

Land grid array sockets for server applications

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The design and performance of land grid array (LGA) sockets are discussed with respect to high-performance server applications. Motivations for the use of this technology are presented, and the specific challenges associated with its application are discussed from a mechanical perspective. A variety of mechanical performance considerations are identified for LGA socket technologies, and a detailed evaluation of competing socket-actuation designs is presented using finite element structural analysis. Some design approaches are shown to suffer from excessive mechanical flexure, which can consume the allowable range of motion of the contact, resulting in excessive contact load variation within the LGA. Statistical considerations for the mechanical deflections and tolerances that contribute to range-of-motion consumption are developed using Monte Carlo techniques, and a parametric study of the mechanical design variables that influence contact load variation within the LGA is presented.

Introduction

Modern computer systems increase in performance and complexity at a very rapid pace, driven by intense

competition and market demands. In order to meet ever-increasing performance requirements, the area and volumetric interconnect densities of electronic board assemblies must increase accordingly. In combination with other competitive forces, this demand has driven the need for improved high-density socket technologies in server computer applications, and the connector industry has responded with a variety of new alternatives to meet these needs. One of the most attractive of the new connector types is the land grid array (LGA) socket, which permits direct electrical connection between a module substrate and a circuit board. LGA connectors are an evolving technology in which an interconnection between mating surfaces of a module or other area array device and a printed circuit board is provided through a conductive interposer. Connection is achieved by aligning the contact array of the two mating surfaces and the interposer, and mechanically compressing the interposer. There are various competing interposer technologies ranging from compressible conductive spring designs to conductive metal-elastomer composites, among others.

Various implementations of this technology permit high density, good electrical performance characteristics, and rapid product development. Along with these advantages come a set of critical mechanical challenges which must be met in order to achieve desirable cost, yield, and reliability characteristics. This paper summarizes the state of this technology as applied to CPU modules and other large, complex devices, then presents in some detail the

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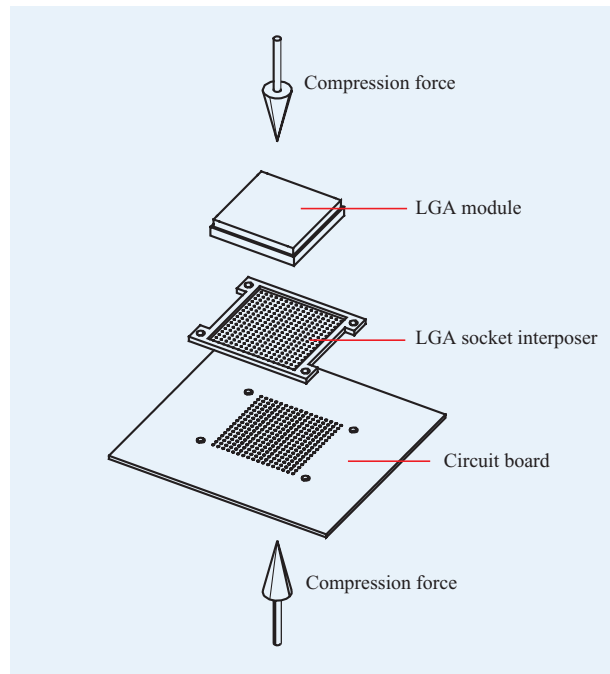


Figure 1

Schematic of exploded LGA socket assembly showing major components.

mechanical subsystem issues that must be considered to successfully implement LGA sockets into mid-level and high-end server systems.

Figure 1 shows a schematic of an exploded LGA socket assembly. The primary components of the LGA socket system are the module, a socket interposer, and the circuit board. Depending on the specific LGA technology, additional mechanical components (such as those required to align the components and those required to generate the compression force) are required to complete the assembly. A rectangular array of contacts on the underside of the module are connected by the interposer to a matching array of pads or lands on the circuit board. A distinguishing feature of LGA connectors is that high contact density is achieved by eliminating much of the traditional connector housing and utilizing simple, miniature contacts embedded within the interposer. Because the traditional connector housing provided much of the mechanical guidance, support, and contact retention for the assembly, these functions must be provided separately as part of the overall LGA mechanical system.

In many LGA sockets, the interposer contacts interface directly with plated contact lands on the module and circuit board. The elimination of large sliding contact surfaces dictates that innovative methods must be used to reliably establish a low-resistance gas-tight connection

interface capable of carrying adequate current. Another variant of the LGA socket allows for interfacing with solder balls attached to the module substrate [1, 2]. This type of socket can provide significant flexibility in implementing the socket interchangeably with a solder ball attachment process, but may deliver reduced electrical performance and reliability compared to designs which do not incorporate solder balls. This paper concentrates on systems using the direct-contact type of socket interposer, but many of the general principles are applicable to both styles.

Motivations for the use of LGA socketing

Density

One of the most compelling motivations for using LGA socketing technology is the interconnection density that is achievable. Just as ball grid array (BGA) or column grid array (CGA) technologies offer substantial increases in interconnection densities over peripherally leaded packages such as quad flat pack (QFP) or plastic leaded chip carriers (PLCCs), LGA devices can achieve much higher connection counts than peripherally connected sockets. For contact spacings of 1.27 mm, for example, the LGA pattern on a common 42.5-mm² module can provide 1089 connections compared to 132 for the peripheral pattern. Even compared to the popular pin grid array (PGA) sockets, which are also area array types, density is much higher because tighter spacings can be achieved without the need to attach the pins to the substrate. Newer LGA designs using 1-mm contact spacings can achieve 1681 connections within a 42.5-mm module footprint, while PGA designs, generally limited to 2.5-mm spacing, can achieve only 289 connections in the same area [3].

Rework

A second reason for increased LGA socket use is the simplicity of rework in manufacturing. If a defect is discovered in either the module or the remainder of the circuit board after assembly, it is often necessary to remove the module to either replace it or salvage it for attachment to another board. BGA and CGA modules must be carefully heated to melt the solder joints and release the module, a process which is slow and sometimes damaging to the board. Socketed components can be quickly replaced with minimal risk of damage.

Prototype and field upgrades

The need for rapid product development dictates that prototype assembly and debug operations must be as simple as possible, with minimal involvement on the part of manufacturing personnel. The ability to remove and replace socketed components is ideal in the development

environment, even if a solder-attach technology is planned for production use. For this reason, sockets are frequently considered for prototype use. Ease of removal and installation is also attractive, however, when field upgrades are required, repairs are needed with minimal downtime, or performance problems must be diagnosed. In high-performance or critical systems, these benefits often outweigh the added cost associated with most socket solutions.

Electrical performance

High-performance systems also require enhanced electrical performance characteristics from any interconnect technology. Inductance and capacitance of interconnects must be reduced to the lowest possible values in order to achieve acceptable signal rise times, overshoot, power dissipation, and signal propagation characteristics. While these characteristics can be controlled within the circuit board by methods such as placement of ground planes, the contributions due to connector design are largely attributable to the connector contact lengths. LGA sockets offer very short contact lengths, resulting in favorable performance properties.

