Uncertainty in Manufacture and Assembly of Multiple-Joint Solder Self-Assembled Microelectromechanical Systems (MEMS)

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Abstract

Surface-micromachined microelectromechanical systems (MEMS) are two dimensional in their "as fabricated" form. Surface-micromachined MEMS can be assembled after fabrication to realize systems with a more three-dimensional form and function. One reliable method of assembly, suited to commercial mass production, is to use the surface tension of microsized droplets of molten solder to assemble the microsized structures, otherwise known as "solder self-assembly." In other works, single-joint solder self-assembled structures have been demonstrated without emphasis on the uncertainty involved in the assembly position. In this work, a reliable process for manufacturing multiple-joint solder self-assembled MEMS was developed, and the impact of process and component tolerances on assembly precision was investigated using statistical and worst-case tolerance analysis techniques. It was determined that assembly precision was affected, from greatest to least impact, by the following assembly variables: solder volume, scavenging and overwetting, residual stress in bilayer structures, temperature, structure dimension, solder pad warpage, hinge play, and residual stress in single-layer structures, respectively. Guidelines on increasing assembly precision are discussed.

Keywords: MEMS, Solder Self-Assembly, Surface Micromachining, Tolerance Analysis

Introduction

Microelectromechanical systems (MEMS) fabrication can be generally categorized into three different techniques: bulk micromachining, micromolding, and surface micromachining [1–6]. Bulk micromachining and micromolding produce three-dimensional (3-D), high aspect ratio (thickness/width) structures of medium to low complexity. Structures created using surface micromachining can have a high degree of complexity in form and function. However, in their "as fabricated" state, they are also two dimensional (2-D) in form and function, or in other words, have a very low aspect ratio.

Surface-micromachined MEMS can be assembled, after fabrication, to realize systems with a more 3-D form and function. One reliable method of assembly, suited to commercial mass production, is to use the surface tension of microsized droplets of molten solder to assemble the microsized structures, otherwise known as "solder self-assembly." The basic principle of solder self-assembly is as follows. *Figure 1* depicts the solder self-assembly of two plate-like structures, where (a) depicts a side and isometric view of the assembly in progress, and (b) depicts a side and isometric view of the final resting position at an equilibrium angle of 84°. Solder is applied at the joint where two microstructures are hinged together. After one or both of the microstructures are free to move, the solder is heated and melted. Once molten, the surface tension of the solder pulls the microstructures together, folding at the pivot created by the hinges. The folding motion ceases when the molten solder reaches a shape of minimum surface energy, given constraints of being wetted to solder pads and possible external loading on the microstructures. Once the plates are at rest at some equilibrium position or angle relative to each other, the heat can be removed and the system allowed to cool. The solder solidifies, resulting in a rigid mechanical and an electrically and thermally conductive connection.
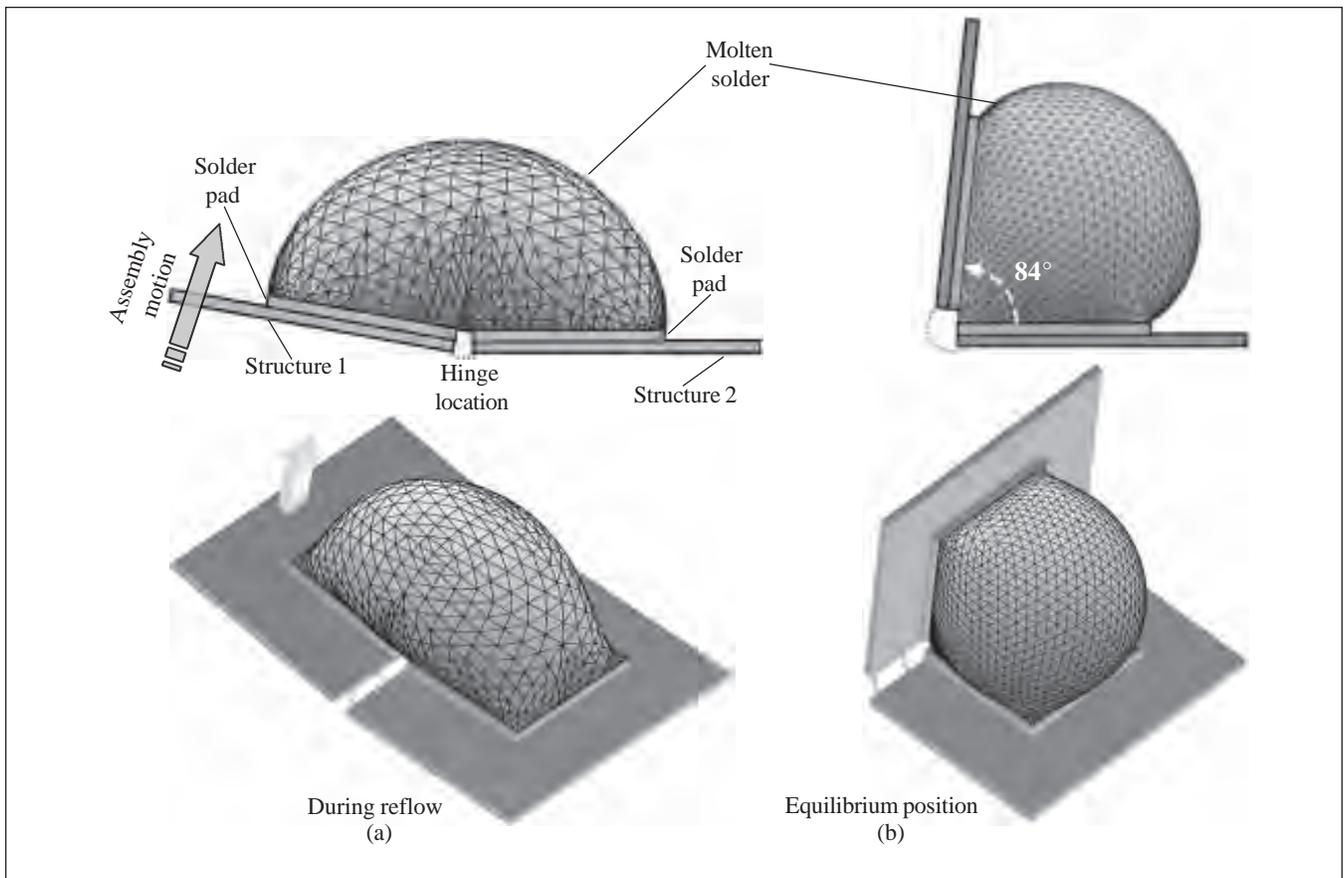
Figure 1
**Depiction of Solder Self-Assembly of Two Plate-Like Structures: (a) side and isometric view of the assembly in progress,
and (b) side and isometric view of the final resting position at an equilibrium angle of 84°.**

Figure 2 is a scanning electron micrograph (SEM) showing an example of a solidified 63Sn/37Pb solder joint of equivalent volume to a 203.2 μm (8 mil) diameter sphere. An oven or hot plate can be used to heat a whole chip that contains massive arrays of solder joints, or individual solder joints can be heated using microheaters imbedded under the solder pads [7].

Solder surface tension lifting small lead-less electronic components was originally considered an undesirable phenomenon, called tombstoning [8]. A desirable use was found in the self alignment of flip chip electronic modules [9], optoelectronic devices [10], and microresonators [11]. Syms and Yeatman [12] first published the idea of using solder surface tension to assemble microstructures. Subsequently, simple single-joint self-assembled structures have been demonstrated using the surface tension of solder, glass, or photoresist [13–18], and includes scanners [19,20], optical components [21–23], inductors

[24–26], and microrobot legs [27]. Furthermore, models have been developed to predict equilibrium angle, available assembly torque, and possible equilibrium angle accuracy of single solder joints [28–32]. A state-of-the-art survey in surface tension powered self-assembly is reported in Syms et al. [33].

Previous works focused on single solder-joint assembly demonstrations. This work demonstrates structures that are self-assembled using multiple solder joints. To realize multiple-joint solder self-assembled structures, a manufacturing process with high yield and repeatable results had to be developed, and is detailed in this work. Furthermore, no comprehensive quantification of the uncertainty involved in assembly precision has been presented in the prior works. This is most likely due to the low yield of experimental results and/or an unreliable manufacturing process of the previous works. The quantification of the uncertainty becomes especially important, with regard to multiple-joint structures,
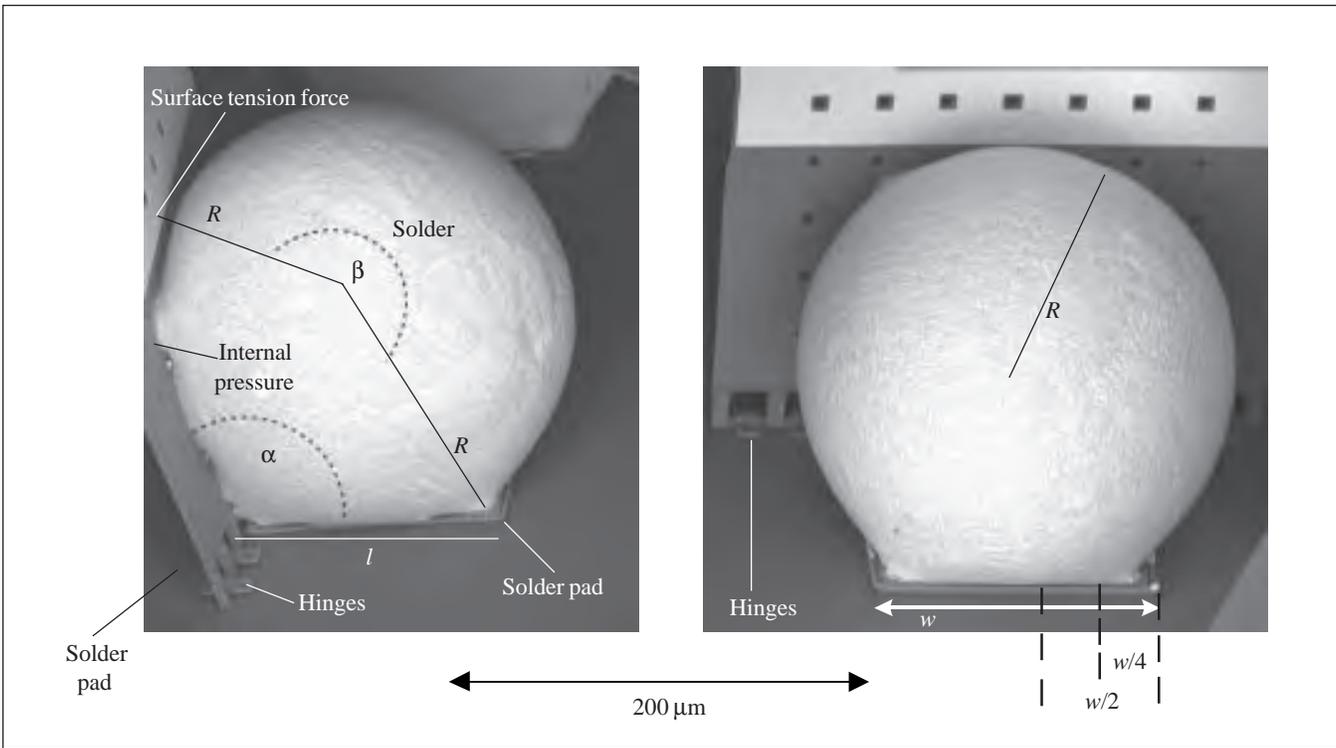
Figure 2
**SEM of Side View (left) and Front View (right) of Solidified Solder Joint Showing Important Modeling
Parameters Referred to Throughout the Paper**

due to the propagation of uncertainty through the multiple assembly components. Given a repeatable manufacturing process, statistical data can now be drawn from the experimental results and compared with theoretical predictions. This work, theoretically and experimentally, investigates the uncertainty involved in the assembly position of multiple-joint solder self-assembled MEMS using statistical and worst-case tolerance analysis techniques.

