ADVANCED MATERIALS

Research News

Silicon Micro-Velcro **

By Michael L. Reed,* Hongtao Han, and Lee E. Weiss

1. Introduction

We have used silicon micromachining technology to fabricate dense regular arrays of microstructures which act as mechanical adhesives. Arrays of structures are fabricated on standard silicon wafers, with an areal density of approximately 200 000 per cm^2, resulting in very strong bonds. Individual components are the order of 4–18 μm wide, and 4–15 μm high above the substrate. Two kinds of microstructures have been developed. The first is a mushroom-shaped structure which mates with structures like itself; two surfaces arrayed with these will bond together like a button snap or velcro. A slight variation in the fabrication process yields the second type, a barb shaped microstructure which can pierce and bond to biological tissues. This "micromechanical velcro" has many potential applications in electronics, microelectromechanical systems, and medicine.

The mating structures are shown in the micrograph of Figure 1. When identical wafers are aligned face-to-face, compressive loading causes the tabs to deform, spring back, and interlock. Minimum loads of approximately 12 kPa are necessary to bond the substrates together. The tensile strength

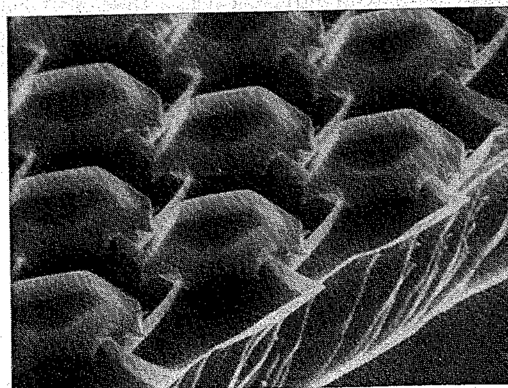

Fig. 1. Mating micromechanical structures. The caps are 1.0 μm thick SiO_2 on silicon pedestals.

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[**] The authors wish to thank M. Wholey, J. Suhan, C. Bowman, L. Rathbun, T. Schlesinger, W. Maly, and P. Steif for their assistance. Mask fabrication was performed at the National Nanofabrication Facility at Cornell University. This research was supported by the National Science Foundation.

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0935-9648/92/0101-0048 $ 3.50+.25/0

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of the bond is in excess of 240 kPa. We have verified that the microstructures are interlocking by a variety of techniques, including direct examination in an electron microscope. The micromechanical fastening system has several advantages, including high strength, precision self-alignment, room-temperature bonding, and thermal tolerance. We are currently investigating using this technology to mount integrated circuit chips directly to an interconnecting substrate; this technique could provide simultaneous electrical, mechanical, and thermal contacting, thus simplifying integrated circuit packaging.

A piercing structure is shown in Figure 2. Like the mating structures, this version is fabricated with a two mask process, and consists of SiO_2 caps on silicon pedestals. The very sharp point (radius of curvature is less than 0.1 μm) enables the structure to pierce biological tissues; the re-entrant supporting profile causes the structure to latch, preventing retraction. Arrays of these microscopic barbs are under development for various medical applications involving tissue joining.

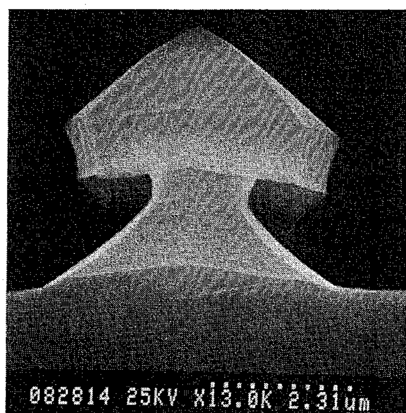

Fig. 2. Barb-shaped piercing micromechanical structure for joining tissues.

In the following sections, we describe the fabrication process, mechanical testing, and the theoretical limits of the mating microstructures; we will then describe our experimental efforts in tissue bonding with arrays of piercing microstructures.

