. Using conventional processes, microscopic structures are fabricated that mechanically interlock with matching, identically processed substrates. The interlocking is accomplished by the elastic deflection of SiO_2 flanges angled in such a way that the bond is permanent. Each structure is 18 μm × 18 μm by 12 μm high; there are approximately 200000 individual structures per cm^2 of substrate, resulting in a strong bond. Preliminary measurements show the tensile strength of the bond to be in excess of 380 kPa (55 psi); the shear strength is similarly high. Applications for this 'mechanical adhesive' technology include medical uses (i.e., joining tissues), integrated circuit packaging, and interfacing of microdynamic machines to the macroscopic world.

1. Introduction

We have used silicon micromachining technology to fabricate surface microstructures that act as mechanical adhesives. Essentially, a two-dimensional zipper has been fashioned from silicon and SiO_2. This 'permanent velcro' has applications in areas as diverse as microelectronic packaging and vascular anastomosis.

Figure 1 is a schematic cross section depicting the bonding principle. The tabs marked 'A' are formed from SiO_2, approximately 1.0 μm thick. Each structure is about 18 μm wide, and the pitch is approximately 34 μm. When two identical surfaces are placed in contact, the structures self-align and mate. Under application of sufficient force, the tabs deform and spring back, resulting in an interlocking of the two surfaces.

One area of application under development is the mounting of integrated circuit chips. Since the surface bonding is self-aligning, precise placement of chips on a mating substrate is possible. Simultaneous electrical, mechanical, and thermal connections would be effected by suitable design of the structures and interconnects. This approach would circumvent many of the problems inherent in the conventional method of wiring chips to packages to boards: (1) no separate packaging is needed; (2) intermediate electrical connections (preforms, wirebonds) are eliminated; (3) the bonding process is purely mechanical, requiring no chemicals, heat, or ultrasonic vibrations.

Another application area is in the interfacing of microdynamic machines to the macroscopic world. By their nature, sub-millimeter electromechanical devices, such as pressure, velocity, and acceleration sensors, operate in a regime where mechanical contacts to the macroscopic 'outside world' are problematical. This technology suggests an approach by which the vastly different scales of conventional- and micro-machining may be

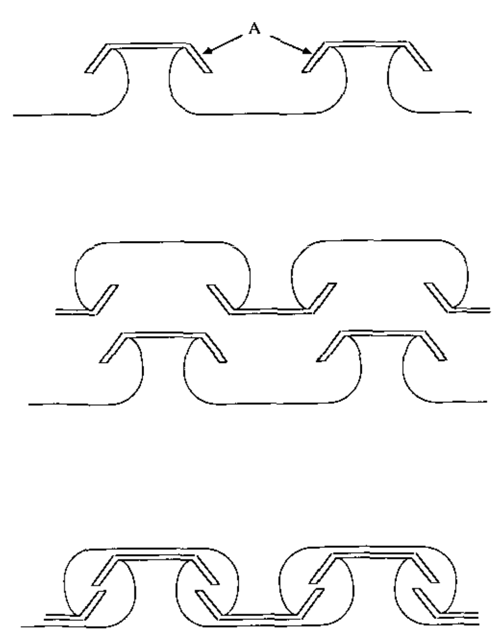

Figure 1. Schematic cross section of the micromechanical structures. The top layer is a 1.0 μm layer of SiO_2. The structures mate with those on another substrate, forming a mechanical bond.

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joined. Advantages of this method over fusion [1–3] and electrostatic [1, 3] bonding include low-temperature processing, absence of external chemical and electrical agents, and simplicity.

A third area of investigation involves medical uses of the fastening system. By modifying the fabrication process, pointed, spear-like structures able to pierce tissue can be made. Again, because the bonding mechanism is purely mechanical (in this case, like a fishhook), compatibility problems inherent to chemical adhesives are eliminated. Efforts to use this approach for joining blood vessels will be reported on at a later time.

In this paper, we describe the fabrication process, initial mechanical tests, and the failure mechanism for the micromechanical fastening system.