This work defines "multiple-joint solder self-assembled MEMS" as a microstructure, or system of microstructures, requiring more than one solder joint for proper assembly and function. The multiple solder joints may be arranged in parallel, series, or both. *Figure 3* is an SEM of a microsized fan [34,35] manufactured using the process described in this work. Each of the eight blades was assembled simultaneously to its proper position with a single 63Sn/37Pb solder joint of volume equivalent to a 101.6 μm (4 mil) diameter sphere. *Figure 3* exemplifies a parallel arrangement of solder joints, where each blade depends on the assembly action of only one joint for proper assembly; however, all blades must assemble properly for proper fan assembly. *Figure 4*
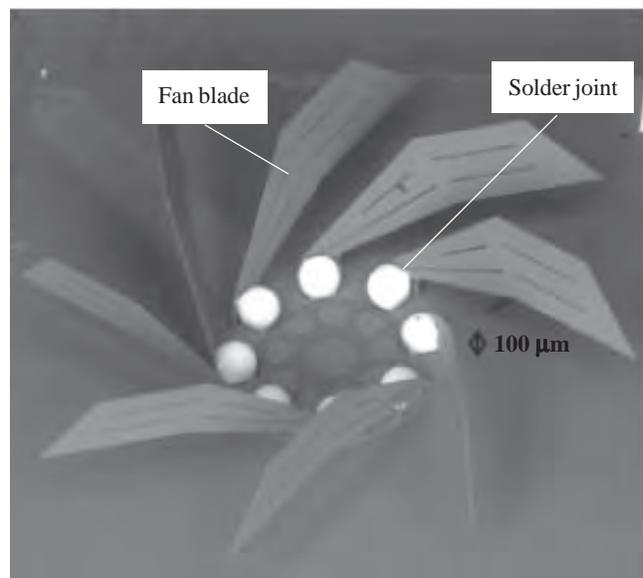

Figure 3
SEM of Solder Self-Assembled Microsized Axial Flow Fan (Kladitis, Linderman, and Bright 2001; Linderman, Kladitis, and Bright 2002)—an example of a parallel arrangement of solder joints.

is an SEM and captured video image of a fiber optic cable gripper, also manufactured using the process described in this work. Each gripper finger was as-
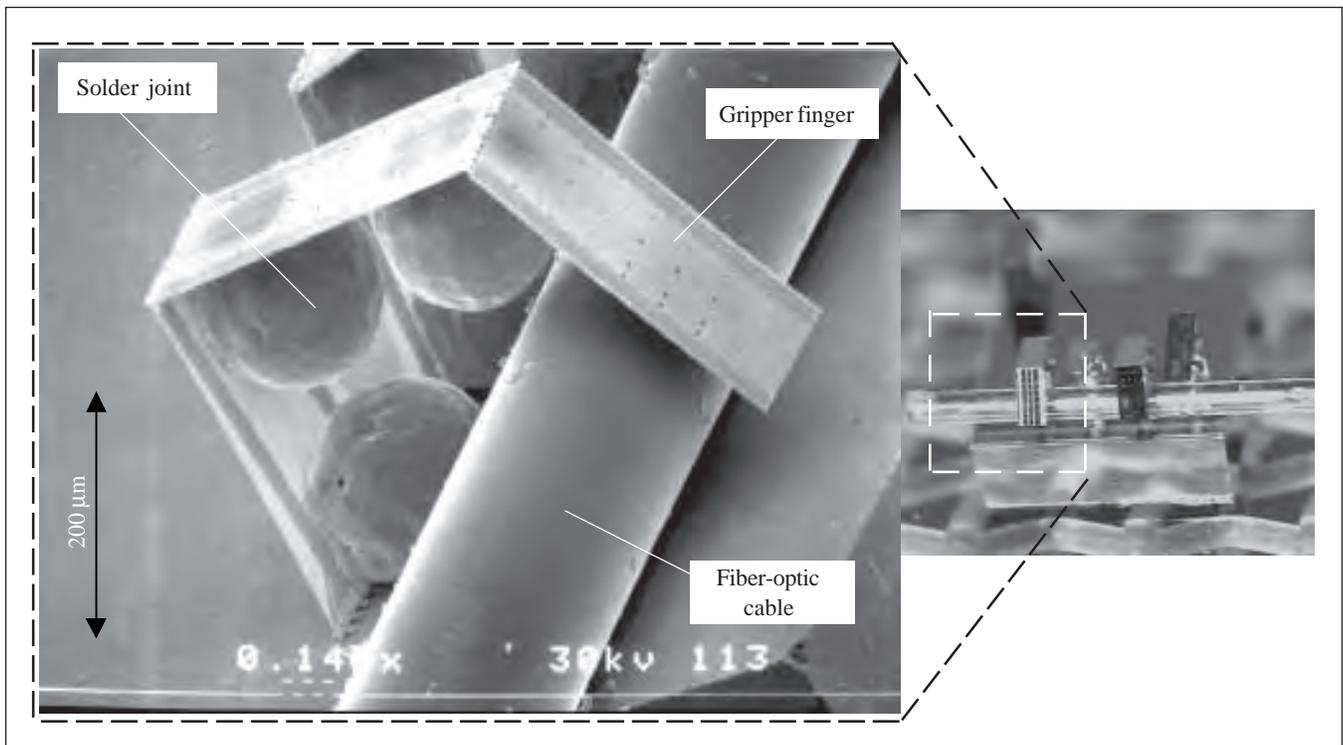
Figure 4
SEM and Captured Video Image of Solder Self-Assembled Fiber Optic Cable Gripper—
Example of a series arrangement of solder joints.

sembled simultaneously with three 63Sn/37Pb solder joints each of volume equivalent to a 203.2 µm (8 mil) diameter sphere. One finger, in *Figure 4*, exemplifies a series arrangement of solder joints, where each finger depends on the assembly action of more than one solder joint for proper assembly.

The effect of propagation of uncertainties in the manufacturing process will be most evident in a structure utilizing a series arrangement of solder joints. Thus, for this work, a series-arranged, two-joint structure is utilized to investigate the uncertainty in assembly position. From this point forward, the two-joint structure will be referred to as the device under test (DUT). The DUT best represents a generalized multiple-joint solder self-assembled MEMS. *Figure 5* shows SEMs, at various perspectives, of a set of seven DUTs assembled at different angle combinations of 45°, 90°, and 135°. Each plate is 500 µm long by 261 µm wide. *The uncertainty of the end position of the DUT, as a function of the uncertainty of the DUT assembly components, is the focus of this investigation.*

Design and Manufacture

Three general variations or "types" of the DUT were designed:

I. Single-layer plates, made from 1.5 µm thick polycrystalline silicon (polysilicon), assembled with volumes of solder equivalent to 203.2 µm (8 mil) diameter spheres,

II. Composite-layer plates, made from 0.5 µm thick gold (Au) on 1.5 µm thick polysilicon, assembled with volumes of solder equivalent to 203.2 µm (8 mil) diameter spheres, and

III. Composite-layer plates (0.5 µm thick Au on 1.5 µm thick polysilicon) assembled with volumes of solder equivalent to 101.6 µm (4 mil) diameter spheres.

The DUTs shown in *Figure 5* are examples of type I DUTs. Type II DUTs are identical to type I with the exception that the plate between the solder joints 1 and 2, and the plate between solder joint 2 and the end, are made from a composite layer of gold on polysilicon. *Figure 6* shows examples of type III DUTs. Type III DUTs are identical to type II DUTs
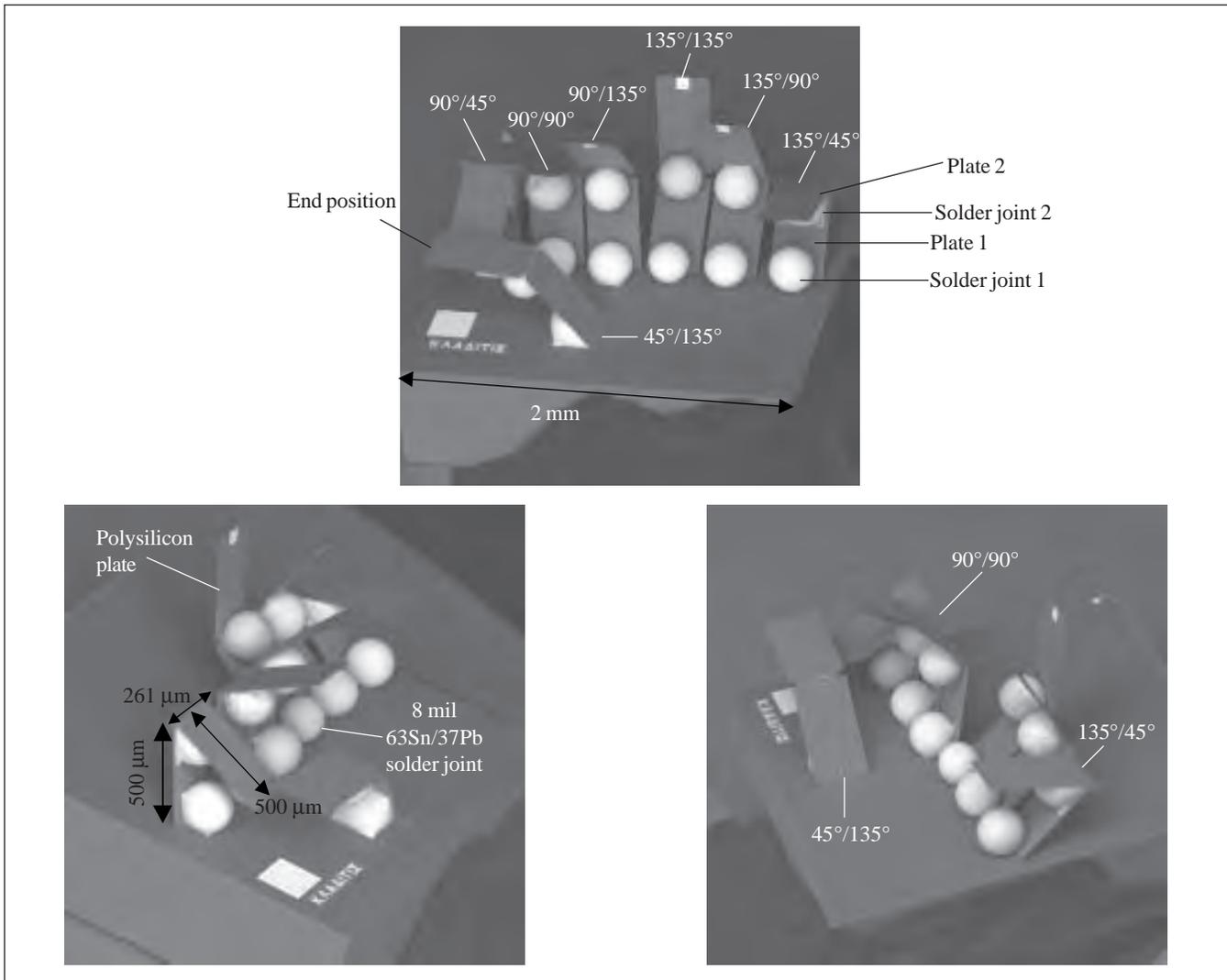
Figure 5
SEM Images, at Various Perspectives, of the DUTs Used to Investigate the Uncertainty in Assembly Position