Mismatched coefficient of thermal expansion (CTE)

One of the limits on the size and long-term reliability of solder-attached modules is the solder joint stress and strain induced by differential thermal expansion between the module and board. When the interconnection can transmit significant shear and bending stress between the module and the board, thermal stresses are an unavoidable consequence of the differences in the CTE and in the temperature between the module and the board. For many solder-attached modules, thermal cycling is relatively slow, temperature gradients are negligible, and significant creep and stress relaxation occur in the solder joints. In these cases, solder joint creep strain is a better indicator of joint reliability and fatigue life. In the limiting case of complete stress relaxation, the solder strain in a particular joint can be represented [4] as

$$\varepsilon = \psi(T - T_0)(a_m - a_b),$$

where ε represents the strain components, ψ is a geometric shape function, T and T_0 are the actual and reference temperatures, respectively, and a_m and a_b respectively are the coefficients of thermal expansion of the module and board. Because cyclic creep strain in the solder joint is directly related to fatigue life in power/thermal cycling, care must be exercised in the design of the module system to avoid premature failure. This imposes limits on both the operating temperature of the module and its maximum footprint dimensions.

While imposing limits on the power dissipation, operating temperature, and module footprint in order to

protect joint reliability is highly undesirable, a substantial improvement in total module performance is possible if an alternate interconnect technology can reduce the sensitivity to differential thermal expansion. This can be achieved if the interconnect is both highly compliant and elastic in shear, while maintaining adequate shear and tensile strength to avoid failure. These characteristics can be achieved in LGA sockets to different degrees using any of several mechanical design approaches, as discussed later.

Applications

Module socketing

The most popular use of LGA technology is in connecting module packages to circuit cards in a removable and reinstallable format. Applications which could benefit from LGA sockets include high-end modules such as CPU packages, prototype or initial production modules that may undergo repeated rework, and firmware modules that are intended to be physically upgraded in the field. High-performance CPU modules or multichip modules may require very high numbers of low-inductance interconnections, which are increasingly difficult to produce reliably with more conventional sockets or solder-attachment methods. In order to be practical, high-I/O LGA designs must overcome the difficulties associated with high insertion or extraction forces that would be expected in traditional socket designs such as PGA. If the insertion force per interconnection cannot be reduced dramatically, mechanical means must be provided to actuate the LGA socket. The design of the mechanisms and structures required to perform and maintain socket actuation is a critical mechanical challenge associated with applying LGA socket technology to large, high-performance modules.

High-performance modules which require LGA sockets frequently also require advanced cooling solutions. Whether a particular design incorporates a large heat sink, a fan sink, liquid cooling, or refrigeration, the module will be in direct contact with a large and probably massive structure. It is natural to conclude that the designs for the cooling hardware and the socket actuation hardware will interact strongly, and should be integrated whenever possible. A comparatively massive and rigid heat-sink base, for example, serves both as an effective heat spreader and as a means to apply significant force to the module and LGA interposer while maintaining adequate dimensional stability. Because the cooling hardware may completely cover the top of the module, it is necessary to consider whether it is more practical to actuate the socket from the module side of the circuit board or from the opposite side, where access may not be as restricted. The

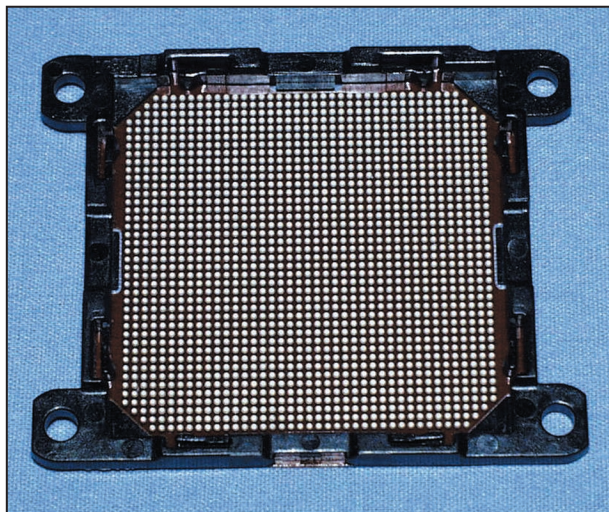


Figure 2

Typical LGA socket interposer. Shown is an MPI conductive-elastomer LGA connector in 42.5-mm form factor.

structural requirements for the LGA socket assembly force on the mechanical designer a compromise among ease of access, space requirements, and assembly complexity which must be weighed for each module socketing application.

Board-to-board connectors

Another application of LGA technology is board-to-board connectors. These connectors, like module sockets, may be required not only to meet stringent performance standards and to have a large number of interconnections in a small area of the circuit board, but also to carry higher currents per contact than module connectors. Mechanical and structural requirements are similar to those of module sockets, but integrated cooling designs are not typically required. In addition to rigid circuit boards, flex circuits may be used for one or both sides of the connector. While auxiliary structural support for the boards and interposer may not be required for small rigid-board connections, larger connectors and flex circuit connectors definitely require such supports. The low-profile connector designs that can be achieved with LGA technology allow minimal offset between the mating boards and are well suited to applications in which the direction of connector engagement is normal to the plane of the boards, although many LGA board-to-board connectors can be artificially extended to provide a substantial offset between boards. Connectors that are actuated in the plane of the board(s) are less ideal LGA applications, and require substantial added mechanical hardware.

LGA socket technologies

Dendritic

An early system developed by IBM is based on dendritic contact technology [2]. Each contact consists of a number of hard palladium dendritic spikes that can be plated directly onto any conductive base metal. In the simplest form, a dendritic interposer consists of a nonconductive interposer, such as an epoxy-glass composite (FR-4) or polyimide, which has contact pads on each side. Contact pad pairs are electrically connected with a via or by other means, and are plated with dendrites. The dendrites project above the pad surface and create a gas-tight connection by embedding themselves into the mating board or module pad, which is plated with a softer contact material. Because each pad has numerous dendrites in contact, a relatively large contact area can be achieved. This technology is well suited to high-volume manufacturing using a bulk plating process, but poses significant challenges in implementation because of the need for both large actuation forces and tight control of planarity on the mating surfaces. Because the actuation distance for this type of connector is small, structural deformation of the mating parts and supporting structure must be very well controlled, or compliant layers [5] must be introduced into the assembly to provide load consistency across the array.

Conductive elastomer

A technology prevalent in the industry today is based on the use of a composite of conductive metal partially embedded in a matrix of elastomer that is often referred to as conductive elastomer. The compliance of the elastomer is used to develop the necessary compressive force across each contact and to provide the range of motion required to accommodate the nonplanar aspects of the components being assembled. Electrical conductivity is provided by conductive fillers in the elastomer. A commercial version of this socket technology is the Metallized Particle Interconnect (MPI**) [6] connector, which is shown in **Figure 2** in a 42.5-mm-interposer form factor.

The construction of the interposer is unique in that an entire array of contacts can be created at once by molding them onto a thin perforated carrier. Each contact then resembles a miniature rivet, with the conductive material extending through a hole in the carrier and forming larger heads on each side of the carrier. A cross-sectional view of an MPI contact is shown in **Figure 3(a)**. This technology has the advantage of ease of manufacture and positive retention of the contacts within the interposer. Careful control of the material properties (particularly from the standpoint of long-term, temperature-dependent creep and stress relaxation) and molding parameters is

required, but the force/deflection characteristics, force requirements, and alignment requirements are similar to those of competing contact types.

Fuzz button

A widely used LGA contact technology is the fuzz button. This contact design consists of a small column of kinked molybdenum wire, typically contained in a cylindrically shaped housing. [A commercial version of this LGA socket technology is the CIN::APSE** [7] connector, a cross section of which is shown in **Figure 3(b)**.] The wire itself is much smaller in diameter than the column (which is approximately 0.5 mm in diameter), and it is formed in a pseudorandom pattern so that the contact resembles a miniature steel wool pad. Because of the shape and the hardness of the wire, the column or fuzz button can be compressed elastically over a relatively large axial displacement, and the force/deflection characteristics of the button can be reasonably controlled. Both the wire and the mating pads on the circuit board and module are plated with noble metals.

