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# Precision Study for Surface Tension Driven Self-assembly of Hingeless Structures

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**Abstract:** Surface tension driven self-assembly has been demonstrated to be a promising method for mass production of highly 3-D MEMS structures. However, factors and their mechanisms affecting the self-assembly precision of the hingeless structures are still barely understood. This study addresses and analyzes some of the factors, including the inherent instability of the hingeless structures, scale effect and the deformations of the limiter structure which limits the self-assembly precision of hingeless structures. An energy based model, verified by the experimental results, was introduced to evaluate the adverse effect of each factor on the precision. This precision study can serve as an optimum guideline for the designs of self-assembly MEMS microstructures and allow the creation of high precise MEMS applications.

**Key words:** MEMS, self-assembly, 3-D microcomponents, laser reflow

## INTRODUCTION

Micro-electromechanical Systems (MEMS) technology has inspired many innovative microsensors, microactuators and microsystems (Jack, 2001). Micromachining techniques were initially borrowed from the planar Integrated Circuit (IC) industry and thereby it is hard to produce highly three-dimensional (3-D) MEMS structures. In order to overcome the problem, microassembly allowing fabricated in-plane components rotating to desired positions was introduced to construct 3-D "out-of-plane" structures (Wu *et al*., 1995). Such assembly process is commonly accomplished in the ways of robotic and manual microhandling, however, the sticking problem and the serial nature of these two methods may limit their application (Brussel *et al*., 2000).

An alternative, competing micro-assembly method is surface tension driven self-assembly technique. This method uses the surface tension properties of a fluidic agent, such as a molten solder, to assemble the microcomponents in MEMS (Fig. 1a) (Syms *et al*., 2003). Solder alloy is placed firstly on the metalized pads and is heated to its melting point. Then the surface tension of the molten solder can pull the free microplate away from the substrate and hold the microplate in position due to the principle of minimum potential energy. The self-assembly method is massively parallel and is rarely destructive to the vulnerable MEMS structures. In addition, solder joint of the self-assembled structures enables a high quality mechanical, thermal and electrical connection.

As the application range of self-assembly has widened, improving the self-assembly yield and accuracy is an urgent and necessary issue. Pioneer works of Harsh has demonstrated that the free microplate of hinged structures can be rotated within an angle control of ±2° by designating solder volumes and pad shapes (Harsh *et al*., 1999). Integrated with a mechanical locking structure, this precision has been increased to ±0.3°. In addition, Harsh has also conducted further precision studies on surface tension self-assembly to allow the creation of extremely precise 3-D microstructures (Harsh *et al*., 2000). However, these studies addressed the self-assembled structures which contain a hinge or a microbearing component, as illustrated in Fig. 1b, complicating the micromachining process. In our precious works, self-assembly of hingeless structures have been performed within an angle control of ±2.5° and this angle error was further optimized to ±0.5° when a wire limiter structure was added (Yang *et al*., 2013). However, factors and their mechanisms affecting the self-assembly precision of the hingeless structures are still barely understood.

The motivation of this study is to analyze and address some of the factors limiting the self-assembly precision of hingeless structures and to serve as an optimum guideline for the designs of self-assembly microstructures.

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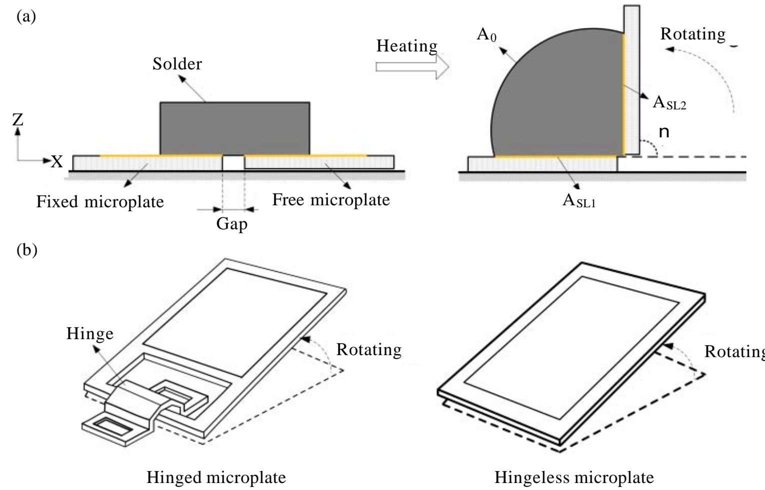


