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Removable fast package technology for MEMS devices using polymer connectors and silicon sockets

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Abstract
This paper describes a novel removable and reusable packaging technique that can act as temporary protection for suspended microelectromechanical system (MEMS) devices during dicing and handling. The technique uses a polymer cover with built-in flexible connectors and is prepared using a molding process, and then mechanically interlocked to the MEMS device with built-in socket arrays. The shapes of the polymer connector and the silicon sockets are easily patterned and tuned using microfabrication processes. The press-fit design of the connectors and the sockets, and the hydrophobic characteristic of the polymers provide waterproofing protection. We have demonstrated that the interlocking of modified SCREAM devices with the PDMS polymer cover was demonstrated at a typical interlocking strength of approximately 1 MPa.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

MEMS (microelectromechanical systems) devices frequently consist of various movable and deformable structures, such as a movable stiff plate for optical mirrors, deformable flexible membranes for pressure sensors, deformable springs and movable proof mass for the inertia sensors, and so on. These movable and deformable MEMS components are fragile and need to be protected after the release from the substrate. However, the suspended MEMS components which are similar to their integrated circuit (IC) counterparts are not currently protected before packaging. Passivation layers, such as nitride and oxide, are generally employed to protect the IC from contamination, scratching or other damage. The traditional passivation technique used to protect the IC is not suitable to protect the suspended MEMS devices, which need to move and deform. Preventing damage of suspended MEMS structures during handling and dicing processes is a critical design consideration.

MEMS packaging to date can be divided into three different approaches: standard packages, wafer level packages and temporary packages. Standard packages include metal packages [1], ceramic packages [2] and plastic packages [3]. Wafer level packages contain a wafer-to-wafer bonding technique [4–7] and thin film encapsulation [8]. The abovementioned approaches can be categorized as permanent packages, and these techniques only provide permanent packaged units with special requirements on temperature, voltage and material composition. Temporary packaging [9] is also required for various applications. During wafer dicing, MEMS components are exposed to a harsh environment of particle contamination. The suspended MEMS structures could be disturbed or damaged by the de-ionized water of the dicing saw with a pressure load in the order of 0.1 to 10 MPa. A temporary packaging technique that can protect MEMS devices during wafer dicing is needed.

This study presents a novel packaging technique using a polymer cover with built-in flexible connectors. The connectors on the polymer cover are mechanically interlocked to the MEMS device chip with built-in sockets. This removable and reusable polymer cover is waterproof and

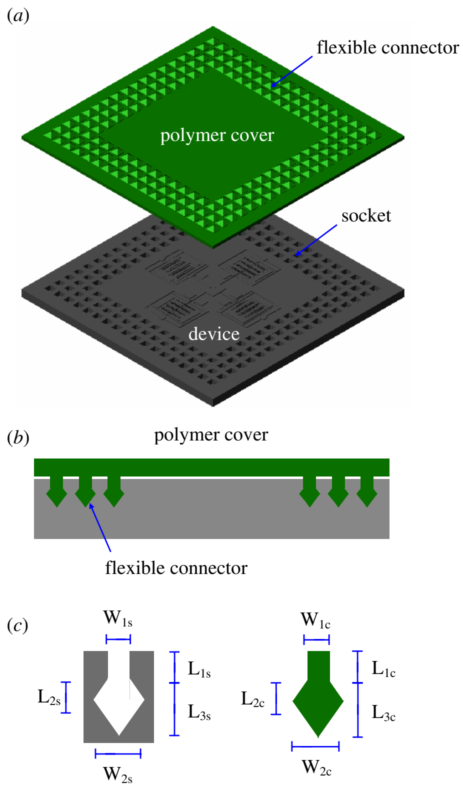


Figure 1. Schematic illustration of the present concept: (*a*) polymer cover and MEMS device before packaging, (*b*) packaging of the polymer cover and the MEMS chip using the interlocking of flexible connectors and silicon sockets and (*c*) tunable dimensions of the present connectors and sockets.