To construct a connector with this technology, a flat polymer carrier or interposer is molded with rows of small holes for the contacts. A fuzz button is inserted into each hole and projects both above and below the surfaces of the interposer. Alignment of the module, interposer, and circuit board must be established by features in the three parts. In order to engage the connector, force must be applied to the module and board in order to compress the fuzz buttons. The contact range of motion is significantly larger than that of dendritic connectors, while the contact force is comparable. This makes the demands on the design of the mechanical connector system less stringent than for the dendritic type, but care must still be taken to ensure that the compressive force on each fuzz button is within its operating range at all times and under all environmental conditions. The deformations of the module, interposer, and board must be well understood in order to ensure reliable operation.

Metal spring

Another LGA connector technology uses individual formed metal contacts that derive their compliance from bending deflection. There are two basic types, the only distinguishing difference being the type of interposer body used to carry the contacts. One type of interposer carrier is compliant, such as the one used in the IBM ELASTICON connector [8], in which gold wires are embedded in a silicone carrier.

Another type of interposer carrier is the more traditional plastic housing, such as the one used in the InterCon Systems cLGA** socket system [9], which is shown in cross section in **Figure 3(c)**. In this LGA technology, individual contacts are formed from plated

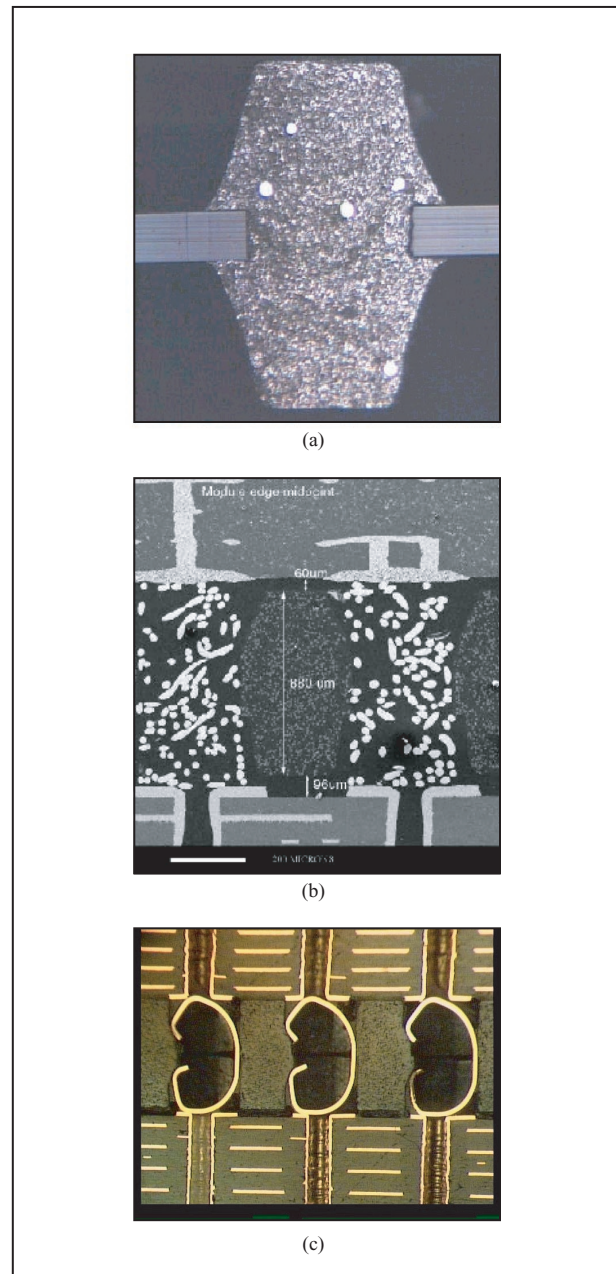


Figure 3

Cross-sectional comparisons of three types of LGA interconnects: (a) conductive elastomer; (b) fuzz button; (c) metal spring. Photos (a) and (b) courtesy of Michael Griffen, IBM East Fishkill. Photo (c) courtesy of Mark Plucinski, IBM Rochester.

spring material in the shape of a small letter “C” and are inserted into individual cavities molded into the carrier. The contacts protrude slightly above each surface of the carrier, and the contact force is generated as the contacts are compressed flush to the carrier. This type of connector

has the advantage of using more traditional contact metallurgies, which have a legacy of reliable operation. However, the mechanical considerations are similar in principle to those for the other LGA technologies: The correct amount of contact force must be applied to the contact array, structural deformation and stability of the connector system must be understood and controlled, and the means of alignment and actuation must be simple and compact enough to make its use commercially practical.

Mechanical considerations

The electrical connection between an LGA device and a printed circuit board is achieved by compressing the LGA device relative to the circuit board with a conductive (and usually compliant) interposer between the two. The required compressive force can often exceed one thousand newtons (N), depending on the number of input/output (I/O) connections of the LGA device and the loading characteristics of the individual contacts required to achieve a specific degree of conductivity. Many mechanical issues must be considered in order to achieve an effective design of an LGA socket assembly.

Mechanical actuation

Various loading or actuation mechanisms can be used to provide the necessary compressive load in the stacked assembly comprising the LGA device, the interposer, and the printed circuit board. In the simplest designs there is a loading plate on top of the LGA device and a loading plate or stiffener on the back side of the printed circuit card. These plates are corner-loaded and compressed relative to each other, typically with multiple screws or other fasteners that extend through the top plate, across the LGA device, through the interposer frame, through the printed circuit board, and to the back-side stiffener where they are anchored.

Load control

Some LGA connectors are designed to operate within a narrow range of applied load, so one of the difficulties associated with a direct-threaded fastener assembly approach is adequate load control. One approach is to actuate the socket hardware assembly through torque control of the threaded fasteners, but variations in frictional characteristics can make this a poor choice. Another approach is to drive the fasteners to achieve a fixed position of the top loading plate with respect to the back-side stiffener through the use of standoffs or similar means. However, the height variations of the module and other components caused by manufacturing tolerances can create substantial load variations due to the inherent stiffness of the assembly.

Improved load control of the actuation hardware can be achieved by introducing a compliant element into the

assembly. This can be done, for example, by extending a threaded post attached to the back-side stiffener through the printed circuit board, across the LGA device, and through the top loading plate. Wound compression springs or the like are installed over the threaded posts and are compressed by nuts or thumbscrews to a fixed position. If the added compliance, in this case the compression springs, is sized correctly with respect to the dimensional tolerances of the assembly, improved load control on the interposer and LGA device can be achieved.

Contact micro-motion

Exacerbating the problem of load control is the fact that the compliant conductive interposer contacts can be damaged by continuous micro-motion that might be experienced in certain vibration environments. One way to avoid this risk is to overload the interposer, typically by compressing the interposer to fixed downstops, with the overload being sufficient to accommodate any dynamic loading that might tend to separate the mating surfaces on either side of the interposer.

Load balance

While the actuation approaches described are simple and effective, they have some shortcomings. One significant problem associated with current designs is that multiple load points or actuation points between the top-side load plate and the back-side stiffener complicate the assembly, or disassembly, process. Care must be exercised during assembly to ensure that the load between the two plates does not become substantially unbalanced, which can cause damage to the LGA device, interposer, or printed circuit board. Incremental or concurrent tightening of each screw or spring-loaded fastener is required to keep the load adequately balanced.