Fig. 1(a-b): Schematic diagram of (a) surface tension driven self-assembly and (b) two types of the free microplate (with hinged and hingeless structures)

## NUMERICAL METHOD FOR PRECISION STUDY

**Energy based model:** In order to study the factors limiting the self-assembly precision, a numerical model involving various parameters is needed to predict the equilibrium self-assembled positions of the microstructures. Energy minimization model is the common solution due to the principle that the self-assembly system (including microstructures and the molten solder) has the tendency minimizing its energy, thereby the equilibrium state can be identified when the energy is minimal. Energy description of the self-assembly system is expressed as:

$$E = \iint_{A_0} \gamma dA + \sum_{i=1}^{2} \iint_{A_{SLi}} -\gamma \cos\theta_i dA + \iiint_V \rho g z dV \quad (1)$$

where, $\gamma$ is the surface tension coefficient of the molten solder, $A_0$ is the area of the solder liquid/vapor interface, $A_{SLi}$ is the area of the metalized pads, $\theta_i$ is the contact angle, $\rho$ is the solder density, g is the gravitational acceleration and the subscript i = 1, 2 representing the fixed and the free microplate, respectively. The first term on the right side of Eq. 1 expresses the surface energy of the solder's free surface, the second term expresses the surface energies on the solid/liquid interfaces and the last term expresses the gravitational energy of the solder.

Given the initial shapes and constraints, Surface Evolver (Brakke, 1996), an interactive finite element program for the study of interfaces shaped by surface tension and other energies, was employed to iterate the energy model and obtain the minimum energy $E_{min}$ of the system. In calculations, the surface energy on liquid/vapor interface is obtained by integrating the surface tension $\gamma$ over all the facets of the free surface. The surface energy on the solid/liquid interface is replaced by integrals around the edges of wetted pads using Stokes' theorem:

$$\iint_{A_{SL}} -\gamma \cos\theta \vec{k} \cdot d\vec{A} = \oint_{edges} -\gamma \cos\theta x \vec{j} \cdot d\vec{l} \quad (2)$$

Moreover, the gravitational energy of the molten solder is calculated by the divergence theorem as:

$$\iiint_V \rho g z dV = \oiint_{\partial V} \frac{z^2}{2} \vec{k} \cdot d\vec{S} \quad (3)$$

The integral is taken over each facet that bounds the solder.

Combined these energy descriptions into Surface Evolver, the energy of the self-assembly system can be minimized efficiently.

In addition, note that each self-assembled positions (characterized by the rotating angle $\varphi$) corresponds to a evolved energy $E_{min}(\varphi)$, thereby the solution for predicting the final self-assembled positions has two steps:

- Firstly, minimizing the system energy E for each interim rotating angle $\varphi$ and then
- plotting the trendline of the energy ($E_{min}$ vs. $\varphi$) to identify the minimum energy during an overall self-assembly process

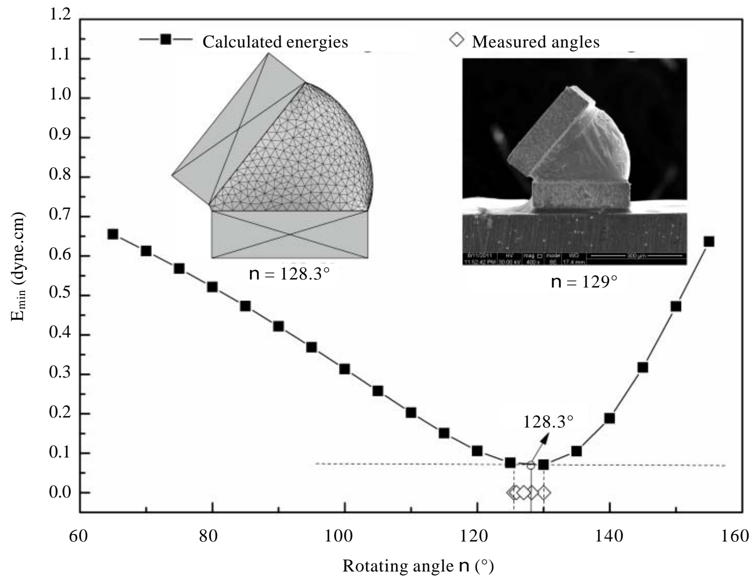


Fig. 2: Trendline of the evolved energy and shape

**Validation of the model:** In order to validate the model, model predictions were compared to the experimental results. The microplate used in the self-assembly experiments had a 330.2×330.2 μm metalized pad. The employed solder alloy was a Sn3.0Ag0.5Cu (wt.%, Senju-M705) sphere with the diameters of 300 μm.