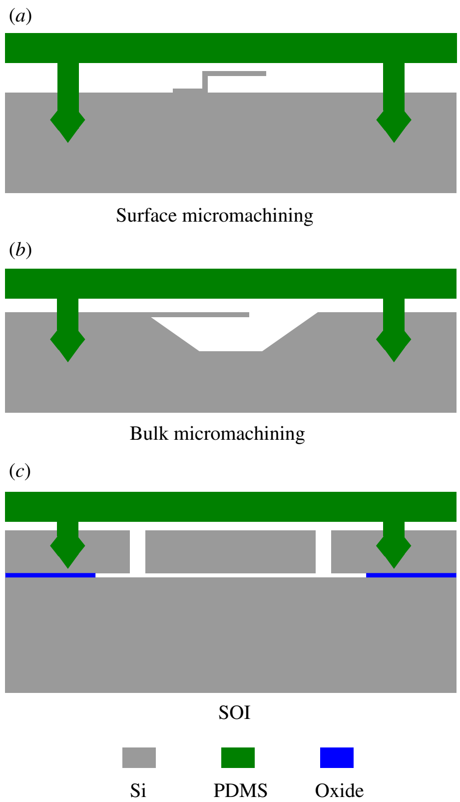


Figure 2. Various potential applications of the polymer cover for (*a*) surface, (*b*) bulk and (*c*) SOI micromachined devices.

particle-proof and provides temporary protection of the suspended MEMS devices, for instance during dicing and handling. Moreover, the fast-package approach is performed at room temperature and has the potential to achieve not only the die-level but also the wafer-level packaging. The fabrication process of the polymer cover and built-in socket is simple and easy to integrate with other micromachining processes. Using a single mask process, we demonstrated the interlocking of SCREAM (single crystal reactive etching and metallization) [10] devices and the PDMS (polydimethylsiloxane) cover. The typical interlocking strength of the present approach was near 1 MPa, which was easily increased by adding the number of connectors. The waterproof characteristic of the PDMS cover has also been demonstrated.

2. Design concepts

Figure 1(*a*) shows a polymer cover with flexible connector arrays and built-in socket arrays surrounding the MEMS device on a silicon chip. The side view in figure 1(*b*) schematically illustrates the inter-locking of the polymer cover and the silicon sockets. In this design, the socket arrays for packaging are directly built-in onto the silicon substrate. The silicon substrate also acts as a mold to define the shape of the polymer cover. The locations and dimensions of the sockets and connectors are all defined using silicon micromachining processes. The dimensions of the connectors and sockets indicated in figure 1(*c*) can be tuned by the present processes. Various design considerations are necessary for the dimensions of the connectors and sockets. The polymer cover will contact or press the MEMS device if the length L_{1c} is smaller than L_{1s}. On the other hand, the flexible connectors act as a spacer between the polymer cover and the MEMS device when $L_{1c} \geqq L_{1s}$. Leakage also needs to be considered during the design of flexible connectors. The polymer connectors consist of an octahedral tip and a rectangular post while the silicon sockets consist of an octahedral cavity and a rectangular groove. The connectors will interlock (or separate) with the sockets after applying an adequate load so as to mechanically assemble the polymer cover and silicon substrate. The alignment of the connectors and sockets is assisted by the octahedral tip of the connector defined by (1 1 1) crystal planes. Figure 2 shows various potential applications of the polymer cover for surface, bulk and SOI (silicon on insulator) micromachined devices.

The interlocking strength is mainly determined by the dimensions of the connectors and sockets indicated in figure 1(*c*). Commercially available simulation software (ANSYS) was used to predict the interlocking force and the stress distribution on the flexible connectors. Figure 3(*a*) shows a typical finite element model of the connectors and sockets. The predicted stress distributions on the silicon sockets and the flexible connectors during demolding are indicated in figures 3(*b*) and (*c*), respectively. In this study, the PDMS, which has a tensile strength of 6.2 MPa (sylgard 184, Dow Corning), is used as the material for the polymer cover. This was the primary consideration while designing