Load uniformity

LGA contacts function properly over a relatively narrow range of compressive force. A mechanical consideration that is closely related to load control and load balance is the degree of load uniformity over the array. Since the force across each contact must remain within an acceptable range throughout the array, force variations attributable to flatness tolerances of the module substrate and back-side stiffener, differences in individual contact height, and variations in circuit board thickness must be accommodated. Substantial structural stiffness is often required (typically in the top-side load plate and back-side stiffener) to contain the structural deflections that occur under load. These deflections, which are also manifested as variations in the compression that occurs in individual conductive contacts within the interposer, must not cause the contact loads to fall outside the allowable load range

for each individual contact. An alternative way of characterizing contact load variation is to consider the allowable range of compressive motion for each contact and the variations in height of the compressed contacts attributable to each of these variables.

Ease of assembly

Ease of assembly is an important aspect of any LGA socket assembly design. The mechanical designs must be sufficiently robust to afford an uncomplicated assembly process, without the need for extraordinary precision or assembly tooling. The ability to easily remove and replace socketed components is also ideal in the development environment, and is one of the primary motivations for using LGA sockets. Additionally, many field activities (such as component upgrades or repairs, or problem diagnosis) are facilitated by ease of assembly of LGA components.

Thermal integration

Another challenge in many of the current socket actuation designs is the manner in which heat sinks or other cooling devices are attached to the assembly. Current LGA socket designs frequently contain heat sinks as part of the assembly. The heat-sink base is usually used as one of the loading plates in the assembly and is typically attached to a back-side stiffener using multiple screws or spring-loaded threaded fasteners. Even these simple attachment means can consume a significant portion of the effective heat-sink volume, since the screws or spring-loaded fasteners protrude through the heat sink and require removal or partial removal of some of the fin structure, thereby reducing its thermal efficiency. Additionally, the deflection under actuation load can create gaps between the heat-sink base and module cap that can compromise the thermal effectiveness of the heat sink.

Component stress levels

The mechanical components in the LGA assembly must be designed to adequately accommodate the stress levels associated with LGA socket actuation forces, which can be substantial. Design of the springs or other loading elements can be especially challenging because of the typically limited availability of space. Consideration must also be given to the stress levels that develop within the LGA module itself [10]. Careful design is required to ensure that stresses in the LGA substrate are contained to acceptable limits.

Mechanical evaluation

Description of mechanical hardware

Figure 4 shows exploded and assembly views of an LGA socket hardware set that is currently used in many product applications within IBM. In this approach, socket

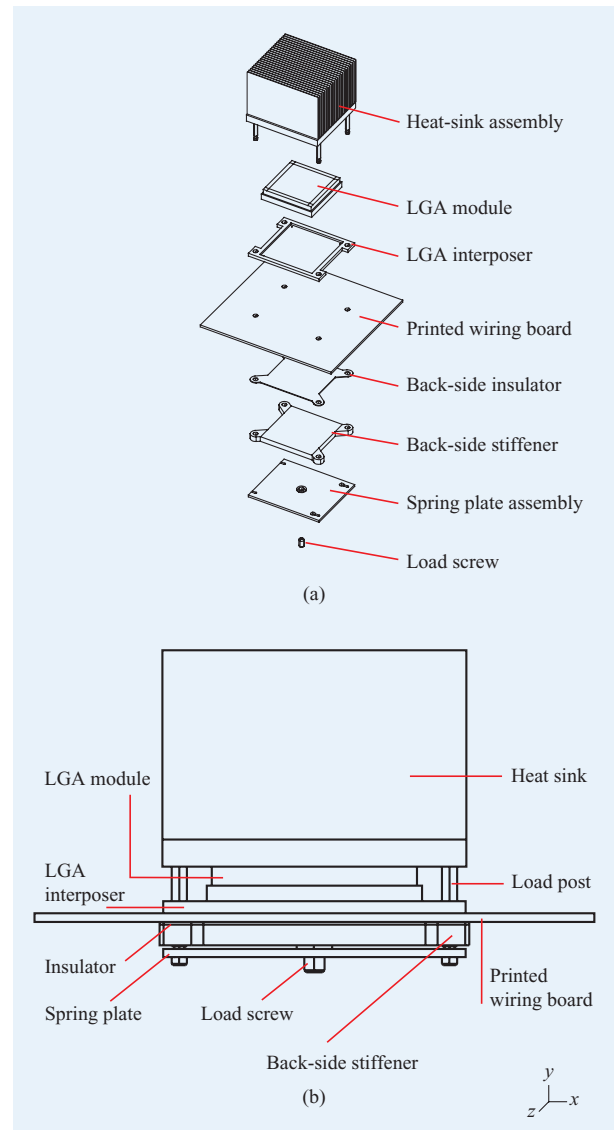


Figure 4

LGA socket hardware: (a) exploded view; (b) assembly view.

interposer loading is accomplished through a back-side spring plate with a simple unique engagement and a single-point actuation that promotes ease of assembly in manufacturing and service environments while automatically balancing the applied compression loads in the assembly. The unique back-side support structure and loading point promotes similar flexure responses between the LGA module and the back-side stiffener, which reduces the variation in individual contact compression within the interposer array.

Additionally, a heat sink is integrated into the assembly to achieve a compact, simple mechanical package.

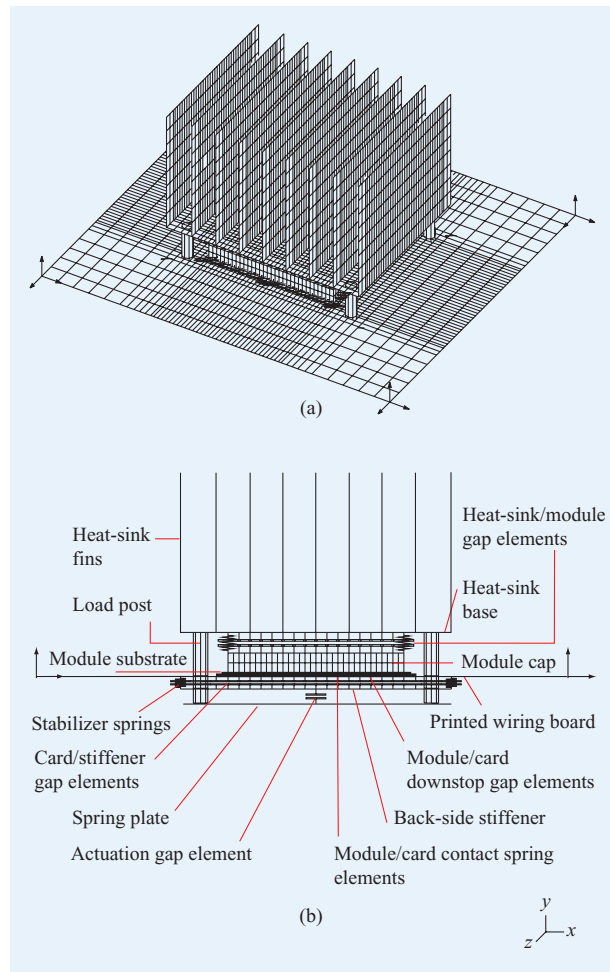


Figure 5

Finite element model of 42.5-mm LGA socket assembly with heat sink: (a) isometric view; (b) side view.

The heat sink serves as the top-side loading plate and effectively segregates the thermal solution on the top side from the actuation mechanism on the back side, which promotes greater flexibility and thermal efficiency in the use of heat sinks or other cooling devices.

