WAFER-TO-WAFER TRANSFER OF MICROSTRUCTURES FOR VACUUM PACKAGING

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ABSTRACT

Vacuum packages based on wafer-to-wafer transfer of polysilicon shells are described. Transfer is accomplished by Au/Si eutectic bonding, in conjunction with break-away tethers. The low bonding temperature (370°C) enables end-process application. The short anneal time (~30 seconds) and wafer-scale parallelism promise high manufacturing throughput. Inexpensive packages of this type are desired for resonant sensors and implantable devices. However, a more general application may lie in assembly of the devices themselves, i.e. by transfer of pre-fabricated sensor structures, circuits, and other components.

INTRODUCTION

Resonant microstructures require a vacuum environment to achieve a high mechanical Q. Examples of this sensor class include resonant accelerometers [1] and vibratory rate gyroscopes [2], [3], [4]. Volume manufacturing of these devices will most likely require a micromachined vacuum encapsulation process, which would allow the sensor chip to be enclosed in a conventional, low-cost electronic package.

Several groups have demonstrated micropackaging processes, based on surface micromachining, wafer bonding, eutectics, and other methods. The current work borrows elements from all of these, but introduces a new technique, namely the batch transfer of released microstructures from one wafer to another. In this method, micromachined shells are fabricated on a handle wafer, using a sacrificial layer process such as HexSil [5]. As shown in Figure 1, the shells are anchored to the substrate by tethers, and coated with gold. The handle wafer is then contacted to a second wafer and heated to the Au-Si eutectic point. When cool, the two wafers are separated, breaking the tethers and leaving the shells welded to the second substrate.

This transfer process achieved 100% yield in chip-level transfers, with 30 packages per chip. Vacuum packaging was achieved by annealing in vacuum. At the end of a 5-month test, substantial vacuum persisted. Precision alignment was obtained by mechanical interference fit between lithographically defined features on the two substrates. An unexpected advantage of this process is its robustness to surface roughness and particulate contamination.

BACKGROUND

Micromachined packaging dates to Wise's 1981 single-crystal silicon hemispherical microshells for inertial fusion targets [6]. Petersen [7] has shown pressure sensors with sealed reference cavities fabricated by silicon fusion bonding. Schmidt [8] produced sealed pressure sensors by Si/SiO₂ wafer bonding and etchback. Ikeda [9] and Guckel [10] have demonstrated surface micromachined encapsulation for resonant beams, evacuated by reactive sealing.

Various glass packages have been shown, typically anodically bonded to millimeter-scale sensor chips or thin-film structures [11], [12].

Mastrangelo [13] and Lin [14] have demonstrated vacuum

FIGURE 1. Above: Layout of a typical polysilicon cap for vacuum packaging. Below: Cross-section view of bonding process.

packages for incandescent microlamps and microresonators, respectively. In this work, a silicon nitride film was deposited over a sacrificial PSG layer; the resulting shells were etched out with HF and sealed by CVD. The final pressure is limited by residual CVD gases.

Several researchers have employed eutectic bonding, both for assembly and packaging [15], [16]. An advantage of this process is its low temperature: e.g. 183°C for the Pb/Sn system, and 363°C for Au/Si.

PROCEDURE AND RESULTS

The basic packaging procedure consists of two parts: fabrication and transfer. The packages – essentially polysilicon hemishells – are fabricated by the HexSil process [5]. Starting with a <100> silicon substrate, an anisotropic plasma etch defines a mold for the package's stiffening ribs. These have a width of 8 µm and a depth of 5 µm, and are laid out in a cartesian grid. A second plasma etch defines cavities 300 µm square and 4 µm deep for the packages themselves. This depth should not be exceeded without special resist coating equipment, or step coverage problems may occur in subsequent lithography.

The etched surfaces are smoothed by a wet silicon etch

(50 HNO₃:20 H₂O:1 NH₄F, 5 min), followed by growth of 0.5 μ m of wet thermal oxide, and removal of the oxide in concentrated HF.