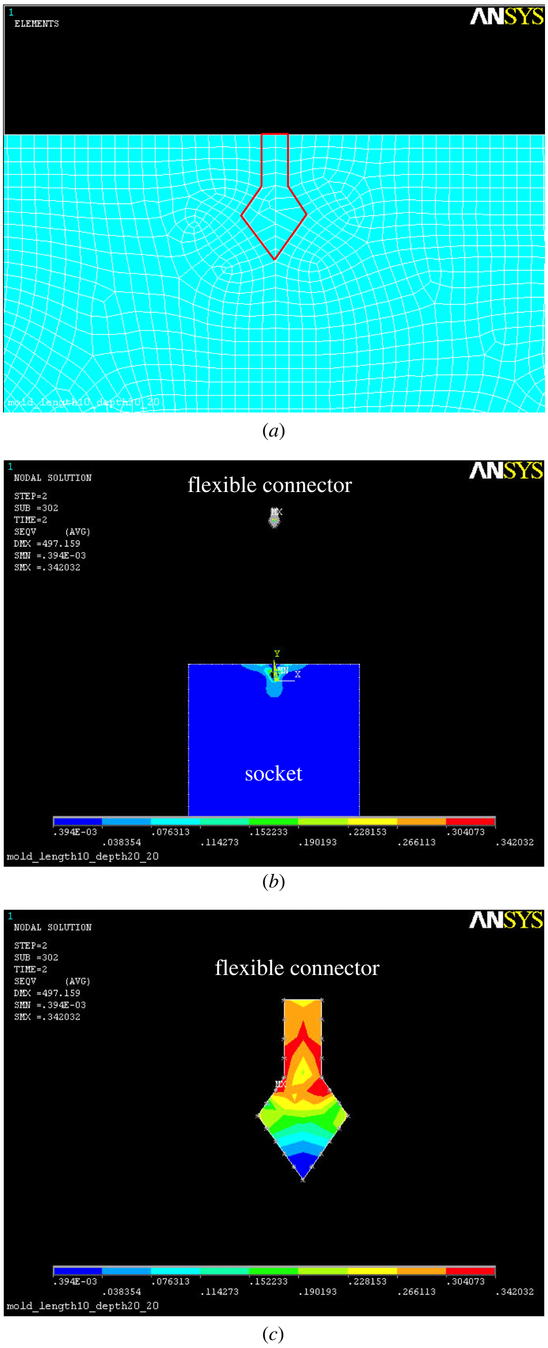


Figure 3. Mechanical characteristics predicted by the finite element simulation: (*a*) the typical finite element model; the typical stress distribution during demolding for (*b*) silicon socket and (*c*) flexible connector.

the interlocking force. Typical simulation results are shown in figure 4. In each case, the dimensions of the connectors and sockets indicated in figure 1(*c*) are assumed to be the same (i.e. $L_{1c} = L_{1s}$, $L_{2c} = L_{2s}$, etc). The lengths of L_{1c} and L_{1s} are fixed at 20 μm. The results show the variation of the interlocking force with the widths of the connectors and sockets, W_{1c} and W_{1s}, at two different lengths of L_{2c} and L_{2s} (20 μm and 40 μm). The typical interlocking force for a single connector is within the range of several tens to several hundreds of micro newtons. The maximum stress on the polymer connector ranges from

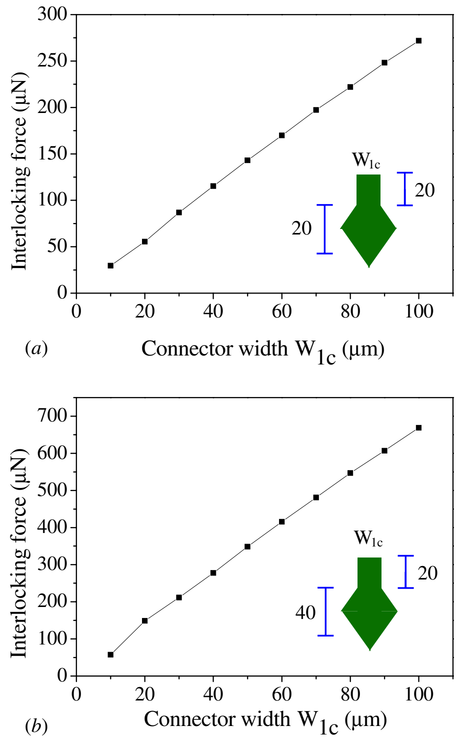


Figure 4. Simulation results of interlocking force for a pair of connectors and sockets at a different connector width W_{1c}. The connector and socket are of the same dimension, and (*a*) $L_{1c} = L_{1s} = 20$ μm and $L_{2c} = L_{2s} = 20$ μm, and (*b*) $L_{1c} = L_{1s} = 20$ μm and $L_{2c} = L_{2s} = 40$ μm.