2. Fabrication Process

The process sequence for the mating structures is outlined here; the piercing barbs are fabricated similarly. A 1200 Å SiO_2 layer is grown at 1000 °C in dry oxygen on (100) oriented silicon wafers. The oxide is patterned into an array of 10 μm square islands, with one edge aligned 45° to the (110) flat. After photoresist stripping, the wafer is immersed into an anisotropic etch bath consisting of aqueous KOH and isopropyl alcohol. The etching results in a truncated pyramid or frustrum, about 5 μm high. The sides of the frustrum, formed from (212) planes, intercept the (100) base plane at an angle of 48°.

After stripping the masking oxide, and cleaning the samples with a conventional chemical sequence, a thick SiO_2 film, about 1.0–1.5 μm, is grown at 1000 °C in wet oxygen. The oxide is patterned by a second mask consisting of an array of Greek crosses, each approximately 18 μm wide, aligned to the original array. The SiO_2 crosses act as a mask for a second etch in KOH which removes some of the underlying silicon. Finally, the microstructures are completed by etching the wafer in an isotropic etching bath (15:5:2 HNO_3:CH_3COOH:HF) for ≈ 1 minute. This step provides the vertical clearance for the interlocking mating structures, and the lateral undercut necessary to produce the four overhanging arms. The inside corners of the Greek cross pattern are filleted to prevent the silicon support post from being eroded.

The process sequence for the piercing structures is similar. To achieve a pointed pyramid, the first etch is continued until the SiO_2 masking layer lifts off. The second level lithography reuses the first level mask, with a significant lateral overetch of the SiO_2 cap, to produce the structure shown in Figure 2.

The second masking step poses particular difficulties, especially for the pointed structures, since the surface is highly nonplanar after the first mask. We have successfully patterned the wafers by using a nominal 2.1 μm thick photoresist film, combined with a long exposure time. The resist thickness, as measured from electron micrographs, is highly nonuniform; it reaches about 3.0 μm in the field regions, and is severely thinned over the tops of the frustums. However, there is adequate thickness to prevent the buffered HF etchant from attacking the SiO_2 caps.

3. Mechanical Testing

Although the microstructures themselves are tiny, useful bonding strengths are realized when macroscopic scale arrays are utilized. Our present design uses a pitch of 22 μm, which results in areal density of over 200000 per cm^2. The bond strength of the mating structures was characterized by direct measurements of the tensile load needed to induce failure.

Patterned samples, nominally 8 mm × 8 mm, were mounted on glass microscope slides using cyanoacrylate adhesive. The mating surfaces were placed together in rough azimuthal alignment, as observed with a low power microscope. Slight shaking of the samples was sufficient to precisely align the microstructures into a mating position. Interlocking was accomplished by applying pressure to the upper substrate; the loading force was monitored by placing the entire assembly on an electronic scale. Bonding was considered to have taken place once the weight of the lower sample and glass slide could be supported by the upper sample. The minimum load necessary for interlocking corresponds to a pressure of 12 kPa.

Bond strength was determined by applying a tensile load through a pulley and measuring the force necessary for separation. We find that separation of the samples is always accompanied by damaged areas on corresponding regions of the mating surfaces. Examination of the microstructures in

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these areas reveal fracturing of the SiO_2 tabs near the silicon support post. We interpret this as evidence the samples are interlocking only over the damaged region. Furthermore, the fraction of damaged area is proportional to the initial loading. For example, a loading of 110 kPa results in an interlocked area of 13%; increasing the insertion load to 330 kPa causes 21% of the microstructures to latch. Partial interlocking could be caused either by insufficient loading, or by particulate contamination which would prevent uniform loading of the samples.