A plot of the evolved energy trendline is shown in Fig. 2. In this case, evolved energy reached its overall minimum point at a position where φ = 128.3°. This prediction fell within the angle range 125.8-130.2° measured from the experiments, validating the energy based model. Evolved shapes of the self-assembled 3-D microstructures were also compared to the experimental results, as illustrated in Fig. 2. It is obvious that the predicted shape matches well with the observed shape, demonstrating the validity of the model as well.

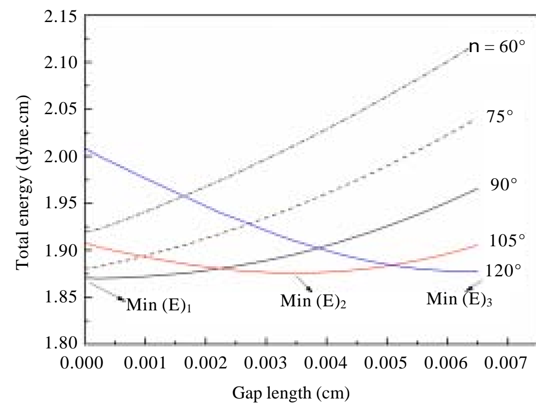


Fig. 3: System energy versus the gap for a number of interim φ, for $φ_e$ = 90°

## FACTORS LIMITING THE PRECISION

**Inherent instability of the hingeless structure:** Design factors, including the solder volume, pad size etc., have been addressed to affect the self-assembled positions and precision (Yang *et al*., 2013). In this work, these factors are not studied repeatedly; whereas the effect of a hinge, scale effect and the deformations of the wire limiter are discussed.

A hinge structure can restrict the motion freedom of the rotating microplate. This hinge structure improves the self-assembly precision, however complicates the fabricating process. On the contrary, although hingeless self-assembly structures are costless, the motion of the pulled microplate cannot be considered as a pure rotation.

Contrary to our expectation, hingeless structures seemed to yield an acceptable precision similar to the hinged structures; a hinge structure seemed unnecessary. The gap between the fixed and the free microplate was unconstrained in hingeless self-assembly process. Figure 3 shows the evolved system energy versus the gap with a number of interim angles φ, for a final angle of $φ_e$ = 90°. For φ<90°, the energy increases monotonically with the increasing gap length. Using the virtual work principle, the existence of a force gap acting on the microplates which tends to close the gap, was noticed.

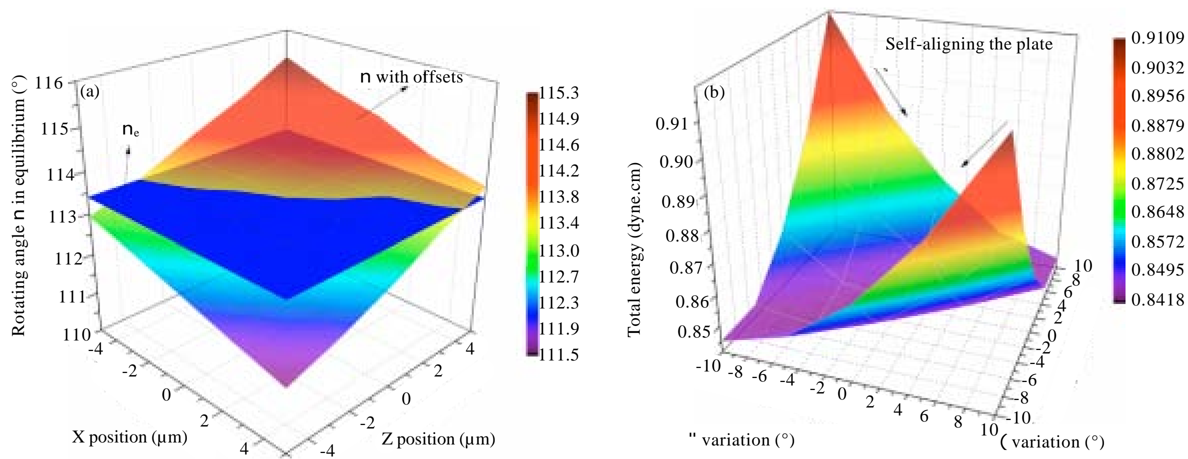


Fig. 4(a-b): (a) The final angle $\varphi_e$ versus the displacements ($\delta$x, $\delta$z) of the rotating axis and (b) the system energy versus the rotations of the free microplate around x and z axis ($\delta\alpha_x\Delta\delta\gamma_z$)

This gap closure force is effective until the free microplate reaches its equilibrium ($\varphi = 90°$). Since the existence of the closure force, the solder free surface on the gap can be considered as a virtual hinge which explains the findings that a hinge seems unnecessary. It is worthy to note that for $\varphi>90°$ the gap closure force vanishes and the minimum energy point can also be found at an uncertain angle with greater gap length. This over rotation is adverse to the high precise self-assembly.