A sacrificial oxide is then deposited. PSG is preferred, since release of the caps will require 250 μ m of undercut. LTO may be used as a diffusion barrier to protect adjacent layers from doping. The film is densified at 1000°C for 1 hour in nitrogen.

The oxide is patterned with anchor holes. A 20 μ m square geometry proves adequate, though other sizes may be possible. In photoresist application, care should be taken to ensure adequate coverage around the cavities. Multiple coats may be required, particularly if plasma etching. Adhesion promoters such as HMDS may be detrimental. If a spin coater is used, "stale" photoresist must be purged from the feed line. A minimal hardbake should be used, as resist tends to pull back from steps.

Polysilicon deposition is preceded by a 15 second buffered HF dip and 2 minute DI rinse, to remove native oxides from the anchor contacts. Particular care must be taken, because of the long HF release step which will follow. Doping and grain size in the polysilicon film may be chosen to suit; undoped, coarse-grained (605°C, 100 nm roughness) material was mainly used, since this gave the highest growth rate. Undoped material should be isolated from PSG to prevent doping-induced stress gradients. Films were annealed in nitrogen at 1000°C for 1 hour to remove residual stress. A thick film – e.g. 4-5 μ m – is desired, to avoid damage during release and bonding. The film should fill the trenches defined for the stiffening ribs. A test structure consisting of a long cantilevered beam should be included for thickness measurement, since optical methods fail beyond ~ 1 μ m.

Polysilicon is defined by plasma etch. Again, photoresist step coverage is vital, to avoid "burnthrough" at the edges of the cavities. Tethers were designed to be robust, to prevent structures from detaching during the release. 4 μ m wide x 10 μ m long, and 30 μ m wide x 30 μ m long designs both worked satisfactorily. Eight anchors were provided for each 500 μ m square package. Flanges on the packages were 100 μ m wide. Narrower designs may be possible.

Gold deposition is preceded by a BHF dip, as above, to ensure adhesion in the release. In addition, 100 nm of chrome was deposited as an adhesion layer. This also seems to prevent excessive diffusion of the gold during bonding, and the layer is apparently not undercut in the HF release. An evaporated gold film of 0.7 - 1.0 μ m thickness yields good results in bonding. Problems were encountered with films in the 100 nm range.

Following metallization, wafers were diced and released. Release required 25 minutes in concentrated (49%) VLSI-grade HF. A surfactant (Triton X-100) was added to prevent collapse due to surface tension. A 5 minute DI rinse was followed by critical point drying in CO₂ [17].

Target substrates consisted of 2 μ m thick polysilicon on a single-crystal substrate. Roughness was 10 nm peak-to-peak. Targets were prepared with the BHF dip procedure, followed by blow-dry with nitrogen. Handle and target chips were then contacted in a Class 100 environment. Contact was performed by laying one edge of the handle chip down on the target chip, then allowing the handle chip to fall flat. The handle could then be positioned laterally to align the two chips. The chips were placed in the bonding apparatus and clamped. The target chips were diced about 10% larger than the handle chips to simplify handling of the sandwich.

Approximately 60 kPa of contact pressure was applied to

the chips in the apparatus, shown in Figure 2. Note that this force is distributed only over the bonded areas, making the actual contact pressure about 1.2 MPa. Dummy structures were placed at each corner of the layout to ensure parallelism of the chip faces.

FIGURE 2. Bonding apparatus. The apparatus is placed in a quartz vacuum chamber and heated from below with an external lamp. The clamping spring (right-hand side) applies contact pressure to the test sample.

Bonding was performed in a vacuum of ~ 10⁻⁵ T. The anodized aluminum surface of the bonding apparatus provides a susceptor, allowing consistent heating by the external lamp. A temperature of 370°C was found to be effective for Au/Si eutectic bonding. Temperature was monitored by a thermocouple mounted inside a sandwich of two silicon chips, clamped adjacent to the sample (see Figure 2). The thermal ramp-up to 370°C required approximately 5 minutes, after which cooling was begun immediately. Approximately 30 - 60 seconds was spent above the eutectic temperature. After cooling, the two chips were carefully separated to avoid shearing the microstructures. Separation breaks the polysilicon tethers (see Figure 1), leaving the shells bonded to the target. Results are shown in Figure 3.