Assembly is accomplished by first placing the socket interposer frame on the LGA site on the printed wiring board. Different socket technologies (fuzz button, metal beam, conductive elastomer) can be used in the same mechanical form factor with approximately the same height requirement. The socket interposer is typically registered to the pad pattern on the printed wiring board using two or more pins molded into the interposer frame which are placed into mating registration holes drilled in the printed wiring board. The LGA module is next positioned with respect to the socket interposer. Spring

fingers, which are typically integrated into the socket interposer, serve to register the contact array on the LGA module to the array in the socket interposer. The heat sink is next positioned on top of the LGA module. Forming part of the heat-sink assembly are the load posts, which transmit the compressive load into the LGA module and interposer. These posts are typically threaded into the corner sections of the heat-sink base, passing through clearance holes in the LGA interposer, printed wiring board, and back-side stiffener. The load posts protrude through the card on the back side and accommodate an insulator which prevents shorting between any potentially exposed pads on the back side of the printed wiring board that might come in contact with the back-side stiffener, which is typically metallic and electrically conductive. The back-side stiffener is positioned on the protruding posts, which pass through clearance holes in the back-side stiffener corners. Finally, the spring plate slides laterally onto the posts, allowing a keyhole feature on the spring plate to engage a load-groove feature on the ends of the load posts. Actuation is accomplished by turning a load screw installed in a bushing which is press-fitted into the spring plate. The rotated load screw bears against the back-side stiffener and deflects the spring plate, creating tension in the load posts, which compressively load the module against the LGA interposer, printed wiring board, insulator, and back-side stiffener.

Structural analysis

Finite element model—single-point vs. multipoint actuation

An isometric view of a finite element model used to evaluate competing methods of mechanical actuation is shown in **Figure 5(a)**. This three-dimensional model represents the previously described single-point actuation hardware mounted on a small printed wiring board (or card), but with minor modification it can also represent a four-corner actuation hardware set. The module is a 42.5-mm substrate (4.2-mm-thick 9211 ceramic) with 1089 contacts on 1.27-mm spacing, and with an aluminum cap nominally 2.8 mm thick. The heat-sink base is 6-mm-thick aluminum. The printed wiring board is 2.67-mm-thick epoxy glass (FR-4), and the back-side stiffener is 3.81-mm-thick steel. The spring plate is 1.57-mm-thick hardened steel that creates a nominal load of 1100 N when an actuation displacement of 1.4 mm is applied.

Since most of the structural phenomena of interest are related to bending, the model is constructed primarily of linear quadrilateral shell elements. Linear elastic beam elements represent the load posts, while the contact array itself is modeled with linear elastic spring elements (contact stiffness of 7.2 N/mm). The interactions between

the heat-sink base and module cap, the module substrate and interposer, the interposer and card (including downstops), and the card and back-side stiffener are modeled with contact gap elements. The card model is simply restrained at each of the corners. The in-plane (x - z plane) motion of the load posts with respect to the card, of the back-side stiffener with respect to the load posts, and of the spring plate with respect to the load posts is constrained with coupled degrees of freedom. Loading is accomplished with an actuation gap element, which is a single node-to-node gap element that creates the relative displacement loading between the spring plate and the back-side stiffener. A side view of the finite element model is shown in **Figure 5(b)**.

This model can be modified slightly to represent a four-corner loading pattern by eliminating the load posts, spring plate, and actuation gap elements, and replacing them with load pairs acting downward at the four load points on the heat-sink base, and acting upward at the four load points on the back-side stiffener. These models were created and run using I-DEAS** Master Series** Release 7.0 software.

Component motion under load

A significant characteristic of single-point socket loading is the deflection patterns that result in the back-side stiffener and LGA substrate. The loading pattern on the LGA module consists of an essentially uniform upward-acting load distribution on the bottom of the module in the vicinity of the contact array. This upward-acting load distribution is counterbalanced by the load distribution acting downward on the LGA module that results from the interface pressure between the LGA module and the heat sink. Since the heat-sink base bends with respect to the module, the interface pressure is more concentrated near the corners of the module and results in a convex curvature of the device as viewed from the top.

Concurrently, the loading on the back-side stiffener consists of an essentially uniform downward-acting load distribution on the top of the back-side stiffener in the vicinity of the contact array. The counterbalancing single-point load acting upward on the bottom of the back-side stiffener to maintain static equilibrium comes from the load screw. This set of forces results in a convex curvature of the back-side stiffener as viewed from the top. The deflection shapes of the principal socket components for single-point actuation loading are shown in **Figure 6(a)**. The component displacements along the module diagonal for single-point actuation loading are plotted in **Figure 6(b)**.

This relative deflection pattern is contrary to that obtained in four-point socket actuation designs which rely on corner loading (as would be the case in assemblies that are simply screwed together or spring-loaded at the

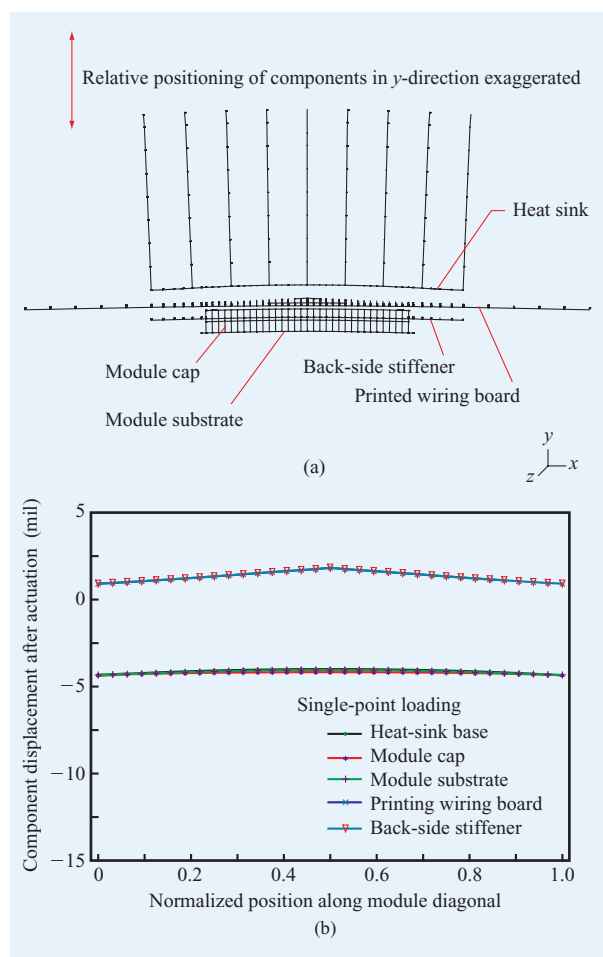


Figure 6

Finite element analysis of 42.5-mm socket assembly with single-point actuation: (a) Deflection shape of LGA socket assembly. (b) Component displacement and shape along module diagonal after actuation.

corners) of the back-side stiffener. Corner loading creates a module deflection pattern similar to the single-point case, but the deflection pattern of the back-side stiffener is concave as viewed from the top; this, in conjunction with the convex deflection pattern of the LGA module, can rapidly consume the available range of motion of the individual conductive contacts within the interposer unless substantially increased stiffness is provided by the structural members of the assembly. Single-point back-side loading, on the other hand, promotes matched flexure between the LGA module and the back-side stiffener that reduces the variation in individual contact compression within the interposer array. The deflection shapes of each of the principal socket components for four-point

