WIREBONDER ASSEMBLY OF HINGELESS 90° OUT-OF-PLANE MICROSTRUCTURES

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ABSTRACT

A novel design and analysis for the assembly of 90° out-of-plane microstructures using a standard microelectronics wirebonder is presented. The microstructures can be assembled by a single point actuation and use a selectively compliant spring system that converts an in-plane motion to an out-of-plane rotation. The single point actuation can be provided by a standard microelectronics wirebonder. A wirebonder is a common piece of equipment for microelectronics packaging and therefore the assembly method described here introduces a practical and economical approach. The microstructure designs were fabricated using either PolyMUMPs or a prototyping process developed at Simon Fraser University that uses SU-8 as a structural layer. The designs were modeled using the Finite Element Analysis (FEA) software ANSYS, and tested for positional repeatability and reliability verifying the proof of concept.

INTRODUCTION

Out-of-plane components have numerous applications for on-chip optics [1] and RF systems [2]. These components must be fabricated in-plane and assembled afterwards to achieve out-of-plane orientation. The current methods for assembly can be integrated on-chip using electrostatic [3] or thermal actuators [4] to produce the motions necessary for assembly, but these actuators require a large sacrifice of chip area. External systems, such as robotic pick-and-place [5] are also currently in use but require a significant investment in specialized equipment. More recently, there has been development in thermal kinetic assembly [6] and centripetal assembly [7] of micro devices, but both methods require the use of hinges to allow the structures to rotate out-of-plane. Because the creation of hinges requires the use of multiple structural layers, hinges cannot be used when processes are limited to a single structural layer. Furthermore, hinges are susceptible to friction and mechanical jamming, which reduces the yield of assembled structures. Other assembly methods proposed employ the surface tension of solder-ball reflow [8] or residual stress mismatch between epitaxial layers [9] to lift and assemble micromachined flaps. However, these systems require special processing to accomplish the required reflow or materials incompatible with standard integrated circuits to achieve enough stress mismatches to make these systems viable for system integration.

We present a design for a novel method of assembling hingeless 90° out-of-plane microstructures using a single lateral push provided by a wirebonder tip. The out-of-plane rotation is accomplished by constraining the lateral displacement of the microstructure using a serpentine spring such that the lateral motion causes the microstructure to flip upwards into a 90° out-of-plane orientation. Once assembled, the devices are held in place

by frictional force [10], which is further increased by the downward restoring force of the serpentine springs.

THEORY

Out-of-plane rotation can be accomplished by constraining the lateral displacement of the microstructure with a spring such that a lateral push will cause the microstructure to flip upwards 90° out-of-plane. The intermediate steps and force balancing that causes the rotation is shown in Figure 1. The lateral assembly force combined with the restoring force of the springs produces a torque out-of-plane when the base of the microstructure contacts the substrate (Figure 1B). As the bottom lip slides forward, the rotational torque increases until the structure becomes upright.

Figure 1. Sequence A-F shows the force diagram for the concept of assembling hingeless microstructures to 90° out-of-plane, using a single lateral push. F_A denotes assembly force, F_S denotes the restoring force of the spring, F_N denotes the normal force and F_F denotes the frictional force.

Once assembled, any lateral perturbations must overcome the force of friction and the restoring force of the spring in order to dislodge the upright structure. The assembled position of the structure is a state of local stability allowing the structure to remain assembled after the assembly force is removed.

Designs have been fabricated using the commercially available PolyMUMPs [11] process as well as an SU-8 prototyping process developed at Simon Fraser University [12]. One PolyMUMPs design that was fabricated, assembled and simulated is shown in Figures 2 through 4.

DEVICE MODELING

The bending of the spring system is heavily non-linear, therefore, finite element models were necessary to solve for the spring deflection and stress concentrations. Using Young's modulus (158 GPa) and Poisson's ratio (0.22) for PolyMUMPs, the assembled model is generated and shown in Figure 4. The boxed off areas of Figure 4 indicate the locations of maximum stress which is also indicative of the expected location of structural failure. Furthermore, the model determined that the restoring force of the spring produces a downward ($-Z$ direction) component of 0.159mN and a lateral ($-Y$ direction) component of 0.366 μ N at the bottom lip of the assembled device where contact with the substrate occurs. Because the force of gravity can be neglected for micro-scale devices, the resultant frictional force is given by

$$F_f = \mu F_N = \mu F_{Z_{Spring}}, \quad \text{Eq. 1}$$

and using a value of 4.9 for μ (static coefficient of polysilicon on polysilicon)[10], a maximum frictional force of 0.779mN is generated at the base of the structure. The force of friction is three orders of magnitude greater than the restoring lateral force and allows the structure to remain assembled in place. Furthermore, because of the strong force of friction, and the downward restoring force of the spring the assembled structures are highly resistant to shock. The amount of shock that the assembled structure can survive without collapsing can be derived by examining the maximum acceleration required to dislodge the bottom lip of the assembled device. The assembled structure is most vulnerable to shock in the Z -direction since reducing the Z force component by F_{Shock} reduces the frictional force by $4.9 \times F_{Shock}$. To solve for the shock force that causes the assembled structure to collapse, we use the following equation:

$$F_{Shock} = ma = F_z = \rho Va, \quad \text{Eq. 2}$$

where ρ is the density of silicon ($2.33 \times 10^3 \text{ Kg/m}^3$), and V , the volume of the device ($3.66 \times 10^{-14} \text{ m}^3$). Therefore, solving for the maximum acceleration, gives a value of $2.63 \times 10^6 \text{ m/s}^2$ which is equivalent to exposing the structure to approximately 270,000 Gs. As illustrated by the device model, the structures are highly resistant to shock and will remain assembled once the assembly force is removed.