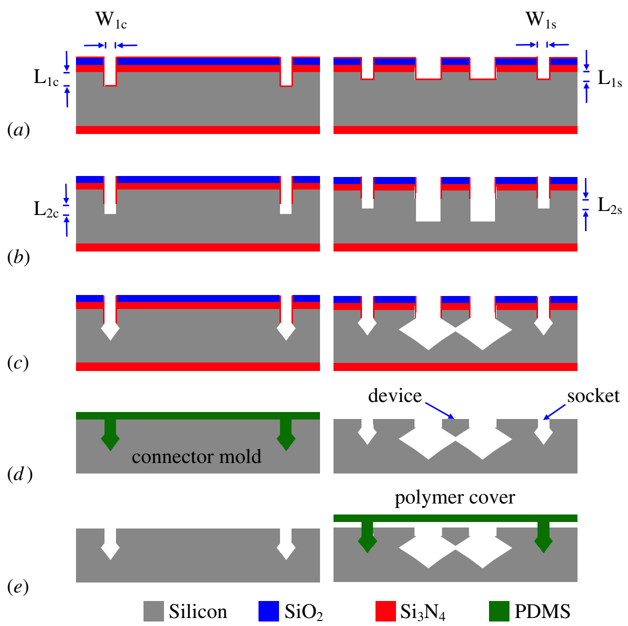


Figure 5. The present fabrication process steps.

0.03 MPa to 0.6 MPa, so that they will not be broken during demolding. The interlocking force can be further improved by adding elastic Coulomb friction at the side wall of the connectors and sockets by means of the press-fit designs (i.e. $W_{1c} > W_{1s}$, $W_{2c} > W_{2s}$).

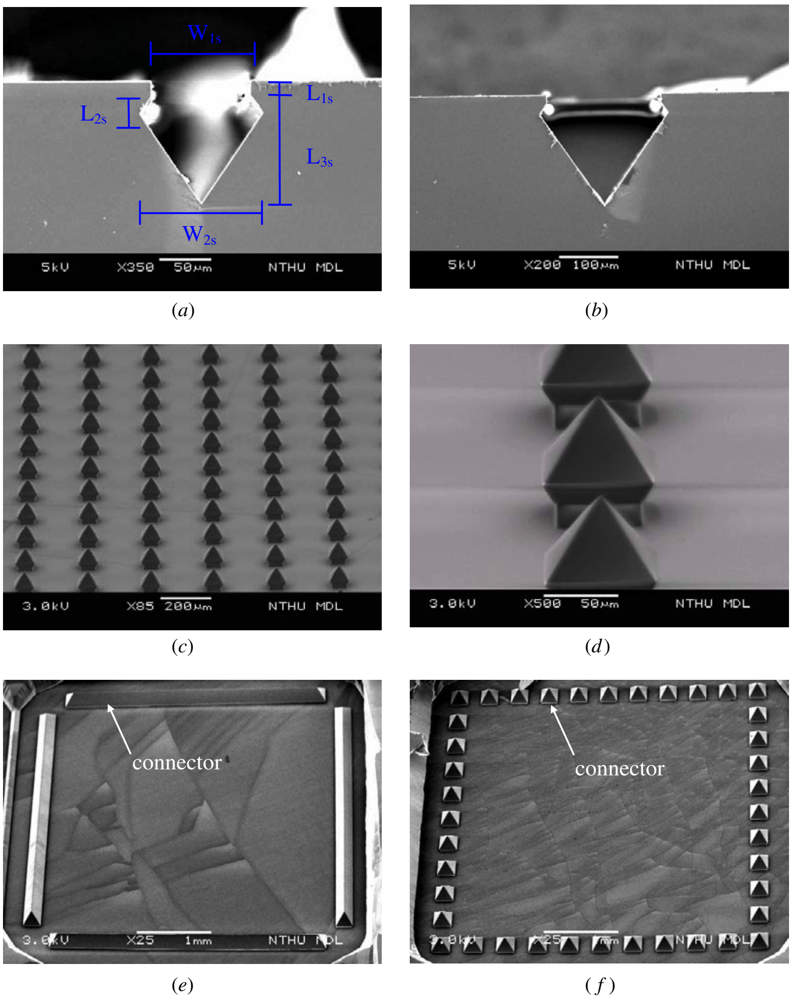
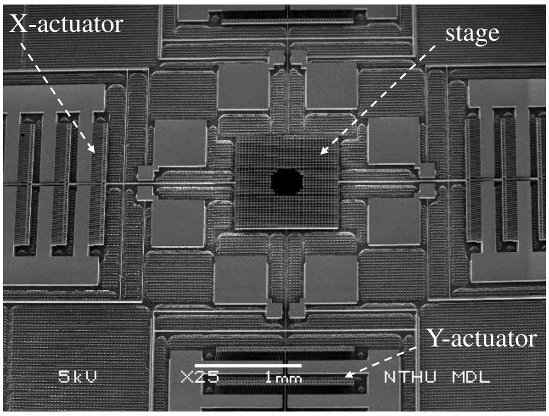