2. Fabrication

Figure 2 describes the process sequence. ⟨100⟩-oriented silicon wafers are thermally oxidized (1000 Å) and patterned into a matrix of 10 μm squares. The SiO_2 squares mask an anisotropic silicon etch in KOH [4–7], about 5 μm deep, to form a pattern of frustrums. The wafer is again oxidized, this time to a thickness of 1.0 μm, and patterned with the mask depicted in figure 3. The patterned oxide acts as a mask for the final step, an isotropic silicon etch to a depth of about 7 μm. An electron micrograph of the completed structure is shown in figure 4.

The second masking step in this process poses particular difficulties since the surface is highly non-planar. We have successfully patterned the wafers by using a nominal 2.1 μm thick photoresist film, coupled with a relatively long exposure time. The resist thickness, as measured from electron micrographs, is highly non-uniform; it reaches nearly 3.0 μm in the field regions, and is severely thinned over the tops of the frustrums. However, there is adequate thickness to prevent the SiO_2 caps from being attacked in the buffered HF etchant.

The isotropic silicon etch after the second masking step results in considerable lateral undercutting. To prevent this encroachment from weakening the silicon 'post' supporting the SiO_2 'cap', we use two techniques: (1) the inside corners of the Greek cross mask pattern are filleted to reduce the undercutting; and (2) the isotropic etch (in $HNO_3/CH_3COOH/HF$) is preceded by an anisotropic etch in KOH. This step reduces the undercutting by supplying most of the needed vertical clearance, without compromising the integrity of the silicon support.

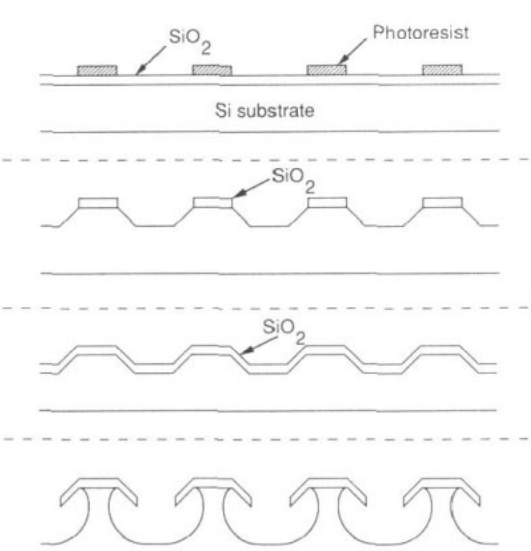

Figure 2. Fabrication process. Oxidized silicon substrates are patterned with photoresist, which acts as a mask for an anisotropic silicon etch. After reoxidation and masking, an isotropic silicon etch defines the microstructures.

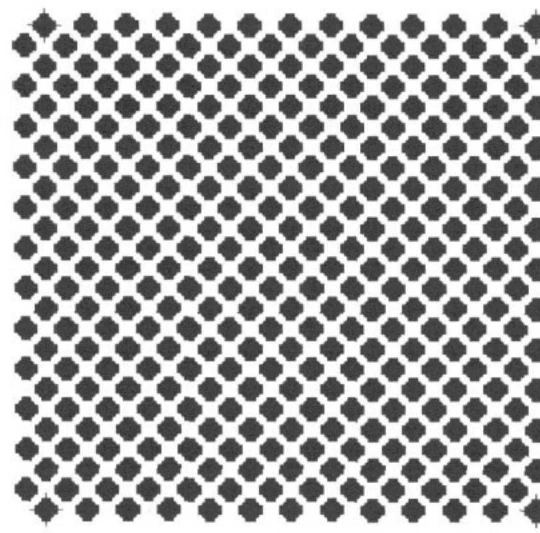
Figure 3. Second mask pattern. The inside corners are filled in to reduce lateral undercutting during the isotropic etch, which would erode the silicon support pedestal.

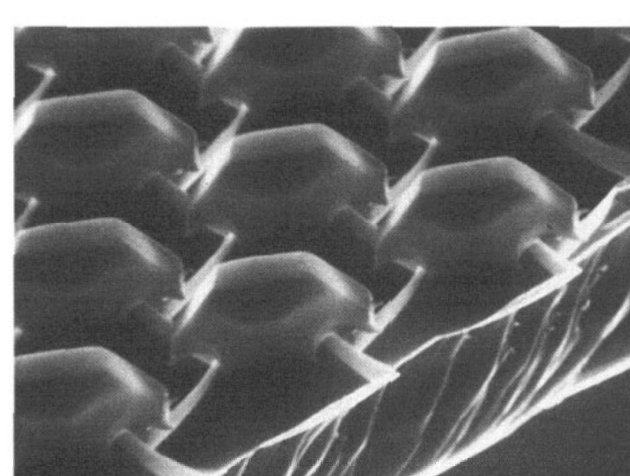
Figure 4. Electron micrograph of microfastening structures.