EXPERIMENTAL DETAILS

The lateral force that can be obtained from a wirebonder tip is much greater than necessary for assembly. Therefore, the only important control variable is the lateral displacement required for the compliant spring system to fully assemble. The wirebonder assembly of the structure is performed by lowering the bonding tip until it touches the substrate adjacent to the bottom lip of the microstructure. Because the substrate is significantly stronger than any microstructure that can be produced, using the substrate as a physical limit for the wirebonder tip to adjust the Z position easily allows this assembly method to position the tip at the correct height above the substrate. By sliding the X - Y table in the lateral direction while the tip is down, the tip pushes the structure causing it to rotate and lock into place. Figure 5 shows a sequence of photomicrographs illustrating the motion of assembly for the SU-8 fabricated structures. Figure 6 shows the SEM of the same device after assembly. Figure 7 shows rotation angle vs. lateral displacement of the microstructures. The time required to assemble the structure using a manual wirebonder (Mech-El Industries NU-829) is approximately 1 second. Using a fully automated wirebonding system, the assembly time can be significantly reduced.

Figure 2. Scanning electron micrograph of an out-of-plane microstructure fabricated in PolyMUMPs. The serpentine springs are 130 μ m in length, with a 1:2 (height to width) aspect ratio.

Figure 3. Scanning electron micrograph of the 90° hingeless out-of-plane microstructure shown in Figure 2 assembled out-of-plane.

Figure 4. Finite element solution of the 90° hingeless out-of-plane microstructure fabricated using the PolyMUMPs process

Figure 5. Sequence showing the wirebonder assembly of a hingeless microstructure fabricated using an SU-8 prototyping process. The out-of-focus secondary image is the reflection of the wirebonder tip off of the substrate. The serpentine spring system for this structure is $20\mu\text{m}$ thick and $60\mu\text{m}$ wide, with $700\mu\text{m}$ long segments.

Figure 6. Scanning electron micrograph of the wirebonder assembled structure. Device fabricated using an SU-8 prototyping

Figure 7. Relationship between the lateral displacement versus angular rotation of the devices created in SU-8 and PolyMUMPs. After the toggle point, the structures will remain assembled when the assembly force is removed.

REALIABILITY AND POSITIONAL REPEATABILITY

Because we are unable to access a fully automated wirebonder, the reliability and positional repeatability for the assembly of the microstructures were tested using a fully automated system by mounting three computer controlled Zaber Technologies T-LS28-M microstages together to provide the X-Y-Z degrees of freedom. Using the open-loop computer controlled microstages, several chips, each containing 31 out-of-plane SU-8 devices, were assembled and disassembled 6 times with 100% success (total of 186 successful assemblies). In addition, a single randomly selected device was cycled through assembly and disassembly 220 times without failure. Devices that are free from fabrication defects achieved 100% successful assemblies. The yield for successful assembly is highly process dependent rather than device dependent. If the devices are defect free, successful assembly is expected. By capturing photomicrographs of the assembled devices and using the National Instruments Vision Builder for analysis, we are also able to determine the positional repeatability of the system. Figure 8 illustrates a single frame of the photomicrographs that was used to determine the positional repeatability.

Figure 8. Photomicrograph of one frame of the automatically assembled microstructure fabricated in SU-8.

With the open-loop system, we are able to achieve an average 515.48 μ m of displacement over 60 cycles with a standard deviation of 1.24 μ m. The average angular accuracy achieved by cycling the single device is 89.98° with a standard deviation of 0.24°. By comparing the angle of the assembled devices and the displacement of the microstages, the positional repeatability is shown to be primarily dependent on the external assembly system and not on the microstructures. Therefore, by moving towards an industrial closed-loop automated wirebonding system for assembly, a high degree of repeatability is expected.

APPLICATIONS

Because the design of the out-of-plane microstructures do not require hinges, a reliable electrical connection to the out-of-plane devices can be made. Applications such as thermal accelerometers, micro-inductors, micro-antennas, and micro-grippers can easily be fabricated and assembled out-of-plane using this method. Figure 10 illustrates an assortment of devices that have been prototyped and assembled using the open-loop automated assembly method.

Figure 10. An assortment of out-of-plane devices: A) Fractal Antenna B) Microgripper C) Thermal Isolation Platform D) Meander Inductor

CONCLUSION

Out-of-plane assembly for microdevices has typically involved complex post processing or integrated actuators. Both methods can be costly in time and money and frequently result in poor yield. The design described here can use a standard microelectronics wirebonder or low cost micro-stages for assembly. Because wirebonding is already an integrated step for packaging commercial MEMs devices our assembly design has the potential to produce commercially viable 3-dimensional assembled devices. The work presented here provides a method for implementing the wirebonder for assembly to reduce cost and complexity for manufacturing out-of-plane microstructures. The devices have been analyzed, fabricated and tested in two distinct micromachining technologies, indicating its viability for many micromachining processes. The designs are highly resistant to shock, and have shown high yield. The main criterion for assembly is good control of lateral position for the single point actuation which can be programmed using automated wirebonding for the assembly of out-of-plane devices.

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