with the exception that the solder joints are designed for assembly using 4 mil solder joints. Composite-layer plates were chosen in order to reveal design and manufacture limitations and to explore the effect on assembly position uncertainties due to the uncertainty in the deformation of the composite because of mismatch of thermal coefficients of expansion. Note the curved deformation of the *Figure 6* DUTs compared to the straight plates of the *Figure 5* DUTs.

Each type of DUT has the same seven variations in angle combination (denoted by *angle of joint 1 / angle of joint 2*) as shown in *Figure 5*. The seven joint angle combinations are as follows: 45°/135°, 90°/45°, 90°/90°, 90°/135°, 135°/135°, 135°/90°, and 135°/45°. The joint angle combinations were cho-

sen in order to reveal design and manufacture limitations and to explore the effect on the propagation of component uncertainties in the assembly.

For all of the types, the first plate structure is hinged to the substrate with staple hinges, and the second plate is hinged to the first plate with scissors hinges—refer to *Figures 5* and *7*. The hinge is carefully designed, for each joint angle, to avoid binding of the hinges. The plates, including the solder pad areas, have 4 μm square etch holes spaced every 30 μm; etch holes provide etchant access underneath the plates during the removal of the sacrificial layer. Gold solder pads are used as the wettable areas of the solder joints. The gold solder pad nominal dimensions used for types I and II are as follows: 70

μm × 70 μm pads for 135° assembly angle, 131 μm × 131 μm pads for 90°, and 217 μm × 217 μm pads for 45°. The gold solder pad dimensions used for the type III DUT is as follows: 33 μm × 33 μm pads for 135° assembly angle, 69 μm × 69 μm pads for 90°, and 96 μm × 96 μm pads for 45°. The relationship between solder pad size and assembly angle will be explained later.

Figure 8 is a depiction of an example cross section (not to scale) of the substrate solder-joint part of the DUT at various stages of the manufacturing process. Refer to *Figures 8a–8f* in the following discussion. The basic steps of the manufacturing process are as follows:

(a) *Surface Micromachining*: Begin with surface-micromachined structures fabricated in a commercial foundry.

(b) *Pre-Release*: Clean and partially release the structures. The partial release is necessary to remove sacrificial layer in areas where etchant access will be later blocked by the solder deposition.

(c) *Solder Deposition*: Deposit solder at the solder pads.

(d) *Preflow*: Reflow the solder to ensure that it is securely wetted to the solder pads. No assembly occurs at this time because the structures are not full released.

(e) *Release*: Fully etch away the sacrificial layer.

(f) *Reflow*: This second reflow assembles the structures.

This manufacturing process, first reported in this work, has a yield of 94.3%. The yield for this process was calculated as follows: several microstructures, consisting of 866 individual solder joints, were assembled using this process. Of the 866, 817 solder joints assembled successfully; therefore, 817/866 = 0.943. Next, the manufacturing process is described in detail.

Surface Micromachining

The process begins with surface-micromachined DUTs that have been fabricated in a commercial surface micromachining process [36] that uses polysilicon as the two releasable structural layers, 1.5 μm and 2 μm thick. Phosphosilicate glass (PSG) is used as the sacrificial layer. A 0.5 μm thick gold metallization layer is also available and was used to make the solder pads used in the solder self-assem-

Figure 6
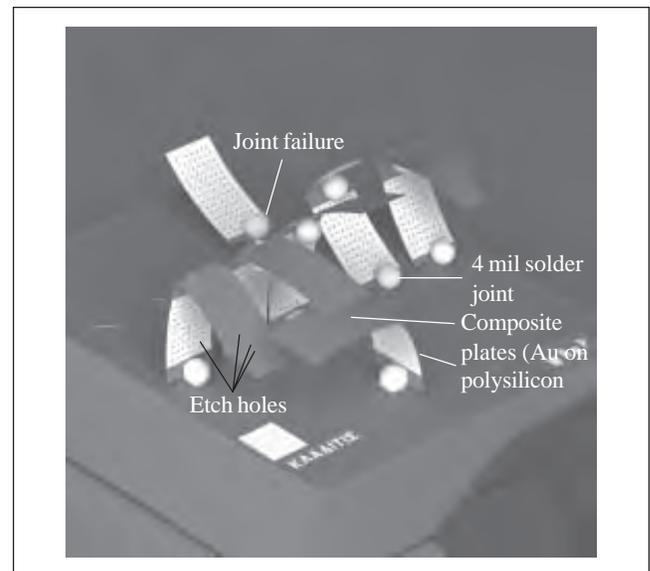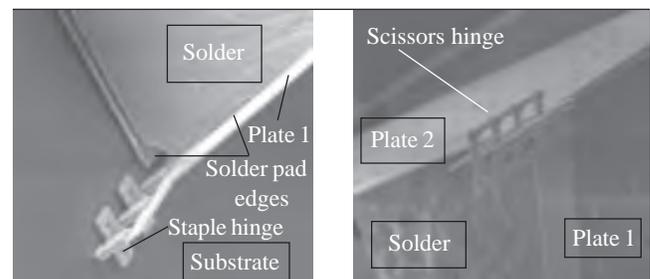**SEM of Type III DUT**

Figure 7
SEMs of Different Types of Hinges Used at the Solder Joints

bly. The DUTs are fabricated on the surface of a (100) n-doped Si wafer and subdiced into 2 mm × 2 mm dice, as shown in *Figure 5*. A depiction of a cross section of an unreleased and unassembled DUT, still protected by a protective layer of photoresist for shipping, is shown in *Figure 8a*. The remaining manufacturing process is outlined, for one 2 mm die, as follows. Also, unless stated otherwise, all steps are performed at 22°C.

Pre-Release

First the die is cleaned by soaking in 25 ml acetone for 15 minutes, 25 ml 2-propanol for 5 minutes, and rinsed in deionized and purified water (DIW) for 15 seconds. Next the PSG is removed by soaking the die in 25 ml of 48% HF for 30 seconds, gently rinsed by immersion in a 50 ml mixture of methanol:DIW 3:1 for 15 seconds, and soaked in methanol. Next the die is dried in a BAL-TEC CPD
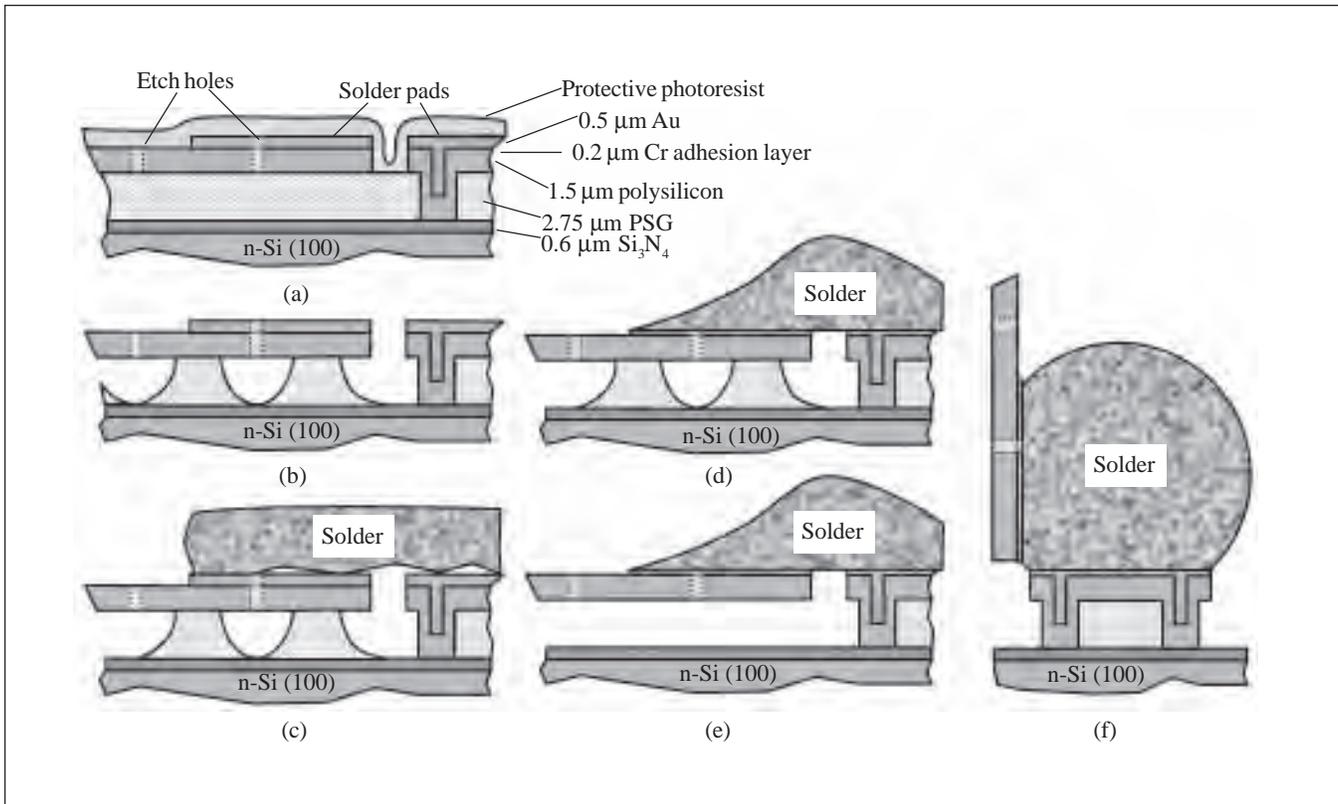
Figure 8
Illustration of Example Cross Section (not to scale) of Substrate Solder Joint at Various Stages of Manufacturing Process.
Staple hinges are not shown.