3. Results

Patterned samples, approximately 9 mm × 9 mm, were mounted on glass microscope slides using cyanoacrylate adhesive. The mating surfaces were placed together in rough mechanical alignment, as observed with a low-power optical microscope. Slight shaking of the samples was sufficient to align the microstructures precisely into a mating position. Interlocking was accomplished by placing successively larger weights on the upper substrate. Bonding was considered to have taken place once the weight of the lower sample and glass could be supported by the upper sample. The minimum load necessary for interlocking corresponds to a pressure of 12 kPa, or about 1.7 psi. (This compares with a value of 7×10^5 kPa ($\approx 10^5$ psi) which is needed to crush the silicon wafers.)

The bond strength was determined by applying a tensile load and measuring the force necessary for separation. We found that separation of the samples is always accompanied by damaged areas on corresponding regions of the mating surfaces. An optical micrograph of a separated surface is shown in figure 5. Close-ups of the microstructures in these areas reveal fracturing of the SiO_2 tabs near the interface with the silicon support post. We interpret this as evidence that the samples are interlocking only over the damaged region. Taking the ratio of applied load to the observed interlocked area, we obtain a tensile strength of approximately 380 kPa, or about 55 psi. We believe the partial interlocking was caused by particulate contamination which prevented uniform loading of the samples.

It is well known that two silicon wafers placed in intimate contact will bond to each other, especially if moisture is present [3, 8–10]. To distinguish this phenomenon from the latching mechanism, we repeated our measurements with wafers without the arrays of microstructures. Depending on the surface treatment (native oxide, thermal oxide, HF-dipped) and the relative humidity (38% to 100%), the tensile strength of the bonded pairs varied from 12 to 20 kPa (1.7–2.9 psi), well below the strength of the patterned samples.

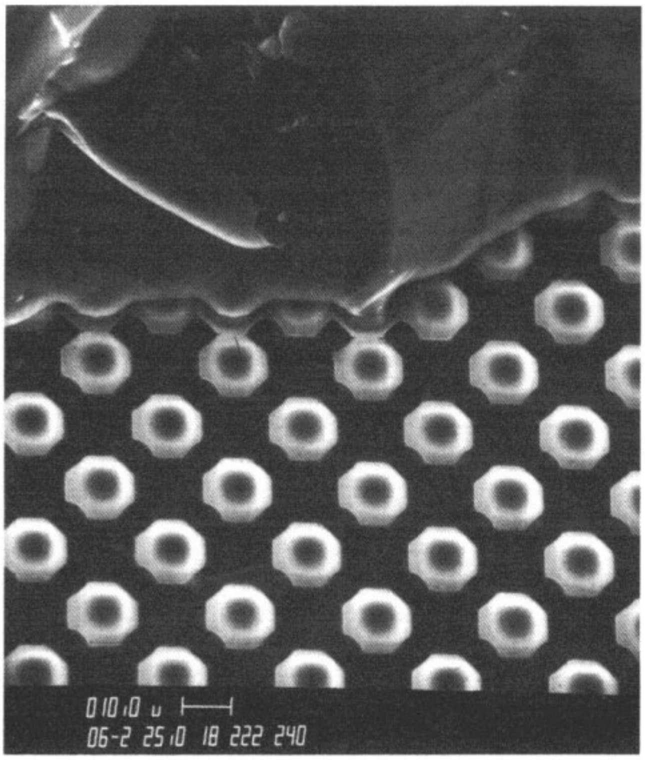

Figure 6. Electron micrograph of mated structures (top-down view along edge).