FIGURE 3. SEM of vacuum cap after transfer. Above: Some tethers are still partially attached to edge of cap. Flange (surrounding ribbed square) is 100 μ m wide. Below: Cleaved cross-section of ribbed cap.

Most of the packages were designed with ribs, so that there would be minimal deformation under atmospheric pressure. However, several packages were designed without ribs so that Nomarski imaging (Figure 4) could reveal a displacement of the shell. Profilometry indicated a displacement of up to 680 nm on 300 μ m square, 4.47 μ m thick structures. The displacement disappeared when the package was punctured. Substantial vacuum persists at the end of a five-month test, as shown in Figure 5.

Profilometer measurements after transfer indicate significant compression of the seal structure. From an initial thickness of 730 nm, the gold layer is compressed to an apparent thickness of 346 nm. Some of this compliance may have occurred in the adjacent

FIGURE 4. Cap without ribs was designed to deflect under pressure differential. Left: after assembly and anneal. Right: same, after being punctured. Nomarski imaging.

FIGURE 5. Package internal pressure as a function of time. layers of the structure (refer to Figure 1).

DISCUSSION

The transfer and bonding process described here displays several important features and unexpected advantages. Since a high degree of roughness is tolerated on the mating surfaces, packages can be pumped out after being assembled. This simplifies the apparatus considerably. In addition, the compression of the seal – more than 500 nm in some cases – suggests application to feedthroughs and other planarization problems.

There is evidence that complex, high-aspect structures can be transferred. The sample in Figure 6 was prepared by a “wet transfer” process, in which release occurs after the two chips are contacted. Residual SiO_2 from the DI rinse most likely causes bonding [18]. Subsequent processing included sputter deposition of 100 Å of gold.

FIGURE 6. SEM of HexSil structure placed on SCS substrate by “wet transfer” method. The vertical feature is 80 μm in height.

Although these transfer processes appear robust to surface roughness and a modicum of particulate contamination, released structures are generally fragile and are potential particle generators themselves, if accidentally detached from the substrate. Fortunately, robust anchors can be liberally distributed, because of the high strength of the eutectic bond.

Shear strength of the bond was measured by bonding two unpatterned silicon chips. The resulting sandwich was supported

along two opposite edges and a load applied at the middle. A crack formed and propagated through the sandwich, with no evidence of de-bonding. A value of at least 0.39 GPa may be calculated for the shear strength in this case. This is given by the shear stress at the neutral axis of the two-chip sandwich, when the maximal stress reaches the yield strength of silicon. The value seems reasonable in light of Lee's result of 5.5 GPa for the tensile strength, achieved under similar annealing conditions [16].

To ensure survival of the caps during release and contact, it may also be useful to avoid stress concentrators in the design. For example, hexagonal ribbing is preferred to square, and rounded corners to right angles.

A process has been developed for patterning the shells with reinforcement ribs. In fabrication, the rib structures are etched first, followed by the package cavities. In this way, the mask stepper need only focus at the plane of the wafer surface. Trench widths should be chosen as with HexSil [5]. Oxide thickness was minimized, on the premise that a thin sacrificial layer would prevent damage during contact, by avoiding excessive strain at the anchors. Thicker layers may be usable.

Patterning of the sacrificial oxide is complicated by the topography. Poor resist coverage tends to occur at the edges of the cavities, leading to loss of the oxide and failure to release. Softening of these steps with an isotropic etch may be beneficial. Generous use of photoresist is recommended, e.g. 4 μm or more, depending on step height. Alternately, the cavity depth may be reduced, since sagging of the ribbed packages is negligible.