030 Critical Point CO_2 dryer using methanol as the intermediate fluid. During the drying procedure, the die will experience the following temperature history: a drop in temperature from 22°C to 0°C in 10 minutes, constant 7°C for 7 minutes, a rise from 7°C to 40°C in 14.5 minutes, constant 40°C for 4.5 minutes, and an immediate return to 22°C. At this point, a cross section would appear as in *Figure 8b*.

Solder Deposition

There are several commercial solder deposition techniques available: pick and place, thin film, electroplating, screen printing, paste ejection, jet printing, and wave soldering. For this experiment, 4 or 8 mil diameter commercially manufactured 63Pb/37Sn solder spheres, manufactured by Alphametals, were placed across the solder pads by manual pick and place using micromanipulators. The resulting profile would look like that shown in *Figure 8c*, and *Figure 9* shows a captured video image of a set of type II DUTs after solder pick-and-place solder deposition. Flattened solder spheres are shown placed over pairs of solder pads of the various sizes: 70, 131, and 217 μm.

Preflow

The purpose of the preflow is to wet the solder to the pairs of solder pads. The preflow is performed in a custom-built, chamber-enclosed, temperature-controlled heating stage (*Figure 10*). The enclosure has an inlet for N_2 and N_2/formic acid vapor created by bubbling N_2 in formic acid. The formic acid vapor is used as a flux. The die, with pick-and-placed solder, is set on the heating stage and covered with the chamber. N_2 is flowed into the chamber at 1 liter/minute, and the stage is heated from 28°C to 180°C in 4 minutes and held at 180°C for 3 minutes longer. Next the temperature is increased to 183°C and held for a total of 3 minutes. Next the temperature is increased 1°C per minute to 186°C. Next, N_2/formic acid vapor is flowed at 2 liter/minute for 22 seconds, then stopped. Next, the N_2 flow is increase to 3.8 liter/minute and the heating stage power is turned off and

allowed to return to room temperature (28°C). The temperature of the stage is controlled using a Watlow series 965 temperature controller. Properly preflowed assemblies should look as shown in *Figure 11*, where (a) shows an unreleased, preflowed die containing an array of type I DUTs, (b) shows a die containing type II DUTs, and (c) – (e) are close views of individual solder joints with scale bars indicating solder pad dimensions. At this point, the cross section would look like that shown in *Figure 8d*.

Release

Next, the sacrificial PSG must be completely removed in order for the DUTs to be released so that they can assemble when the solder is reflowed. The release procedures are identical to the steps outlined in the Pre-Release section above, starting at the HF step, with an etch time of 4 minutes instead of 30 seconds. The initial cleaning step is not performed. At this point, the cross section would look like that shown in *Figure 8e*. The reflow step, discussed next, should be performed immediately after the release (within an hour after release). Solder joints that are allowed to sit for approximately one day or longer before being reflowed take a longer time to reach and/or never fully reach their equilibrium position, during reflow—the reason for this has not yet been determined by the authors. An elemental analysis of the solder joints, over time, should indicate whether or not the surface of the solder is changing.

Reflow

The purpose of the reflow step is to assemble the DUTs. The reflow is performed using the same enclosed heating stage used in the Pre-Flow step. The die is placed on the heating stage and covered with the chamber with a N_2 flow of 1 liter/minute. The heating stage is activated at a rate of 30°C/minute. When the heat controller indicates 170°C, the N_2/formic acid vapor is flowed at 2 liters/minute. Structures begin assembling when the heat controller indicates 180°C. The N_2/formic acid vapor is flowed for 107 seconds, then stopped, N_2 flow is increased to 3.8 liters/minute, and the heating power is turned off. The heating stage is allowed to cool and will return to 28°C in 23 minutes. All solder joints are usually solidified by the time the heating controller reaches 150°C; at this point the N_2 flow is decreased to 1 liter/minute.
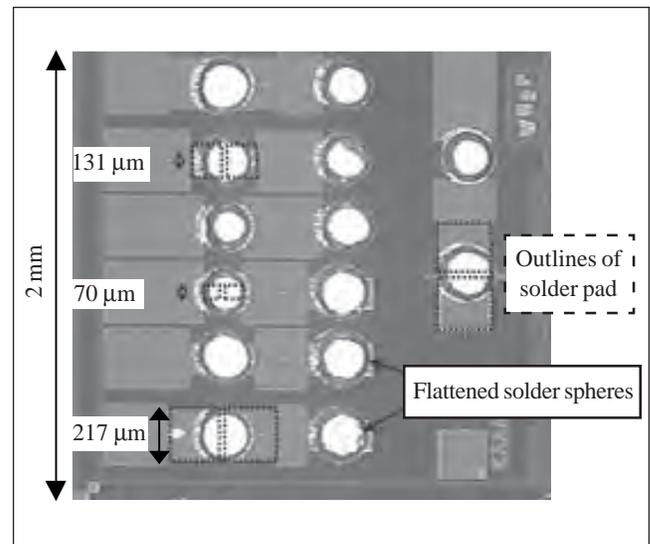

Figure 9
Captured Video Image of a Set of Type II DUTs After Solder Pick-and-Place Solder Deposition. Flattened solder spheres are shown placed over sets of solder pads of the various sizes: 70, 131, and 217 μm.
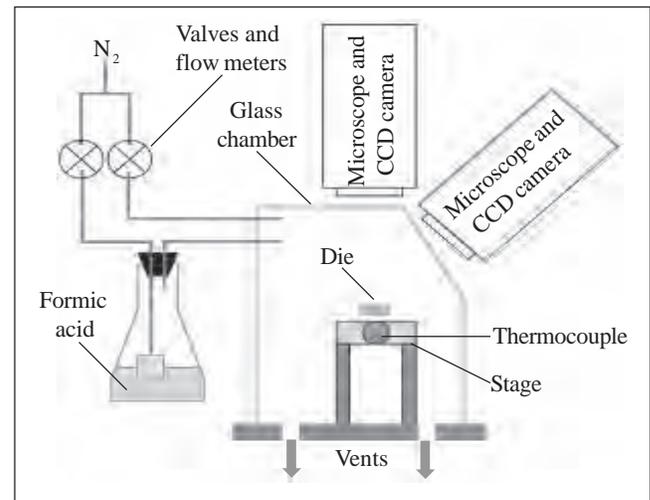
Figure 10
Depiction of Custom Built, Chamber-Enclosed, Temperature-Controlled Heating Stage

At this point, the cross section of a solder joint would look as illustrated in *Figure 8f*. Examples of properly reflowed type I, II, and III DUTs are shown in *Figures 5*, *2*, and *6*, respectively. *Figure 12* is a sequence of captured video images showing assembly of a die containing an array of type I DUTs. The total time of assembly, from (a) to equilibrium (h), is 45 seconds. The time duration of images (a) – (f) is 28 seconds. Image (f) is captured at the point when the scissor hinges solder joints begin to melt.

Figure 11
SEMs of (a) unreleased, preflowed die containing an array of Type I DUTs, (b) a die containing Type II DUTs,
and (c)–(e) are close views of individual solder joints with scale bars indicating solder pad dimensions.
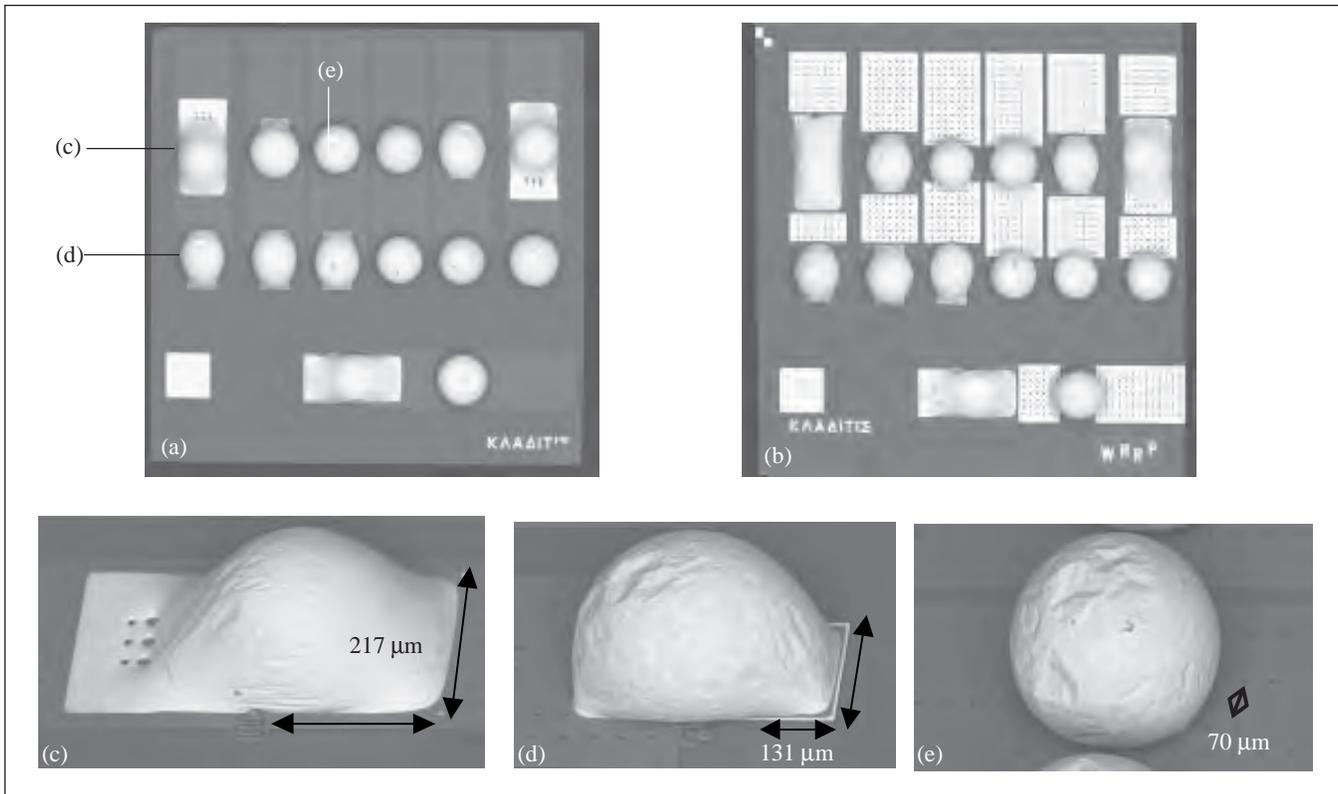
Assembly Component Uncertainty

The design and manufacture process is helpful in discovering which components of the DUT (assembly) contribute to uncertainty in the final assembly position. *Figure 13b* is an SEM of a type II DUT, illustrating the components that contribute to the uncertainty of the assembly endpoint position. *Table 1* lists the component tolerances that are used to predict the assembly tolerance, which will be covered later. The "Description" column is a categorization of the DUT components, the "Type" column indicates which DUT type the specific component is relevant to, the "Variable" column refers to the variables defined in *Figure 13b*, and "Sample Size" refers to the number of samples used to estimate the mean, standard deviation, and/or tolerance. In what follows, each component variable, and allocation of tolerance, will be discussed.