In the absence of a hinge, the rotating axis of the free microplate (y axis) is unfixed and the rotation may happens around x or z axis (Fig. 1). The final rotating angle $\varphi_e$ versus the displacements of the rotating axis in x-z plane for the free microplate is plotted in Fig. 4a. The result shows that with the increase of the displacements, the variations of the final self-assembled angle $\Delta\varphi_e$ are greater. Specifically, ±5 μm offsets from the original rotating point in x-z plane yields a final angle variation less than ±2°. In addition, system energy versus the extra rotations around x and z axis of the free microplate is shown in Fig. 4b. The energy has a great peak at the positions where ($\delta\alpha_x$, $\delta\gamma_z$) equals (10°, -10°) or (-10°, 10°). Since the model has the tendency of minimizing its energy, the free microplate at positions of high energy tends to evolve to a new position which has a lower energy. It also means that the surface tension of the molten solder can self-align the free microplate for limiting the extra rotations around x or z axis, validating the existence of the virtual hinge effect as well.

**Scale effect:** A dimensionless parameter, defined as the ratio of the characterized pad length and the diameters of

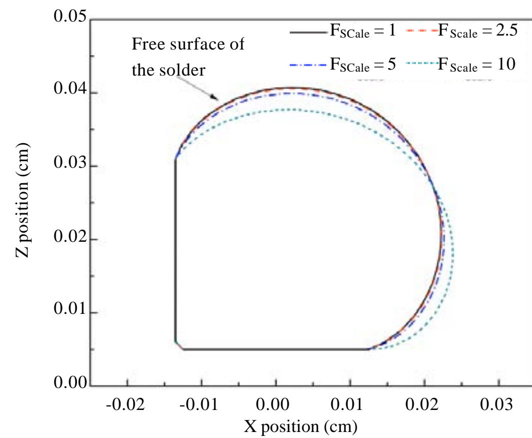


Fig. 5: Evolved solder profiles with different $F_{scale}$ values, for $F_{scale}>1$, the profiles are zoom out views

the solder sphere $\eta = L_{pad}/D_s$ has been found to have a relation with the final self-assembled angle (Yang *et al*., 2011). Designed self-assembly structures with the same $\eta$ value tend to have the same final angle $\varphi_e$. The scale effect on the self-assembly precision was studied by comparing the self-assembled positions of structures for the same $\eta$ value at different sizes. Figure 5 shows profiles of the solder free surfaces after self-assembly with different scale factors, $F_{scale}$ = 1, 2.5, 5 and 10 ($L_{pad} = F_{scale}\times a$, $D_s = F_{scale}\times b$, where a = 250 μm and b = 400 μm). The calculation showed that for the design structures with $F_{scale}$ = 1, the predicted final angle $\varphi_e$ = 85.4°; once the structure size was increased 10 times the original design, the predicted $\varphi_e$ reduced to 80.4°. It is mainly due to the