Figure 6. SEM micrographs of typical fabrication results: (*a*) and (*b*) two different octahedral sockets on the device substrate, (*c*) the PDMS flexible connector array, (*d*) zoom-in photo of polymer connector with octahedral tip, and (*e*) and (*f*) polymer covers with different connector array distributions.

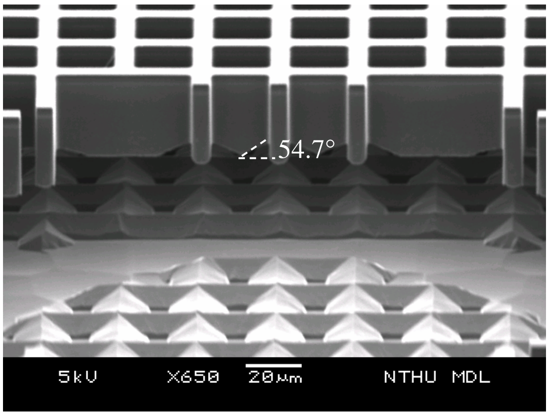
3. Fabrication processes

Our novel fast packaging technique can be applied to protect MEMS devices fabricated by various processes including surface micromachining, bulk micromachining and SOI (figure 2). This study established a modified SCREAM process to simultaneously fabricate the sockets, and modified SCREAM devices onto a silicon substrate using only one photo mask demonstrating the feasibility of protecting the modified SCREAM device chip using the polymer cover. The modified SCREAM processes on the device substrate are illustrated on the right-hand side of figure 5. The left illustrations in figure 5 show the fabrication processes on a mold substrate to implement the polymer cover and connectors. The processes in figure 5 need only two masks: one for the polymer mold substrate and another for the device and socket substrate.

First, nitride and oxide films were deposited on both the device and mold substrates. As shown in figure 5(*a*), after defining the widths of W_{1c} and W_{1s} using photolithography, DRIE (deep reactive ion etching) was used to define the etching depths of L_{1c} and L_{1s} on the mold substrate and the device substrate, respectively. The height of the connector posts, the depth of the socket grooves and the thickness of the modified SCREAM devices were determined. As illustrated in figure 5(*b*), after depositing and patterning a nitride film for sidewall protection, the mold and device substrates were etched by DRIE again to define the depths of L_{2c} and L_{2s} for wet anisotropic etching. In this step, the loading effect of DRIE was used to fabricate trenches with different depths on the device substrate. Anisotropic silicon etching by KOH (or TMAH) (figure 5(*c*)) was used to form the shape of the connector tips and socket cavities, and to release the MEMS devices. Anisotropic etching was only performed at the side walls and the bottom of the trenches without the protection by the nitride film. A cavity of octahedral shape was formed on the silicon substrate after the silicon etching was stopped by the (1 1 1) crystal planes. Nevertheless, the dimensions of the octahedral cavity had already been determined by the widths of W_{1c} and W_{1s}, and the depths of L_{2c} and L_{2s}. A lateral anisotropic silicon etching was employed to fully suspend the MEMS structures onto the device substrate, as indicated in figure 5(*c*). The primary difference between modified SCREAM and conventional SCREAM is that the latter employs the isotropic silicon etching to release the MEMS structures. A polymer



(*a*)



(*b*)