The volume of each solder joint is described by the volume of an equivalent sphere of diameter D. The equilibrium angle of each joint is a function of solder volume. The tolerance of this component was estimated by measuring the diameter of the solder spheres using an optical microscope measurement system calibrated with an Olympus B-0550 0.01 mm optical calibration slide.

The geometry of each pad in the pair of solder pads is described by the length (l) and width (w). The equilibrium angle of each joint is also a function of solder pad geometry. The variation in solder pad geometry is due to scavenging and overwetting. Scavenging occurs when the solder completely absorbs the gold solder pad material and pulls away from the area originally defined by the gold solder pads. Scavenging occurred mainly in the solder pad pairs designed for 90° and 45° equilibrium angles. *Figure 14* is an SEM showing an example of a scavenged solder pad, after the Pre-Flow step. The original dimensions of the solder pad were 217×217 µm.

Overwetting occurs when the solder wets past the boundaries of the gold solder pads and onto the bare polysilicon structure. This phenomenon was not anticipated in this research and was the cause of assembly failure for many of the type II and III DUTs.
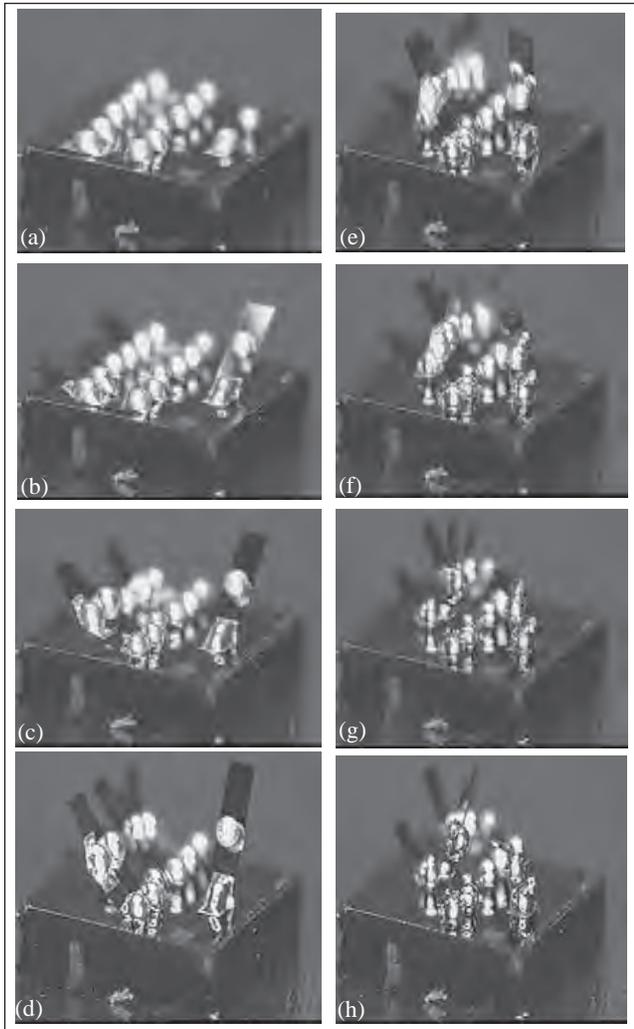
Figure 12
**Sequence of Captured Video Images Showing Reflow of a Die
Containing an Array of Type I DUTs. Total time of assembly,
from (a) to equilibrium (h), is 45 seconds. Time duration of
images (a)–(f) is 28 seconds. Image (f) is captured at the point
when the scissor hinges solder joints begin to melt.**

The solder would wet further than the gold solder
pads, across bare polysilicon, and onto the gold part
of the composite structure regions. These DUTs
would then become one large solder joint.
Overwetting occurred mainly in the solder pad pairs
designed for a 135° equilibrium angle. *Figure 15*
shows two examples of overwetting. The view is from
the back of the solder pad where the denser solder
can be seen through the polysilicon plate. The origi-
nal dimensions of the solder pads were 70×70 μm
and 131×131 μm, and have now become effec-
tively larger. The degree of scavenging and
overwetting comes from estimates made after in-

specting several assembled DUTs in the scanning
electron microscope.

Residual stress, in the plate structure parts of the
DUT, is a product of the surface micromachining
fabrication process and will cause deformation in
the plate parts between the solder joints. Parts of the
structure may be composed of polysilicon alone, with
residual stress σ_{poly}, or a composite of gold on
polysilicon, with residual stresses σ_{gold}. The residual
stress tolerance was estimated from data provided
by the surface micromachining foundry.

When the solder joint solidifies onto the relatively
thin polysilicon solder pad, deformation of the sol-
der pad occurs and can be described by an average
radius curvature (R_{sp}) at that region. The radius of
curvature was characterized from experimental mea-
surements of the curvature of assembled solder joints,
using a ZYGO interferometric microscope.

Due to the mismatch of coefficients of thermal
expansion in gold on polysilicon composite layers,
a change in temperature (T) will also cause the mag-
nitude of deformation of the structure to vary. The
temperature variation was estimated form typical tem-
perature fluctuations in the laboratory.

Each plate has a length L, and the interconnection
of the plates with each other or the substrate, through
hinges, which will have an amount of hinge play in
the *x-y* plane, described by $h_{x,y}$. The magnitude of
hinge play and structure geometry variation is based
on worst-case limits of the surface micromachining
fabrication process.

Theoretical Modeling

In this work, classical tolerance analysis methods
[37–43] are used to investigate the effect of the many
component variations on the DUT's (assembly's) fi-
nal end position. The assembly function, denoted
by f_{assy}, relates component variables (x_i) to the di-
mension of interest on the assembly by a multivari-
able function of the form

$$f_{assy} = f(D, l, w, \sigma_{gold}, \sigma_{poly}, R_{sp}, h_{x,y}, L, ..., T)$$

$$= f(x_1, x_2, x_3, ..., x_n) \tag{1}$$

In this work, the component variables (x_i) are the
variables listed in *Table 1*. Furthermore, it will be
assumed that the component dimensions are nor-
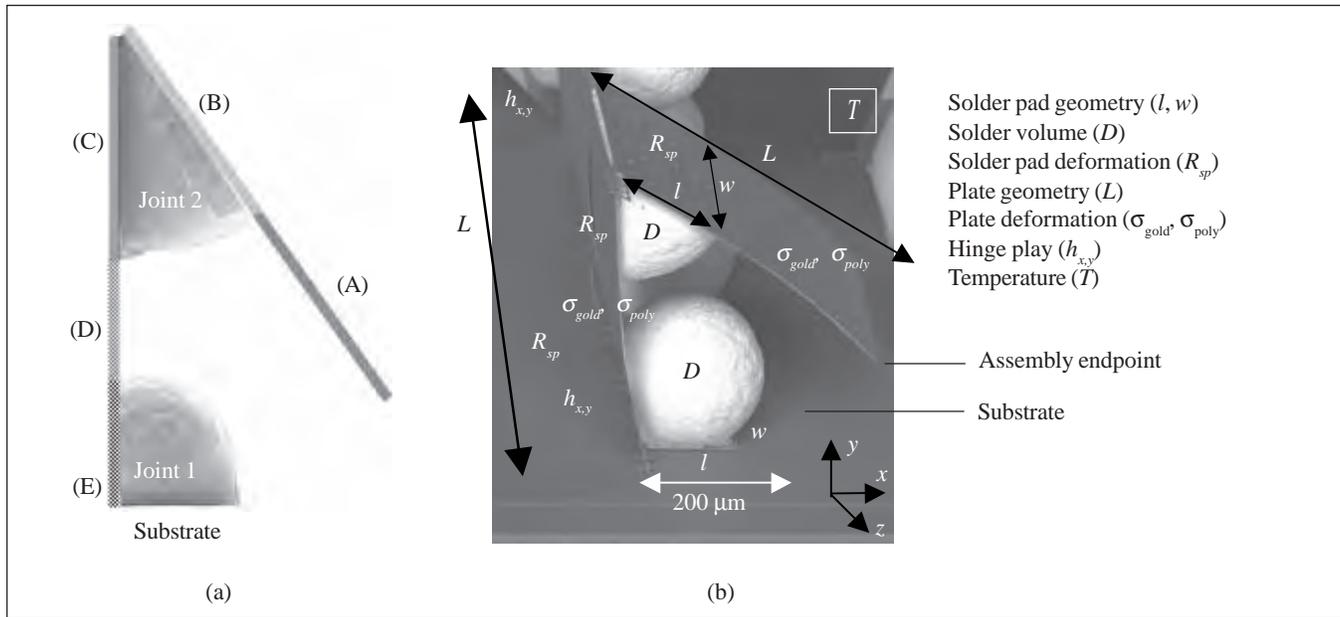mally distributed random variables. Two classical

Figure 13
Depiction of Assembly Components that Contribute to Variation in Assembly Position of a DUT

methods are utilized for the tolerance analysis, namely: worst-case or stack-up and statistical tolerance analysis.