Taking the ratio of applied load to the sample area, we observe tensile strengths of the order of 10–250 kPa. However, if these values are corrected by the fraction of interlocked area, as estimated from the pattern of damage after separation, the tensile strength per unit of interlocked area is higher, about 400–1100 kPa. These values are in reasonable agreement with the calculated strength, which is given approximately by Equation 1[1] where σ_{yp} is the yield point stress of the tabs, b, h and l are the tab width, thickness, and length, d is the microstructure spacing, α is the tab angle, and μ is the coefficient of static friction.

$$F = \frac{2\sigma_{yp} b h^2 \sin\alpha}{3 d^2 l}(1 + \mu \cot\alpha) \quad (1)$$

Substituting our design values into Equation 1 ($b = 10\ \mu m$, $h = 1\ \mu m$, $l = 7.5\ \mu m$, $d = 22\ \mu m$, $\alpha = 42°$) and taking $\mu = 0.5$ and $\sigma_{yp} = 6.0 \times 10^5$ kPa,[2] yields a tensile strength of $F = 1.1 \times 10^3$ kPa. Equation 1 assumes that the dominant failure mode is breaking of the SiO_2 tabs, and not failure of the silicon pedestal; experimental observations bear this out.

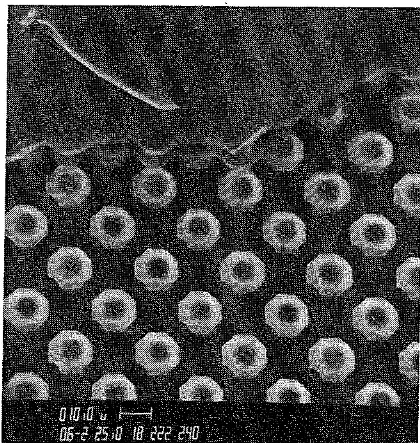

Fig. 3. Electron micrograph of mated structures (top-down view along edge). The simultaneous interlocking of thousands of tabs produces a strong surface bond.

It is well known that silicon wafers placed in intimate contact will bond to each other, especially if moisture is present.[3–6] 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 (38–100%), the tensile strength of the bonded pairs varied from 12 to 20 kPa, well below the strength of the patterned samples. Similar results were obtained when the microstructure arrays were grossly misaligned. Figure 3 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.

4. Piercing Microstructures

Arrays of piercing microstructures (Fig. 2), each approximately 4 µm high, were fabricated and tested for gross adhesion capability. One-sided arrays, approximately 1 cm^2 square, were pressed into sections of a human vena cava obtained from a cadaver. The samples successfully bonded to the tissue, but the tensile strength is, as yet, below that required for clinical application. Electron micrographs of delaminated tissue show four distinct regions which are characterized by the following features:

- Holes where the barbs have penetrated and retracted from the tissue.
- Broken barbs where penetration and bonding have taken place, but the silicon pedestal supporting the pointed cap failed.
- Intact pieces of silicon which remain bonded to the tissue. The silicon substrate itself fractured, probably during insertion.
- Separation of the endothelial lining from the vessel wall, with the microstructure arrays remaining bonded to the lining.

These results indicate the microstructures can be useful in bonding to biological tissues, but the size and shape of the barbs must be optimized. In particular, it appears that the barbs are much smaller than needed for satisfactory latching, since the delamination is occurring within the vessel wall. We are currently exploring ways of building larger scale structures which will overcome this difficulty.

A primary application of this technology is to provide a means of joining or bonding to biological tissues. Such a capability could be employed in several promising ways: vascular stents, wound or incision bandages, local drug delivery systems, and vascular anastomosis. The latter application represents an alternative to conventional suturing; instead of threading a polypropylene filament with a curved needle, a surgeon could join blood vessels using a connector whose surface is blanketed with the piercing microstructures.

5. Summary

We have described two versions of a micromechanical fastening system based on silicon micromachining technology. Since the bonding mechanism in both types of structures is purely

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mechanical, it can be used in applications where chemical resistance, thermal tolerance, and/or biological compatibility are paramount. Successful demonstration of the bonding principle has been achieved for each version. Calculations of the tensile strength of the mating microstructures have been shown to be in approximate agreement with experimental results.

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