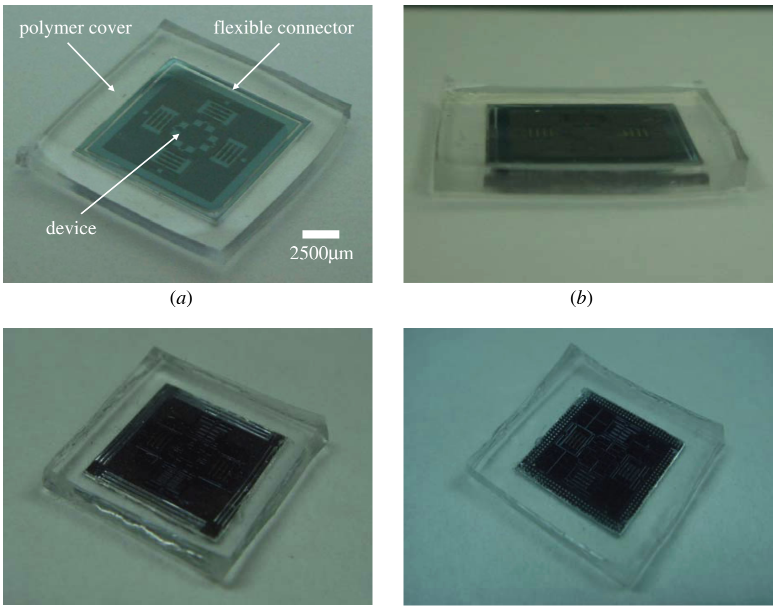
Figure 7. SEM micrographs of a typical fabricated device on the silicon substrate: (*a*) a 2D position stage and (*b*) the full release of the MEMS structure.

molding technique using a mold substrate was used to implement the polymer cover as shown in figure 5(*d*). First, a Parylene film was conformaly deposited onto the surface of the mold substrate as the release agent for demolding. The PDMS polymer was then poured onto the mold substrate, and the air trapped inside the trenches was fully removed by the vacuum pump. The molded PDMS attached to the mold substrate was cured at 100 °C. Finally, the polymer cover was demolded from the mold substrate, and ready to package with the device substrate through the interlocking of connectors and sockets, as shown in figure 5(*e*).

In summary, it is easy to define the distributions and shapes of the connectors and sockets using lithography and anisotropic etching processes to further tune the interlocking characteristics of our packing technique. Our novel packaging technique can easily adapt to specific design considerations of various applications. For instance, the increasing of the connector length L_{1c} by DRIE can be applied to increase the out-of-plane moving space for the MEMS devices.

4. Results and discussions

The SEM photos in figures 6 and 7 show typical fabrication results. Figures 6(*a*) and (*b*) show two different octahedral sockets on the device substrate. The dimensions defined by photolithography (W_{1s}), DRIE (L_{1s} and L_{2s}), and (1 1 1) crystal planes after wet anisotropic etching (L_{3s} and W_{2s}) are indicated in figure 6(*a*). Figure 6(*c*) shows the polymer (PDMS) connector array after demolding. The polymer connector with an octahedral tip is shown in figure 6(*d*). The photos in figures 6(*e*) and (*f*) show two PDMS covers with different connector designs. Figure 7(*a*) shows a typical modified SCREAM device of a 2D in-plane position stage. This position stage was driven by two pairs of comb-drive actuator arrays integrated with the socket array on the device substrate. This suspended MEMS structure is clearly observed from the side view photo of figure 7(*b*). In addition, the (1 1 1) crystal planes at the bottom of the suspended structure, as indicated



(*a*) (*b*) (*c*) (*d*)

Figure 8. The polymer cover with different connector designs and the MEMS device chip after packaging.

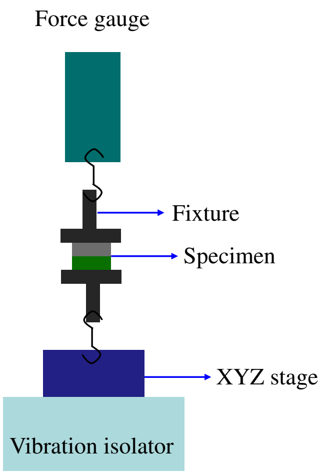


Figure 9. A pull-test setup to measure the interlocking force of connectors and sockets.