The worst-case analysis uses a linearized assembly function, represented by a multivariate Taylor series expansion truncated to the first order. In general, the assembly function may or may not be linear. If the assembly function is linear, it may be used as is. If the assembly function is nonlinear, as in this case, the first partial derivatives must be calculated or estimated about a nominal position. Assuming a bilateral component tolerance (tol_i), the worst-case assembly tolerance (T_{WC}) is calculated as follows:

$$T_{WC} = \sum_{i=1}^{n} \left| \frac{\partial f_{assy}}{\partial x_i} \right| tol_i \qquad (2)$$

The statistical analysis involves analyzing the assembly function as a function of random variables and finding the mean and variance of the assembly function. It is assumed that the component characteristics are independent (uncorrelated) random variables (x_i), their Process Capability Index (CP_i) = 1, their nominal dimension is their mean (μ_i), and their upper (UL_i) and lower (LL_i) limit tolerances are bilateral and set at $3\sigma_i$, where σ_i is the standard deviation of the assembly components. Therefore, given the upper and lower limit tolerances for each com-

ponent dimension, the standard deviation for each component is calculated as follows:

$$\sigma_i = \frac{UL_i - LL_i}{6CP_i} = \frac{UL_i - LL_i}{6} \qquad (3)$$

The assembly mean (μ_{assy}) and variance (σ_{assy}^2) can be estimated by finding the appropriate joint moments of the assembly function modeled by a multivariate Taylor series expansion truncated to the first order:

$$\mu_{assy} = E[f_{assy}(x_i)] \cong f_{assy}(x_i)\big|_{x_i = \mu_i} \qquad (4)$$

$$\sigma_{assy} = \sqrt{E[(f_{assy}(x_i) - \mu_{assy})^2]} \cong$$

$$\sqrt{\sum_{i=1}^{n} \left(\frac{\partial f_{assy}(x_i)}{\partial x_i} \right)^2 \sigma_i^2 \Bigg|_{x_i = \mu_i}} \qquad (5)$$

If $CP_{assy} = 1$, the "3σ" statistical tolerance of the assembly (T_S) can be determined by

$$T_S = \pm 3CP_{assy}\sigma_{assy} = \pm 3\sigma_{assy} \qquad (6)$$

Next will be presented mathematical models predicting solder self-assembly equilibrium angle and plate deformation due to residual stress and solder

Table 1
Allocation of Component Tolerances

Description	Type	Variable (x_i)	Mean Value (μ_i)	Standard Deviation (σ_i)	Tolerance ($tol_i = \pm3\sigma_i$)	Sample Size
Solder volume	I & II	"8 mil" solder diameter (D)	214.7 μm (8.455 mil)	8.7 μm (0.341 mil)	26.1 μm (1.023 mil)	145
	III	"4 mil" solder diameter (D)	111.5 μm (4.388 mil)	3.81 μm (0.150 mil)	11.43 μm (0.450 mil)	121
	I & II	217 μm pad length (l)	202 μm	5 μm	15 μm	3
	I & II	217 μm pad width (w)	210 μm	2.3 μm	7 μm	3
	I & II	131 μm pad length (l)	125 μm	2 μm	6 μm	3
	I & II	131 μm pad width (w)	125 μm	2 μm	6 μm	3
Solder pad	I & II	70 μm pad length (l)	75 μm	1.7 μm	5 μm	3
geometry	I & II	70 μm pad width (w)	88 μm	6 μm	18 μm	3
	III	96 μm pad length (l)	88 μm	2.7 μm	8 μm	3
	III	96 μm pad width (w)	83 μm	4.3 μm	13 μm	3
	III	69 μm pad length (l)	69 μm	0.7 μm	2 μm	3
	III	69 μm pad width (w)	69 μm	2.7 μm	8 μm	3
	III	33 μm pad length (l)	35 μm	0.7 μm	2 μm	3
	III	33 μm pad width (w)	39 μm	2 μm	6 μm	3
	II & III	Gold residual stress (σ_{gold})	103.5 MPa	6.81 MPa	20.44 MPa	N/A
Structure	I – III	Poly residual stress (σ_{poly})	–7.9 MPa	0.94 MPa	2.82 MPa	32
deformation	I – III	Solder pad rad. of curv. (R_{sp})	6000 μm	333.3 μm	1000 μm	20
	II & III	Temperature (T)	27°C	2°C	6°C	N/A
Hinge play	I – III	x-y Hinge disp. ($h_x = h_y$)	0 μm	0.17 μm	0.5 μm	N/A
Structure geom.	I – III	Plate length (L)	500 μm	0.7 μm	2 μm	N/A

joint solidification. The models will then be used in the synthesis of the assembly function. Refer to *Figures 2* and *13* for illustrations of some of the variables in the following discussion. One of the significant factors that affects the precision of the final position of the assembly is the equilibrium angle of each of the solder joints. The equilibrium angle is a function of the solder pad geometry (*l* and *w*) and the volume of solder (*V*). Consider a molten volume of solder wetted to a pair of solder pads. Because of surface tension, the perimeter of the solder pads experiences a pull by the molten solder surface tension forces, causing the solder pads to be pulled together—constrained to rotate about the hinges. There is an opposing torque about the hinges provided by the internal pressure of the solder joint against the solder pads. At equilibrium, the torque due to surface tension is equally matched by the torque due to internal pressure. At any given angle (α) of the solder pads, there is a net torque T_{NET}) described by the following:

$$T_{NET} = \gamma w l \cos[(\alpha - \beta)/2] - \tfrac{1}{2}\gamma w l \sin(\beta/2)/\sin(\alpha/2) \quad (7)$$

where γ is the surface tension coefficient of the solder-air interface and β is the angle of curvature depicted in *Figure 2*. Furthermore, the volume of the solder joint at equilibrium can be approximated by a sphere of radius *R* less two sections of a sphere—as depicted in *Figure 16*.

$$
\begin{aligned}
V &= V_{Sphere} - 2V_{SpherePortion} \\
&= \frac{4}{3}\pi R^3 - \frac{4}{3}\pi R^3 \left(1 - \frac{3}{2}\cos(\pi/2 - \beta/4) + \frac{1}{2}\cos^3(\pi/2 - \beta/4)\right) \\
&= \frac{2}{3}\pi R^3 \left(3\sin(\beta/4) - \sin^3(\beta/4)\right)
\end{aligned} \quad (8)
$$

Goldmann [44] utilized a similar idea when approximating the profile of controlled-collapse chip joints for flip chipping onto ceramic substrates. An equation relating *R* to the rest of the geometry of the solder joint can be derived as follows:

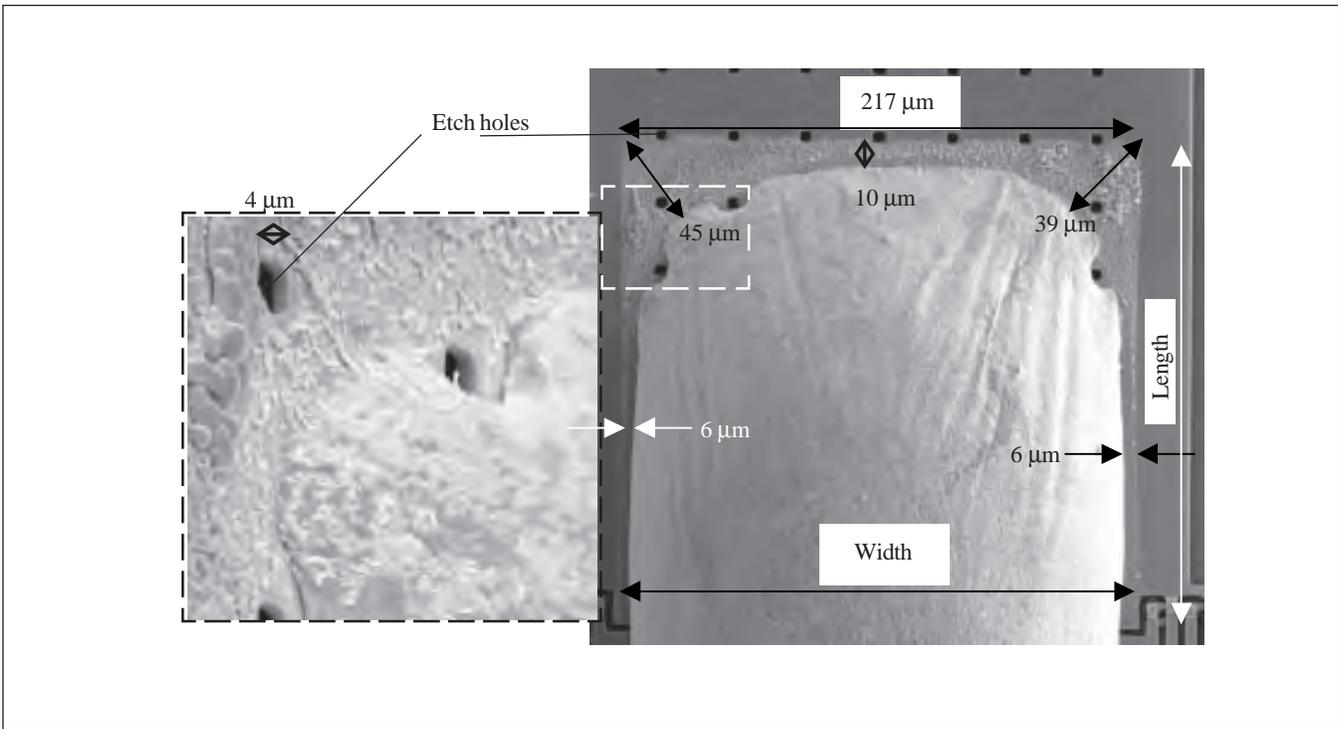$$R^2 = (l\cos(\alpha/2) - R\cos(\beta/2))^2 + (w/4)^2 \quad (9)$$

Figure 14
SEM Showing Example of Scavenged Solder Pad After Pre-Flow Step. Original dimensions of solder pad were 217 × 217 μm.
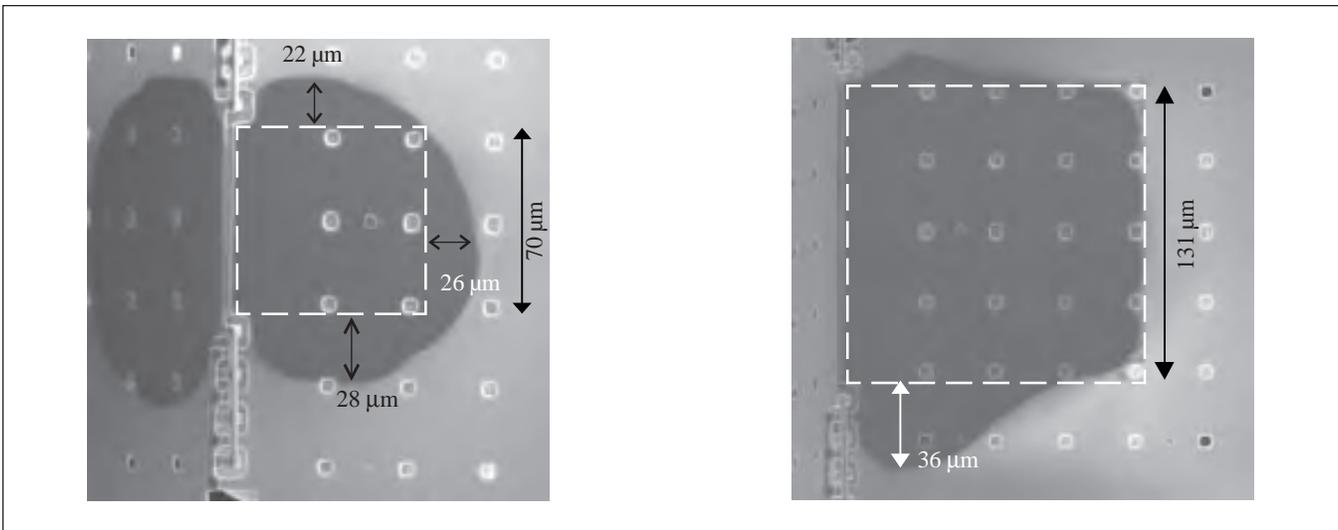

Figure 15
SEMs Showing Two Examples of Overwetting. View is from back of solder pad where denser solder can be seen through polysilicon structure. Original dimensions of solder pads were 70 × 70 μm and 131 × 131 μm.