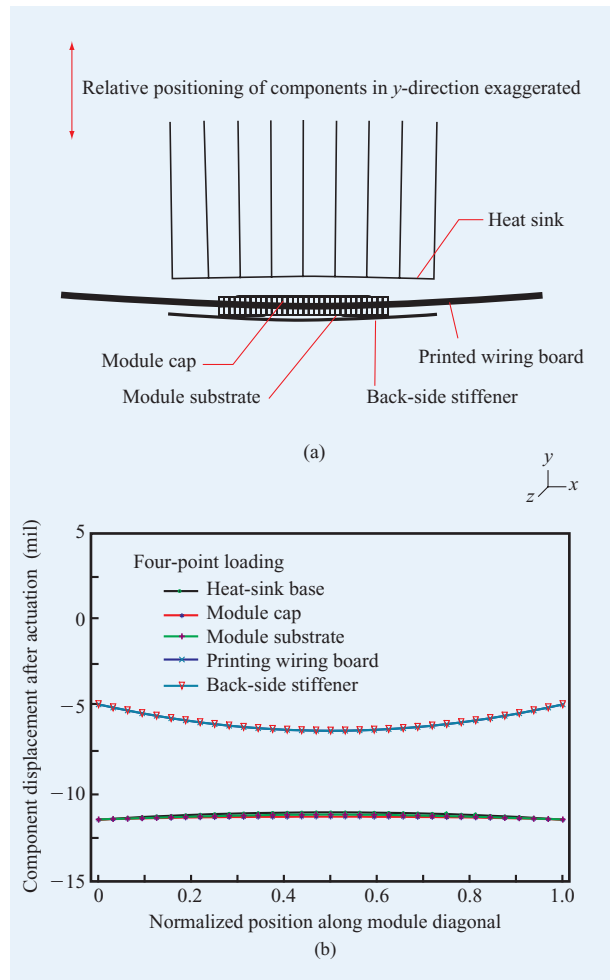


Figure 7

Finite element analysis of LGA socket assembly with four-point actuation: (a) Deflection shape of LGA assembly. (b) Component displacement and shape along module diagonal after actuation.

actuation loading are shown in **Figure 7(a)**. The component displacements along the module diagonal for four-point actuation loading are plotted in **Figure 7(b)**.

Flexural stiffness requirements

The relative deflection pattern that develops between the module substrate and the back-side stiffener contributes directly to contact load variation within the LGA array. The contact load variation within the LGA array was investigated for different back-side stiffener thicknesses, ranging from 2 mm to 3.81 mm, for single-point actuation hardware. The results, in the form of the ratio of minimum to maximum contact force, are plotted in **Figure 8**. The equivalent gap variations due to structural deflections are 0.016 mm, 0.035 mm, and 0.103 mm for

stiffener thicknesses of 3.81 mm, 3.00 mm, and 2.00 mm, respectively.

Also compared in **Figure 8** for different stiffener thicknesses is the contact force ratio as suggested by finite beam on elastic foundation theory [11, 12]. The contact force ratio F is given by

$$F = \frac{4 \cos(\beta L/2) \cosh(\beta L/2)}{2 + \cos(\beta L) + \cosh(\beta L)}, \quad \text{where } \beta^2 = \sqrt{\frac{K}{4EI}}.$$

In the above expressions, β is a constant related to the physical properties of the beam and the elastic foundation, L is the finite beam length (i.e., the length of the back-side stiffener), K is the foundation stiffness (i.e., the load per unit length of beam required to produce a unit deflection in the foundation, which is 190 N/mm² for an individual contact stiffness of 7.2 N/mm, an array of 1089 I/O, and a "beam" length of 42.5 mm), E is the elastic modulus of the beam, and I is the cross-sectional area moment of inertia of the beam.

Finite beam on elastic foundation theory provides a good estimate of the contact load variation determined in the three-dimensional finite element analysis. The finite element analysis is presumably more accurate because it includes both full plate bending and the foundation stiffness contribution from the module. For reference, a similar mathematical description of contact load variation appropriate to corner-loaded assemblies is presented in [13].

The minimum acceptable value of βL is dependent on the available range of motion for the particular LGA socket interposer being considered, and the other major mechanical tolerances in the assembly. For example, for an interposer range of motion (contact motion between fully compressed and that which creates a minimum acceptable contact load) of 0.13 mm (0.005 in.), a consumption budget might consist of 0.05 mm (0.002 in.) maximum module substrate flatness and 0.05 mm (0.002 in.) back-side stiffener flatness, plus 0.03 mm (0.001 in.) maximum of allowable structural deflections that contribute to contact gap variation. To achieve a gap variation due to structural deflections of less than 0.03 mm requires a back-side stiffener thickness in excess of 3.0 mm. In this example, the consumption budget is consumed arithmetically. A more accurate assessment of contact force variation due to mechanical tolerances and deflections can be obtained using a statistical analysis of the consumption of the allowable range-of-motion budget, which is described in a later section.

Another important aspect of flexural stiffness is that associated with the heat-sink base, since excessive heat-sink flexure can create gaps between the heat-sink base and the module cap that can degrade the thermal effectiveness of the assembly. Since the module is loaded

primarily on the corners of the cap on the top, and loaded by the LGA interposer on the bottom, it experiences bending and displaces into a convex shape. The heat-sink base also deforms in a convex pattern. Although not apparent in Figure 6, the gap that opens between the heat-sink base and the module cap is 0.0045 mm for a nominal 6-mm aluminum heat-sink base thickness. This heat-sink base thickness is acceptable for most thermal applications, but the gaps can expand dramatically with a thinner heat-sink base. Neglecting module cap bending (which could be reduced in the model if the cap were compliantly coupled to the substrate, i.e., with a Sylgard** interface), the gap under load could be as much as 0.0090 mm.

Contact load variation

The contact load variation across the module diagonal for the finite element models of four-point actuation and single-point actuation is shown in Figure 9. This is simply an alternative demonstration of the degree to which structural deflections affect gap variation between the substrate and back-side stiffener. Note that the contact load variation for a four-point actuation assembly will exceed the contact load variation for a single-point actuation assembly by a ratio of about 3:1 for the nominal back-side stiffener thickness of 3.81 mm.

Statistical considerations in LGA assemblies

Statistical analysis of the consumption of allowable range-of-motion budget

A more accurate assessment of contact force variation due to mechanical tolerances and deflections can be obtained by using a statistical analysis of the consumption of the allowable range-of-motion budget, as opposed to an arithmetic sum of the maximum amplitude of each of the major contributors. Monte Carlo techniques can be used to investigate the influence of the major assembly variables on contact load within the LGA.

Described here is a Monte Carlo simulation that views the contact load from the module center along the diagonal of a 42.5-mm LGA socket assembly and creates a gap variation function that is the arithmetic sum of randomly scaled shape functions. These shape functions are related to the major assembly variables that contribute to contact load variation, which are module flatness (camber), back-side stiffener flatness (camber), contact-free height variation, and structural deflection under load. A major advantage of combining shape functions that are related to the major assembly variables is that the effect of phasing (i.e., whether variables are additive or subtractive in a particular region of interest) between competing variables can be fully determined.