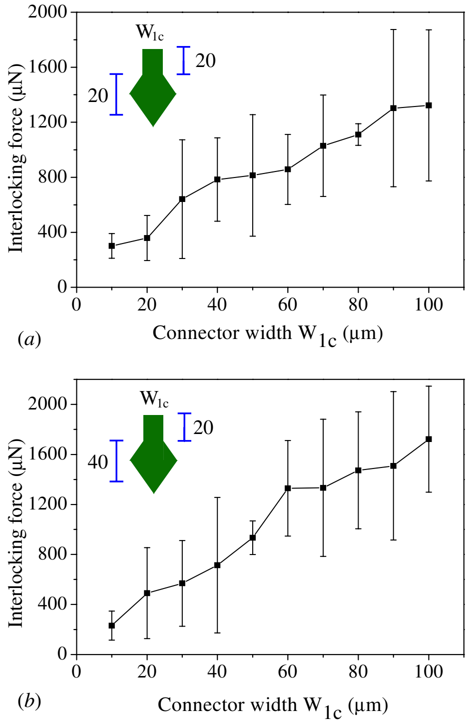


Figure 10. Measurement results of interlocking force for a pair of connectors and sockets at a different connector width W_{1c}. The connector and socket are of the same dimension, and (*a*) $L_{1c} = L_{1s} = 20\ \mu$m and $L_{2c} = L_{2s} = 20\ \mu$m, and (*b*) $L_{1c} = L_{1s} = 20\ \mu$m and $L_{2c} = L_{2s} = 40\ \mu$m.

in figure 7(*b*), show the anisotropic lateral silicon etching of the modified SCREAM process. The photos in figure 8 show the MEMS device chip and PDMS cover after packaging. As shown in figure 8(*a*), the 2D position stage can still be clearly observed after protection by the PDMS cover. The lateral view of the same packaged device is shown in figure 8(*b*). The packaged devices with two other connector designs are also demonstrated in figures 8(*c*) and (*d*).

The experimental setup in figure 9 was established to characterize the interlocking force of the polymer cover. The

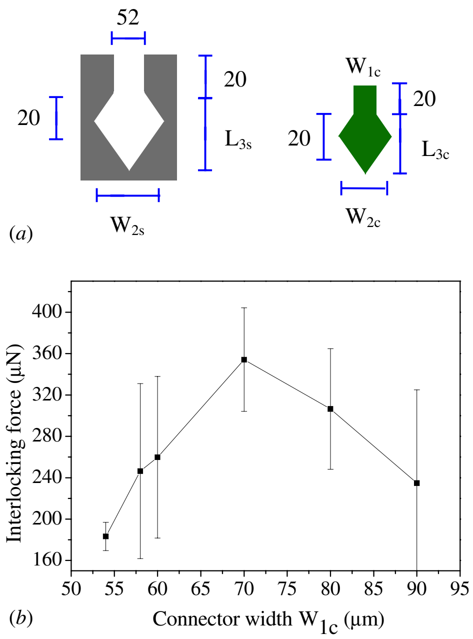


Figure 11. The measured interlocking force of connectors and sockets with press-fit designs.

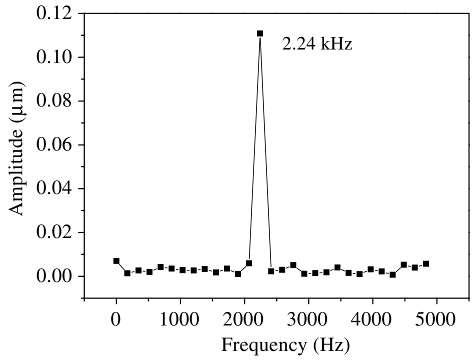
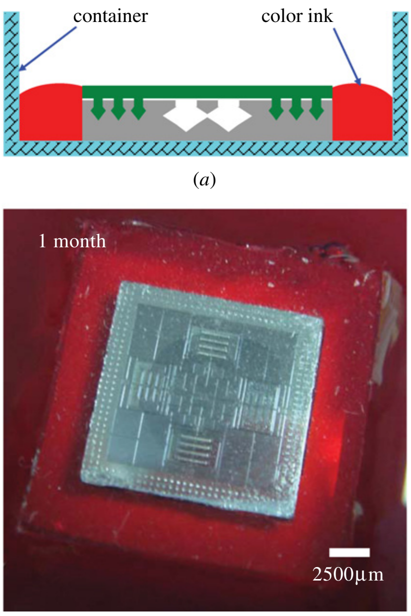


Figure 12. The measured frequency response of the 2D position stage after the package.