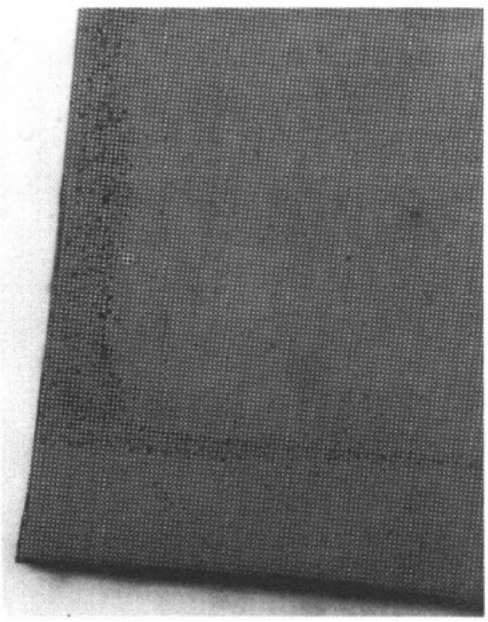

Figure 5. Optical micrograph of sample surface after separation. The dark (damaged) areas are regions where the microstructure tabs have broken.

Figure 6 shows two interlocked samples, as viewed from above the edge of the upper sample. Close examination of this and other regions confirms that the bonding is indeed due to latching of the microstructure tabs.

An approximate calculation of the expected tensile strength is outlined in figure 7. Ignoring frictional forces,

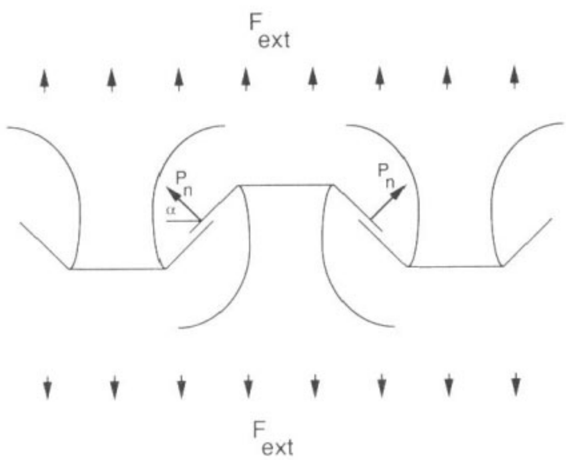

Figure 7. Nomenclature for force calculation. F_{ext} is the external applied force; P_n is the normal force on the microstructure tab; α is the angle between P_n and the substrate plane.

an applied external pressure F_{ext} (tensile) results in a force on each microstructure beam of

$$P_n = F_{ext} d^2/4 \sin \alpha \quad (1)$$

where P_n is the force acting normal to the beam, and $4/d^2$ is the areal density of cantilevers (four beams on each structure, placed in a square array d cm apart). This force produces a torque around the point where the silicon and SiO_2 join. From standard cantilever theory [11–13], the beam will fail when the stress induced by the lever arm reaches the yield stress σ_{yield} of the SiO_2; the maximum external tensile load is given by

$$F_{ext} = \frac{2\sigma_{yield} b h^2 \sin \alpha}{3d^2 l} \quad (2)$$

where l, b, and h are the length, width, and thickness of the beam. Substituting our design values, and using a value of 6.0×10^5 kPa for σ_{yield} [14, 15], gives a maximum tensile loading of $F_{ext} = 780$ kPa (113 psi), in general agreement with our experimental results. As mentioned before, the samples were observed to fail by yielding of the SiO_2 beams near the point of maximum stress; thus, the analysis above should give a reasonable estimate of the ultimate strength. (This calculation underestimates the tensile strength somewhat, as it ignores both frictional forces and the three-dimensional nature of the tabs; both of these act to increase the bond strength.)

4. Summary

We have demonstrated a surface adhesion technology based on interlocking silicon microstructures. The bonding principle is purely mechanical, and is expected to find application in mounting of integrated circuit chips, and also where chemical or thermal influences rule out conventional adhesives. Interlocking of the microstructures has been verified by direct examination, and also by damage patterns from separated bonds. Preliminary calculations and experiments show a tensile bond strength in excess of 380 kPa.

Acknowledgments

The authors wish to thank M Wholey, W Novogradac, C Bowman, L Rathbun, T Schlesinger, W Maly, and P Steif for many stimulating discussions. This research was supported by the National Science Foundation. Mask fabrication was performed at the National Nanofabrication Facility at Cornell University.

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