Equations (7), (8), and (9) are three equations with five unknowns (α, β, R, V, and T_{NET}) that can be solved numerically given two of the unknowns. At equilibrium, $T_{NET} = 0$, the volume, V, is equal to the known deposited volume of solder. So, it is seen that any variation in V, l, or w will result in a change in equilibrium angle, α. A more detailed derivation of simi-

lar equilibrium angle models can be found in Kladitis et al. [30]. This model neglects the affect of solder weight and the weight of structures attached to the solder joint in the determination of equilibrium angle.

Another contributor to the precision of the final position of the assembly is deformation of the structural elements due to residual stress. Residual stress
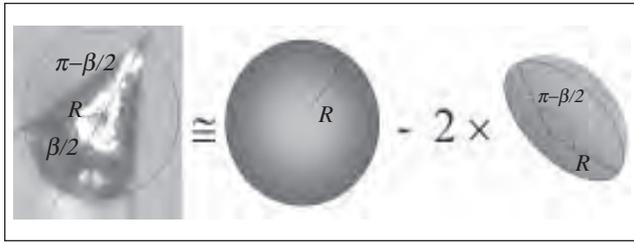
Figure 16
**Depiction of Approximation of Solder Joint Volume by
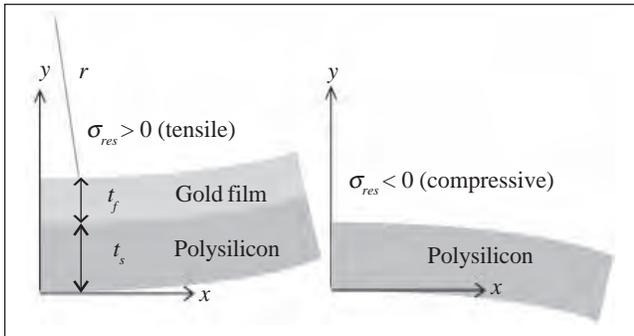Sphere Minus Two Spherical Sections**

Figure 17
**Illustration of Side Profiles of Different Deformation States
of Structural Elements of the Assembly**

is a byproduct of the fabrication process or the result of the structure being a composite of different materials with different coefficients of thermal expansion. *Figure 17* illustrates side profiles of different deformation states. Please refer to *Figure 17* for the following discussion. The following models are one-dimensional deformation models derived from beam theory.

If experimental measurements of the radius of curvature, *r*, of the deformation are available, then the deformation in the *y*-axis can be modeled as:

$$y = \frac{1}{2r}x^2 \tag{10}$$

For single-layer polysilicon structures, there will be an internal residual stress, σ_{poly}, due to the fabrication process. If reported values for this residual stress are available, then the deformation can be approximated by the following:

$$y = \frac{\sigma_{poly}}{E'_s t_s}x^2$$

where $E'_s = E_s / (1 - \nu_s)$ is the biaxial modulus derived from the Young's modulus of polysilicon (E_s) and Poisson's ratio (ν_s) for polysilicon, and t_s is the thickness of the polysilicon layer.

When the structure is made of a composite of polysilicon and gold, the deformation will be a product of the internal residual stress of the films and the residual stress developed from the mismatch in coefficients of thermal expansion of the different materials, which is also a function of temperature. This deformation can be approximated by the following:

$$y = \frac{3t_f \left(E'_f (\alpha_s - \alpha_f)(T - T_0) + \sigma_{poly} \right)}{E'_s t_s^2} x^2 \tag{12}$$

where t_f is the thickness of the gold film, $E'_f = E_f / (1 - \nu_f)$ is the biaxial modulus of gold, E_s is Young's modulus of gold, ν_s is Poisson's ratio for gold, α_s is the coefficient of thermal expansion of polysilicon, α_f is the coefficient of thermal expansion of gold, T is the dependent variable of temperature, and T_0 is the temperature where the misfit strain between the layers is zero. Equation (12) was derived from Stoney's equation [45]. The following values of material properties were used in this work: $E_s = 169$ GPa and $\nu_s = 0.22$ [46]; $\alpha_s = 2.33 \times 10^{-6}$, $E_f = 79$ GPa, $\nu_f = 0.42$, $\alpha_f = 14.2 \times 10^{-6}$ [47]; and $T = 27°C$ (measurement temperature).

The complete assembly function will now be discussed. The assembly function for this work is actually an algorithm that incorporates the models derived above and descriptions of the different segments of the DUT and produces a two-dimensional array of points describing the side profile of the DUT, in final assembled position, as output. First, a DUT is conceptually broken up into five regions, (A) – (E), as depicted in *Figure 13a*. The algorithm proceeds as follows:

1. A 2-D array of *x*-*y* points, describing the deformed shape of region (A), is calculated using Eq. (11) or Eq. (12) for type I or type II and III DUTs, respectively. The plate length, *L*, is taken into account here.
2. A 2-D array of *x*-*y* points, describing the deformed shape of region (B), is calculated using Eq. (10).
3. Regions (A) and (B) are combined into one continuous array (AB) while insuring matching slopes between the two arrays.
4. A 2-D array of *x*-*y* points, describing the deformed shape of region (C), is calculated using Eq. (10).

5. Calculate the equilibrium angle of joint 2 using Eqs. (7) – (9). Rotate, using the calculated equilibrium angle, and shift array (AB), relative to (C), while taking into account any hinge play and the slope at the ends of each array.
6. Regions (AB) and (C) are combined into one continuous array (ABC).
7. A 2-D array of *x-y* points, describing the deformed shape of region (D), is calculated using Eq. (11) or Eq. (12) for type I or type II and III DUTs, respectively. The plate length, *L*, is taken into account here.
8. Regions (ABC) and (D) are combined into one continuous array (ABCD) while insuring matching slopes between the two arrays.
9. A 2-D array of *x-y* points, describing the deformed shape of region (E), is calculated using Eq. (10).
10. Regions (ABCD) and (E) are combined into one continuous array (ABCDE) while insuring matching slopes between the two arrays.
11. Calculate the equilibrium angle of joint 1 using Eqs. (7) – (9). Rotate, using the calculated equilibrium angle, and shift array (ABCDE), relative to the substrate, while taking into account any hinge play and the slope at the end of (ABCDE) only.
12. The result is a 2-D array (ABCDE) that can be plotted to visualize the side profile of the DUT or investigate individual points on the DUT, such as the endpoint.

Results

Figures 18–21 are plots of the experimentally measured end positions of the DUTs (plotted with "*") superimposed over a side profile plot of the mean or nominal position of the DUT, as calculated using the assembly function. The end of the DUT, at its mean, is plotted with an "O". Furthermore, 1σ (68.27%), 2σ (95.45%), and 3σ (99.73%—largest dotted box) statistical tolerance regions, for the assembly, are plotted using dotted lines and calculated from Eqs. (5) and (6). The worst-case tolerance region, calculated using Eq. (2), is plotted using a dashed line and is a larger box than the 3σ box.

The figures also have a captured video image of a representative DUT, which corresponds to one data point, superimposed in the background. The captured video images are illuminated with a combination of direct front and back reflected lighting. The locations of the endpoints, of the DUTs, were measured in the same manner as the manufactured solder sphere diameters. That is, 1500×1125 pixel video images of the side profiles of DUTs were captured through a Javelin CCD camera attached to a National stereoscopic microscope at 25X magnification. This system was calibrated, using an Olympus B-0550 0.01 mm optical calibration slide, at 1.07 µm/pixel. The captured video images were used to measure the *x-y* pixel distances of the endpoints of the DUTs, relative to the staple hinge pin of joint 1.

Table 2 is a tabulated comparison of the estimated mean and standard deviation of the experimental measurements with tolerance analysis model predictions for all the DUT variations and types. The mean was calculated using Eq. (4), which is the assembly function evaluated at the nominal values of the applicable (depends on DUT type) variables listed in *Table 1*. The standard deviations were calculated using Eq. (5) and the applicable component standard deviations listed in *Table 1*. The partial derivatives, needed in Eqs. (2) and (5), were calculated numerically using central differences with a finite difference of magnitude: (typical variable value of x_i) $\times$ (*machine epsilon*)$^{1/2}$.

Possible sources of error that could contribute to any differences between the experimental measurements and model predictions are as follows: human measurement error in the optical measurements of DUT end positions (20 µm diameter of error for DUTs with obscured origins), inaccurate component tolerance allocations, inaccurate solder angle and deformation models, and assuming the weight of the solder and structures is negligible.

Discussion

From the experimental results and model predictions, it is seen that, given the current manufacturing process, the uncertainty in the assembly position is very high relative to the assembly's dimensions; in other words, the assembly position is not very precise. For example, the tolerance in the *y*-direction for a type I 45°/135° DUT is predicted to be as much as $\pm 3 \times 84.04$ µm = ± 252.12 µm for a structure with 500 µm dimensions!