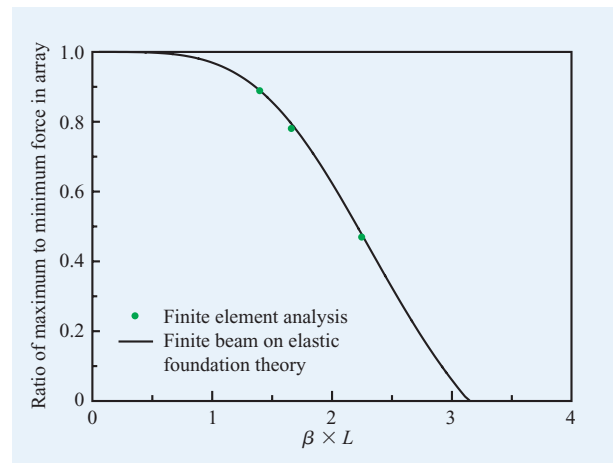


Figure 8

Contact force ratio within LGA. Comparison of finite beam on elastic foundation theory vs. finite element analysis for single-point loading.

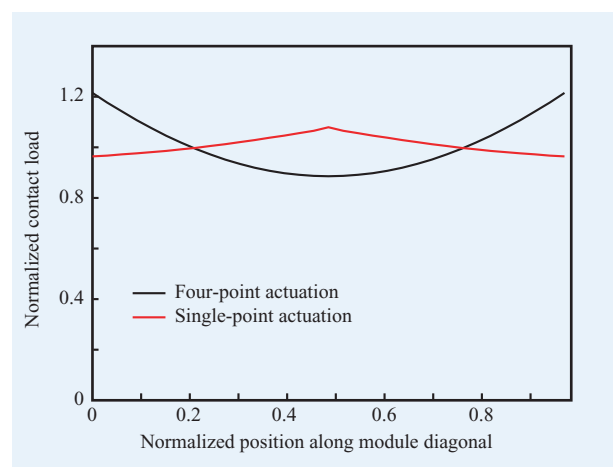


Figure 9

Contact load variation within LGA assembly. Finite element analysis of 4.25-mm socket assembly comparing single-point and four-point actuation.

The shape functions assumed for the module flatness ψ_1 and stiffener flatness ψ_2 are cosine functions with a random amplitude that is specified statistically, and are of the form

$$\psi_1 = a_1 \left[1 - \cos\left(\frac{\pi}{2}\right)\left(\frac{x}{d}\right) \right]$$

and

Table 1 Coefficients used to describe the structural deflection shape functions for single-point and four-point actuation.

Actuation type	C_1	C_2	C_3	a	a_0 (mm)	F_0 (N)
Single-point	0.0091	0.9636	−0.3479	0.6248	0.0159	1,098.7
Four-point	1.7987	−0.0893	−1.7189	1.7987	0.0457	1,098.7

Table 2 Results of Monte Carlo simulation comparing performance metrics of single-point and four-point actuation.

Actuation type	Location of maximum contact force	Maximum normalized contact force	Location of minimum contact force	Minimum normalized contact force	Ratio of minimum to maximum contact force	Range of normalized contact force
Single-point	Center	1.26	Corner	0.74	0.59	0.52
Four-point	Corner	1.43	Center	0.69	0.48	0.74

$$\psi_2 = a_2 \left[1 - \cos\left(\frac{\pi}{2}\right)\left(\frac{x}{d}\right) \right],$$

where (x/d) is the normalized position from the module center along the module diagonal, a_1 is the module shape amplitude, and a_2 is the back-side stiffener shape amplitude. When a positive mean amplitude is specified, the flatness is predominantly convex; a negative mean amplitude allows a predominantly concave shape.

The contact-free height shape function is a constant, but with a statistically described variation at each individual contact position.

The structural deflection shape functions are quadratic polynomials fitted to the gap variation function from the finite element models of both the single-point and four-point actuation assemblies previously described. These shape functions, which do not vary statistically but are scaled to the overall assembly load, are of the form

$$\psi_0 = \left[C_1 + C_2 \left(\frac{x}{d} \right) + C_3 \left(\frac{x}{d} \right)^2 \right] \left(\frac{a_0}{a} \right) \left(\frac{F}{F_0} \right),$$

where a is the maximum shape function amplitude [which is the value of the quadratic polynomial in brackets evaluated at $(x/d) = 1$ for the single-point actuation case, and the value of the quadratic polynomial in brackets evaluated at $(x/d) = 0$ for the multipoint actuation case], and a_0 is the reference amplitude of the gap function determined from the finite element model for a nominal reference load of F_0 . The polynomial coefficients, the maximum shape function amplitude coefficients, and the reference gap function amplitudes and loads for both actuation classes are summarized in **Table 1**.

The simulation determines the contact load variation at a prescribed overall assembly load. The computational sequence is as follows:

1. Assign a random flatness amplitude to the module.
2. Assign a random flatness amplitude to the back-side stiffener.
3. Compute the gap variation function due to structural deflection at the assembly load.
4. Randomly vary the contact-free height along the diagonal.
5. Compute the overall contact gap shape function at the assembly load.
6. Compute the individual contact loads.
7. Limit the individual contact loads if the contact is fully compressed.
8. Iterate the module/interposer position until the total load equals the assembly load.
9. Partition the total load into the portions carried by the contacts and by the downstops.
10. Collect the contact load results and repeat Steps 1–9.

Steps 1 through 9 simulate a single module assembly. Contact load responses are collected into a single population for each actuation class for a module assembly population of 500. The case considered is for a 42.5-mm LGA module with 1089 I/O, an individual contact stiffness of 7.3 N/mm, a total individual contact compression range of 0.20 mm, an individual contact height variation of $\pm 10\%$ of the contact compression range (± 0.2 mm in this case), a module camber with a mean of 0 and a $\pm 3\sigma$ limit of ± 0.025 mm, a back-side stiffener camber with a mean of 0 and a $\pm 3\sigma$ limit of ± 0.025 mm, and a nominal load of 1068 N. The contact load response populations are shown in **Figure 10(a)** for the single-point actuation case and in **Figure 10(b)** for the four-point actuation case.

The contact force variation at each unique position from the module center along the diagonal (since the contact array is 33×33 , there are 17 unique positions) can be characterized statistically. In this case, the resulting

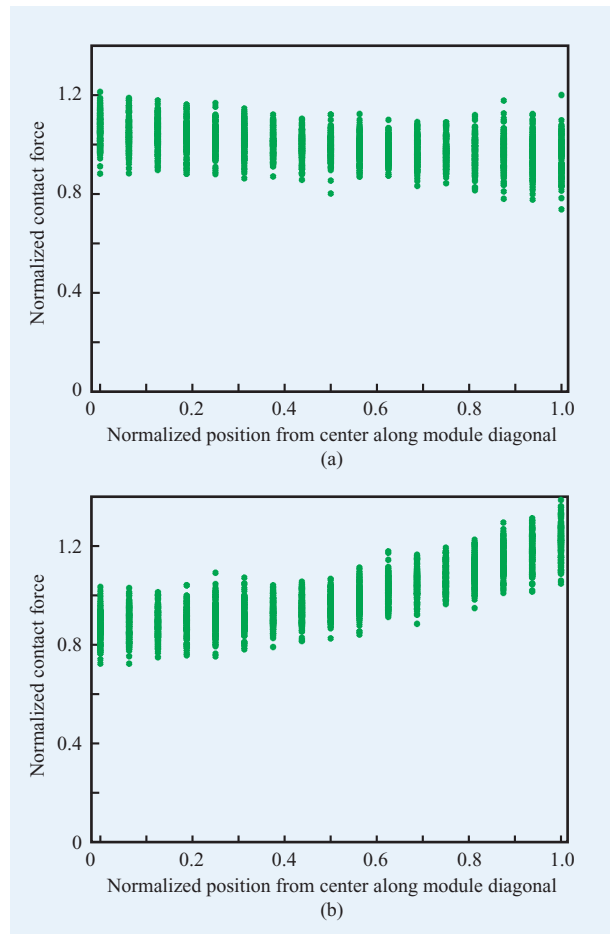


Figure 10

Monte Carlo analysis of 42.5-mm LGA assembly; normalized LGA contact force variation across module diagonal for (a) single-point actuation; (b) four-point actuation.

contact force variation at each unique position is normally distributed (this is not always the case, depending on the underlying distribution assumptions that describe the contributing factors, and depending on the degree of contact force clipping that is caused by full compression of an individual contact), so the mean and mean $\pm 3\sigma$ limits can be computed. These means and limits and the corresponding quadratic regression fits for each are shown in **Figure 11(a)** for the single-point actuation case and in **Figure 11(b)** for the four-point actuation case. The extremes of the mean $\pm 3\sigma$ limit regression equations are summarized in **Table 2**, along with the locations of the contact force extrema and other performance metrics.