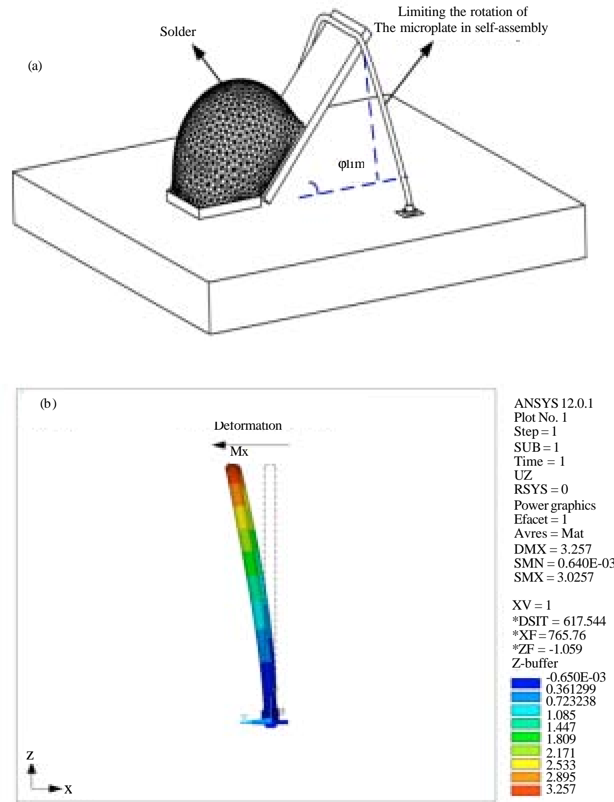


Fig. 6(a-b): (a) A sketch of the self-assembled structures with a wire limiter and (b) The deformations of the wire limiter in the x direction

gravity of the solder which becomes more and more critical in defining the solder profiles with increasing $F_{scale}$. Thus, although the structure size can be efficiently identified by using the $\varphi_e(\eta)$ relation, the gravity effect in the relatively large scale(a few mm ~a few cm) should be carefully considered.

**Deformation of the wire limiter:** In order to fulfill the requirements of high precise self-assembly, wire limiter structure has been presented in our previous work (Yang *et al*., 2013). Limiter structure was formed by a gold wire with the wire bonding process which is a most commonly used bonding interconnection technique in microelectronic packages. Placed at the specified positions on substrate, wire limiter can stop the rotation of the free microplate and improve the self-assembly precision.

A sketch of the self-assembled structures integrated with a wire limiter is provided in Fig. 6a. In this case, the final angle $\varphi_e$ can be derived with geometry relations. The deformation of the wire limiter reduces the precision of self-assembly.

Figure 6b illustrates the deformations of the wire limiter in the x direction. The analysis was accomplished by finite element method and a uniformly distributed load was applied to the top of the limiter. The calculation shows that the maximum x-deformation is 3.2 μm which will lead to a 0.2° angle variations according to the geometry relations. This angle variation due to the deformations is acceptable for the common high precise applications. It can be further improved with a copper wire limiter for extremely high precise self-assembly.

## CONCLUSION

The precision study of the MEMS self-assembly was focused on the inherent instability of the hingeless structure, scale effect and the deformations of the limiter structure. The conclusions of the study are as follows:

- Energy minimization tendency not only applies a gap closure force between the microplates but also self-aligns the free microplate in the hingeless self-assembly

- With the increase of the structure size, the gravity of the solder become more and more critical in defining the solder profiles and the final self-assembled angle
- The deformation of the wire limiter after the self-assembly introduces an angel variation less than 0.2°

## REFERENCES

Brakke, K.A., 1996. The surface evolver and the stability of liquid surfaces. Philosoph. Trans. Royal Soc., 354: 2143-2157.

Brussel, H.V., J. Peirs, D. Reynaerts, A. Delchambre and G. Reinhart *et al*., 2000. Assembly of microsystems. Ann. CIRP, 49: 451-472.

Harsh, K.F., V.M. Bright and Y.C. Lee, 1999. Solder self-assembly for three-dimensional microelectromechanical systems. Sens. Actuators A., 77: 237-244.

Harsh, K.F., P.E. Kladitis, Y.H. Zhang, M.L. Dunn, V.M. Bright and Y.C. Lee, 2000. Tolerance and precision study for solder self-assembled MEMS. Proc. SPIE, 4075: 173-184.

Jack, W.J., 2001. Microelectromechanical systems (MEMS): Fabrication, design and applications. Smart Mat. Struc., 10: 1115-1134.

Syms, R.R.A., E.M. Yeatman, V.M. Bright and G.M. Whitesides, 2003. Surface tension-powered self-assembly of microstructures-the state-of-the-art. J. Microelectromech. Syst., 12: 387-417.

Wu, M.C., L.Y. Lin, S.S. Lee and K.S.J. Pister, 1995. Micromachined free-space integrated micro-optics. Sens. Actuators A., 50: 127-134.

Yang, L., W. Liu, C.Q. Wang and Y.H. Tian, 2011. Self-assembly of three-dimensional microstructures in MEMS via fluxless laser reflow soldering. Proceedings of the 12th International Conference on Electronic Packaging Technology and High Density Packaging, August 8-11 2011, Shanghai, China, pp: 649-652.

Yang, L., W. Liu, C.Q. Wang and Y.H. Tian, 2013. Surface-tension-driven self-assembly of 3-D microcomponents by using laser reflow soldering and wire limiting mechanisms. Trans. Comp. Pack. Manuf. Tech., 3: 168-176.