Given that the assembly function can accurately represent assembled devices, its predictions can be used to answer the question: How does one increase
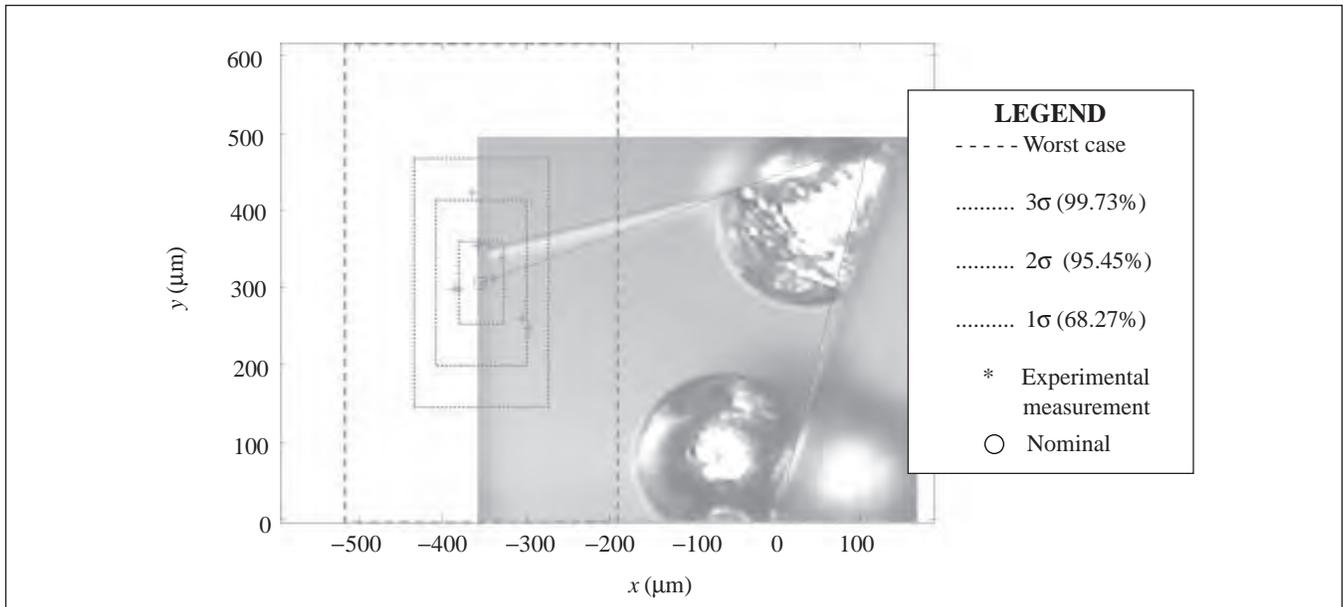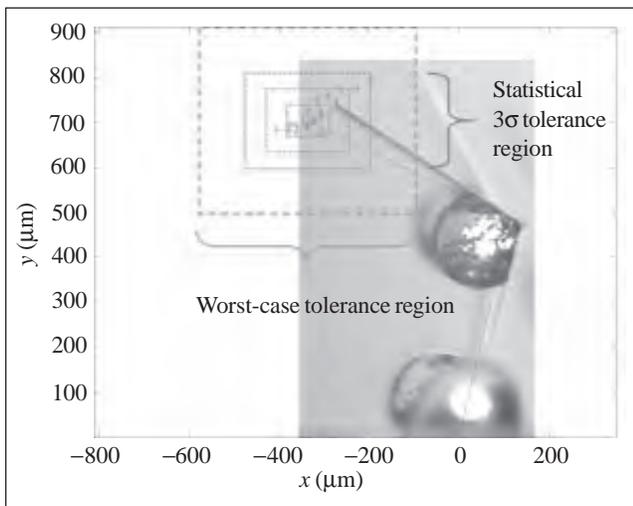
Figure 18
Plot of Results for Type I 90°/45° DUT

Figure 19
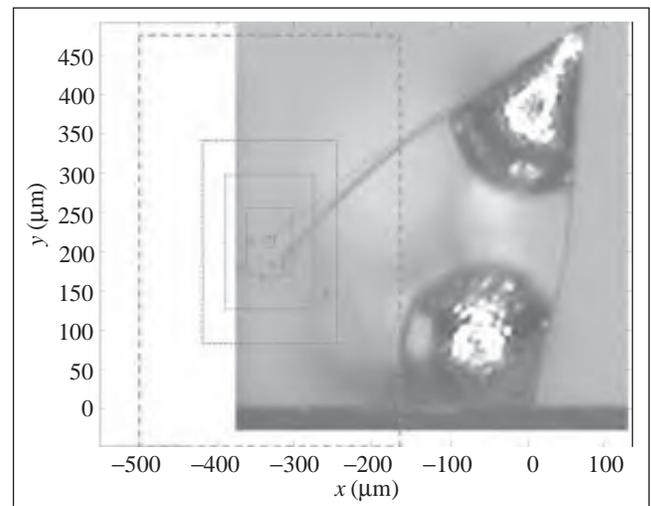**Plot of Results for Type I 90°/90° DUT**

Figure 20
Plot of Results for Type II 90°/45° DUT

the assembly precision of solder self-assembled MEMS? To answer this question, it is necessary to determine the relative order of impact that the assembly components have on the assembly precision. Equation (2) is actually a summation of the impact of each component on the assembly position. The type II and III DUTs have the most component variables and would be good representatives of any solder self-assembled MEMS. Using the type II DUTs as an example, the individual impacts can be calculated for each component using partial derivatives

from the assembly function and the tolerances listed in *Table 1*. Because the type II DUT has seven angle combinations, the impacts of similar components can be averaged across the seven angle combinations for a general feel of impact, that is, average the impact associated with solder volume variation (*D*) of joint 1 on a 90°/90° with the impact of joint 1 on a 135°/135° with, and so on. Furthermore, impacts for similar components can be averaged, that is, averaging the impacts for joint 1 with joint 2. *Table 3* is a ranking of impact from greatest impact to least im-
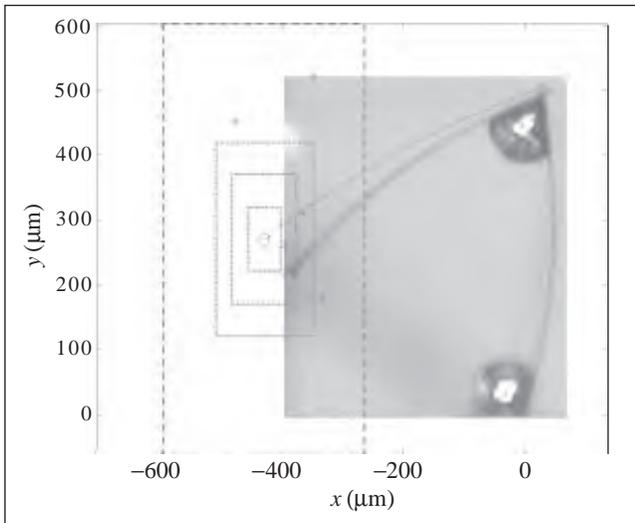
Figure 21
Plot of Results for Type III 90°/45° DUT

pact. From *Table 3*, it is seen that the variation in solder volume has the greatest impact on assembly position uncertainty, the variation in solder pad length is next, and so on. The impacts 6–9 are probably inconsequential for structures of the size of the DUTs in this work.

Next is discussed ways to increase the assembly precision. First, the need for increased assembly precision must be weighed against the cost of achieving the increase. Solder volume variation can be minimized by using more precise methods to define

volumes of solder, for example, depositing well-controlled thin films of solder and patterning the film photolithographically. Variation in solder pad geometry can be minimized by eliminating scavenging and overwetting. This can be achieved by using a solder-solder pad combination where the solder wets well to the pad but the pad does not dissolve completely into the solder. For the materials used in this work, nickel or copper may be a better substitute for the gold solder pads. The residual stress of the gold-polysilicon composite structure is a function of the thin film deposition process and temperature annealing steps that the fabricated device may go through inadvertently. The fabrication process and annealing steps must be consistent from batch to batch to minimize this impact. The same is true for single-layer structures.

To minimize the impact of temperature, the MEMS will either have to have a narrow range of operating temperatures or a tightly controlled environment. Temperature has a more pronounced effect on MEMS because of the small size. The impact of varying structure geometry and hinge play is a function of the precision, consistency, and resolution of the fabrication process. Microelectronics and MEMS foundries are always trying to improve on their fabrication process. Finally, the deformation of the structure due to the solidified solder joint can be minimized by designing solder pad shapes that result in minimized deformation on solidification.

Table 2
**Comparison of Estimated Mean and Standard Deviation of Experimental Measurements
with Model Predictions in the *x* and *y* Directions**

	Test Variant	Sample Size	Experimental Measurements (μm)				Model Predictions (μm)			
			Mean$_x$	Mean$_y$	Standard Dev$_x$	Standard Dev$_y$	Mean$_x$	Mean$_y$	Standard Dev$_x$	Standard Dev$_y$
Type I	*90 /45*	9	-345.08	321.14	31.03	54.20	-354.11	306.27	26.97	53.73
	90 /90	18	-315.70	720.97	53.40	37.39	-335.82	704.31	46.57	35.54
	90 /135	15	-108.76	918.51	80.11	30.23	-141.67	915.40	63.09	17.58
	135 /135	12	397.34	823.27	108.38	29.68	376.31	846.83	57.53	22.00
	135 /90	19	129.04	760.79	146.04	30.20	98.74	774.65	52.70	17.46
	135 /45	9	-122.27	430.67	66.44	43.69	-132.34	450.04	28.37	51.82
	45 /135	12	-731.65	555.02	76.25	106.11	-758.76	529.64	55.43	84.04
Type II	*90 /45*	6	-328.34	178.06	39.44	22.03	-331.93	212.91	28.72	42.95
	90 /90	5	-423.07	569.01	38.43	54.08	-414.36	595.74	38.22	41.00
	90 /135	4	-330.13	800.74	50.10	34.52	-284.90	846.65	56.79	25.85
Type III	*90 /45*	6	-374.29	232.19	22.83	45.60	-429.53	269.91	26.53	49.64
	90 /90	5	-467.52	430.77	45.31	68.25	-486.02	471.43	25.51	39.09

Table 3
Order of Component Impacts to the Assembly Position
for Type II Assemblies

Rank	1	2	3	4	5	6	7	8	9
Variable	D	l	σ_{gold}	T	w	L	R_{sp}	h_x and h_y	σ_{poly}
Impact (μm)	65.28	27.80	15.81	7.30	6.39	1.14	1.12	0.28	0.16

Conclusions

This paper has described the design of multiple-joint solder self-assembled MEMS. A relatively high yield (94.3%) manufacturing process for multiple-joint solder self-assembled MEMS was provided along with analytical models for predicting the assembly position of multiple-joint solder self-assembled MEMS. Experimentally measured positions of multiple-joint solder self-assembled MEMS DUTs were presented and compared to modeled results. The impact of process and component tolerances on assembly position uncertainty of the DUTs was investigated using statistical and worst-case tolerance analysis techniques. The uncertainty in assembly position was found to be as much as ±252.12 μm in some cases. It was found that the assembly position uncertainty was affected, from greatest to least impact, by: solder volume, scavenging and overwetting, residual stress in bilayer structures, temperature, structure dimension, solder pad warpage, hinge play, and residual stress in single-layer structures, respectively. Finally, some ideas for increasing assembly precision were provided.

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