Some latitude is possible in choice of structural material. Both undoped and doped, coarse- and fine-grained polysilicon recipes have been used. Silicon nitride has been shown by Lin [14] in a similar application, and gold is also a possibility.

Gold adhesion in the release step was variable. The preceding BHF dip seems vital, however. In one trial, a short plasma etch ($\text{CH}_3\text{F}/\text{CF}_4/\text{He}$) was used instead, with the intent to maintain a dehydrated surface for the gold evaporation. Poor adhesion resulted in this case.

Accurate temperature control is recommended. Significantly exceeding the eutectic temperature causes distortion of the polysilicon structures, apparently due to consumption by the liquid eutectic. An example is shown in Figure 7. Control of temperature and the initial gold distribution may lead to novel capabilities, such as plastically deformed shells, welded links, or fusible supports.

FIGURE 7. SEM of a corner of a vacuum package, after bonding on a 700 nm Au film at ~ 400°C. Note “smearing” and grainy appearance of material.

In the sealed structures, the differential pressure across the cap may be determined from the expression for plate deformation under a distributed load [19]:

$$\Delta z = \frac{0.00126qa^4}{D}$$

where

$$D = \frac{Eh^3}{12(1-\nu^2)},$$

the Poisson ratio of polysilicon, ν , is taken as 0.23, the Young's modulus, E , is 170 GPa, Δz is the measured deformation of the top surface of the cap, the width of the plate, a , is 300 μm , and the thickness of the plate, h , is 4.47 μm . Rearranging, we find $q = 816 \pm 75$ T. The uncertainty is contributed mainly by E .

Since the ambient pressure at the time of measurement was ~ 752 T, the internal pressure is expected to be in the range of 0-12 torr. The variation of this value with time is plotted in Figure 5. The long time constant suggests outgassing rather than leakage; a more aggressive bakeout, or gettering, might yield improvement.

WORK IN PROGRESS

Alignment of handle and target was achieved by patterning a 1.7 μm oxide step on the target, contacting the two chips, and abutting features on the handle against the step. A sharp piece of silicon was dragged across the back of the handle chip to generate a lateral force. It was expected that this force would be limited by the Si-Si friction coefficient, and thus would be commensurate with the forces present on the front side of the chip. Misalignment after bonding was less than the detection limit of 5 μm .

Encapsulated resonator structures were designed using a periodic pattern of conductive feedthroughs to favor planarization [12]. A 300 nm doped polysilicon film was used in a 5 μm line-space pattern, shown in Figure 8. A 2 μm LTO/PSG layer was overlaid for planarization, followed by 1 μm of low stress silicon nitride to protect it from the release. The same oxide film was also used for the resonator sacrificial layer. 2 μm polysilicon doubles as the resonator structural layer and a buffer layer over the feedthroughs for additional planarization. This surface displayed a 170 nm height modulation due to the feedthroughs, suggesting that a seal should be readily achieved, considering the 500 nm compliance described above. The die also includes multi-bore needles with internal electrical feedthroughs, hinge structures, and transferred resonators.

FIGURE 8. Feedthrough structure for encapsulated resonator. 3000Å doped polysilicon connections are supplied for an electrostatic comb drive, sensing capacitors, and fusible supports.

Subsequent work will pursue both improved vacuum packaging and more general applications. For instance, the transfer process may be proposed for sensor structures, i.e. to combine resonators with CMOS. GaAs devices are also a candidate. This approach avoids many process-compatibility problems, and offers to simplify MEMS development: pre-fabricated, VLSI-scale modules (op-amps, microcontrollers) could be incorporated into many systems by assembly, rather than

monolithic integration.

CONCLUSION

A technique has been demonstrated for batch transfer of complex polysilicon structures between two wafers. A gold/silicon eutectic forms a high-strength bond and hermetic seals. The bonding process is robust to surface roughness and contamination, and can be performed at low temperature. Packages can be evacuated after assembly, simplifying equipment design.

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