force was measured by a commercial pull-test instrument with a resolution of 0.1 gf, and a maximum load of 1 kgf. The typical measurement results in figure 10 show the interlocking force at different widths of W_{1c} and W_{1s}. In this test, the dimensions of the connectors and sockets are the same, and the lengths of L_{1c} and L_{2c} are indicated in figure 10. The lengths of L_{1c} and L_{1s} are fixed at 20 μm. The test demonstrates that the interlocking force can be tuned by varying the shape of the connectors and sockets. The typical interlocking strength of the present approach was near 1 MPa. The trend in figure 10 agrees qualitatively with the results predicted in figure 4. Since the static Coulomb friction between the connectors and sockets was not considered in the simulation, the measured results are higher than the predicted ones. The interlocking force of the present approach can be further increased by employing the press-fit design of the connectors and sockets. This study also measured the interlocking force on connectors and sockets of different sizes, as shown in figure 11. During the tests, the lengths of L_{1s}, L_{2s}, L_{1c} and L_{2c} were fixed at 20 μm,



(*a*)

(*b*)

Figure 13. The preliminary liquid leakage test using color ink: (*a*) test setup and (*b*) no leakage occurred after testing for 1 month.

and the width of W_{1s} was fixed at 52 μm, as indicated in figure 11(*a*). In addition, the width of connector W_{1c} ranged from 54 μm to 90 μm. The measurement results in figure 11(*b*) show the variation of the interlocking force with the width W_{1c}. According to the press-fit design, the interlocking force increases as the connector width W_{1c} increases from 54 μm to 70 μm. However, the tip of the connector cannot fit into the socket properly when the width W_{1c} is larger than 70 μm. Thus, the interlocking force decreases as the width W_{1c} increases from 70 μm to 90 μm.

A test setup was established to characterize the dynamic characteristics of MEMS devices before and after packaging, so as to evaluate the present packaging technique. The MEMS device was driven by harmonic excitations using a PZT shaker. A commercial stroboscope microscope was used to measure the in-plane dynamic response of this MEMS device. Figure 12 shows the typical measured frequency responses of the modified SCREAM position stage shown in figure 7(*a*) after packaging. The frequency spectrum ranges from 0 to 5 kHz, and the resonant frequency of the MEMS position stage is at 2.24 kHz. The frequency response in figure 12 is the same as that before packaging; thus the dynamic characteristics of the MEMS position stage are not influenced by our packaging technique.

A liquid leakage test was performed on the MEMS device packaged with the PDMS cover. As shown in figure 13, the packaged device was immersed into color ink. After testing for more than 1 month, no leakage occurred, demonstrating that the PDMS cover can prevent water from leaking into the surface of the MEMS chip. Both the press-fit design of the polymer connectors and sockets, and the hydrophobic quality of the PDMS material create a waterproof environment. Consequently, the present PDMS cover can be employed to protect the suspended MEMS device during dicing.

5. Conclusions

This study has successfully demonstrated a novel fast packaging technique for MEMS devices using a polymer cover. The PDMS cover with the flexible connectors array is mechanically interlocked to the Si substrate with built-in socket arrays at either die level or wafer level at room temperature. The PDMS cover is prepared by means of polymer molding on a micromachined mold substrate. The dimensions, number, position and distribution of connectors are defined using the micromachining processes and can be easily changed. Moreover, the processes to implement the sockets into the device substrate need only one mask. It is easy to integrate such processes with existing MEMS fabrication platforms and devices, such as MUMPs (multi user MEMS process) [11], SCREAM, MOSBE (molded surface-micromachining and bulk etching release) [12], SOI, etc. To show the feasibility of the present technique, the silicon sockets and modified SCREAM devices have been realized and integrated on the device substrate using only a one-mask process. The packaging of the MEMS chip with the PDMS polymer cover has also been demonstrated. The typical measured interlocking strength of the present technology was near 1 MPa, and temporarily protects the MEMS devices. In addition, the pull tests show that the bonding strength can be easily tuned by varying the shapes of the sockets and connectors through microfabrication processes. Moreover, the hydrophobic characteristic of the PDMS cover provides waterproofing to the packaged device chip. In summary, the removable and reusable PDMS cover temporarily protects the suspended MEMS devices during dicing and handling.

Acknowledgments

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