Again, note the preferential performance of single-point actuation LGA socket assemblies compared to four-point actuation assemblies. This type of information can be

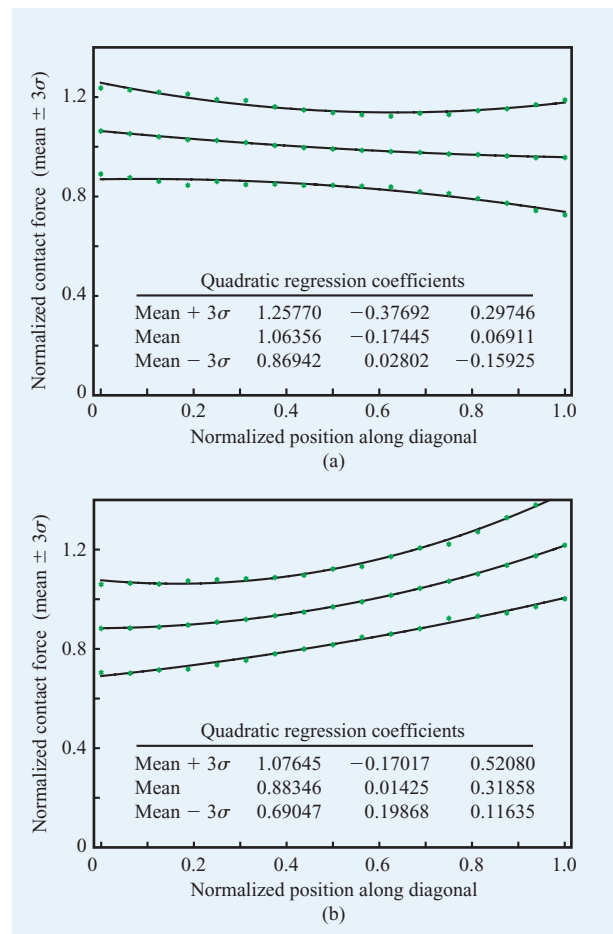


Figure 11

Monte Carlo analysis of 42.5-mm LGA assembly; means and limits for (a) single-point actuation; (b) four-point actuation.

useful in determining actuation hardware design feasibility as well as specifying the tolerance limits for the various components that contribute to the consumption of the allowable range of motion for the particular LGA interposer design under consideration.

Parametric study of contact force variation

The Monte Carlo techniques described previously can also be used effectively in conjunction with design-of-experiments techniques to investigate the parametric sensitivity of the mechanical design variables in an LGA assembly to the contact force variation.

Table 3 shows a designed experiment constructed with the primary variables being the contact stiffness, the mean compression range, the actuation class, and the mean module camber. In all cases, the total assembly load is

Table 3 Experimental trial matrix and responses.

Trial number	Contact stiffness (N/mm) (Variable A)	Mean compression range (mm) (Variable B)	Mean module camber (mm) (Variable C)	Actuation type (Variable D)	Contact height variation (±mm)	Total load (N) (Computed)	Response, ΔF
1	1.75	0.13	0.025	4-point	0.013	242	0.130
2	1.75	0.13	0.025	1-point	0.013	242	0.231
3	1.75	0.13	-0.025	4-point	0.013	242	0.274
4	1.75	0.13	-0.025	1-point	0.013	242	0.181
5	1.75	0.25	0.025	4-point	0.025	484	0.021
6	1.75	0.25	0.025	1-point	0.025	484	0.128
7	1.75	0.25	-0.025	4-point	0.025	484	0.185
8	1.75	0.25	-0.025	1-point	0.025	484	0.077
9	7.00	0.13	0.025	4-point	0.013	969	0.113
10	7.00	0.13	0.025	1-point	0.013	969	0.313
11	7.00	0.13	-0.025	4-point	0.013	969	0.523
12	7.00	0.13	-0.025	1-point	0.013	969	0.101
13	7.00	0.25	0.025	4-point	0.025	1,938	0.212
14	7.00	0.25	0.025	1-point	0.025	1,938	0.207
15	7.00	0.25	-0.025	4-point	0.025	1,938	0.420
16	7.00	0.25	-0.025	1-point	0.025	1,938	0.008
17	1.75	0.13	0	4-point	0.013	242	0.080
18	1.75	0.13	0	1-point	0.013	242	0.024
19	1.75	0.25	0	4-point	0.025	484	0.081
20	1.75	0.25	0	1-point	0.025	484	0.021
21	7.00	0.13	0	4-point	0.013	969	0.317
22	7.00	0.13	0	1-point	0.013	969	0.103
23	7.00	0.25	0	4-point	0.025	1,938	0.317
24	7.00	0.25	0	1-point	0.025	1,938	0.113

set at the full compression value for the contact under consideration, the contact height variation is set at $\pm 10\%$ of the compression range, and the back-side stiffener camber is specified with a mean of zero and a $\pm 3\sigma$ limit of 0.025 mm.

The experiment design is a two-level full factorial, with an additional eight trials added to investigate the performance at a mean module camber of zero. The two levels considered are representative of the ranges associated with LGA interposers commercially available today. These ranges are 1.75–7.00 N/mm for the contact stiffness, 0.13–0.25 mm for the mean contact compression range, and ± 0.025 mm for the mean module camber.

The primary response of interest is the mean normalized contact force variation (ΔF). This response is obtained from the quadratic regression fit of the mean normalized contact force along the module diagonal that is obtained from a Monte Carlo simulation for each parameter condition set defined in the trial matrix.

The full regression equation for the two-level full factorial portion of the trial matrix (trials 1 through 16) is

$$\begin{aligned}\Delta F = & 0.195 + 0.084A - 0.076B + 0.052C - 0.079D \\ & + 0.025AB - 0.080AD - 0.021BC - 0.026BD \\ & - 0.180CD - 0.026ABC - 0.023ABD - 0.077ACD \\ & + 0.024BCD + 0.030ABCD.\end{aligned}$$

All of the main effects are of the same order and therefore of competing significance, which suggests that the contact force variation could be minimized with a combination of minimum contact stiffness, maximum contact compression range, minimum module camber, and maximum actuation type (e.g., single-point actuation). The significant two-factor interactions are AD and CD . The AD interaction suggests that ΔF is much less sensitive to contact stiffness for the case of single-point actuation than for four-point actuation. The CD interaction suggests that ΔF is reduced for four-point actuation when the mean module flatness is convex, whereas ΔF is reduced for single-point actuation when the mean module flatness is concave, which is intuitively correct.

The response contrasts for the full trial matrix are shown in **Figure 12**. Note that the response contrast between single-point actuation and four-point actuation

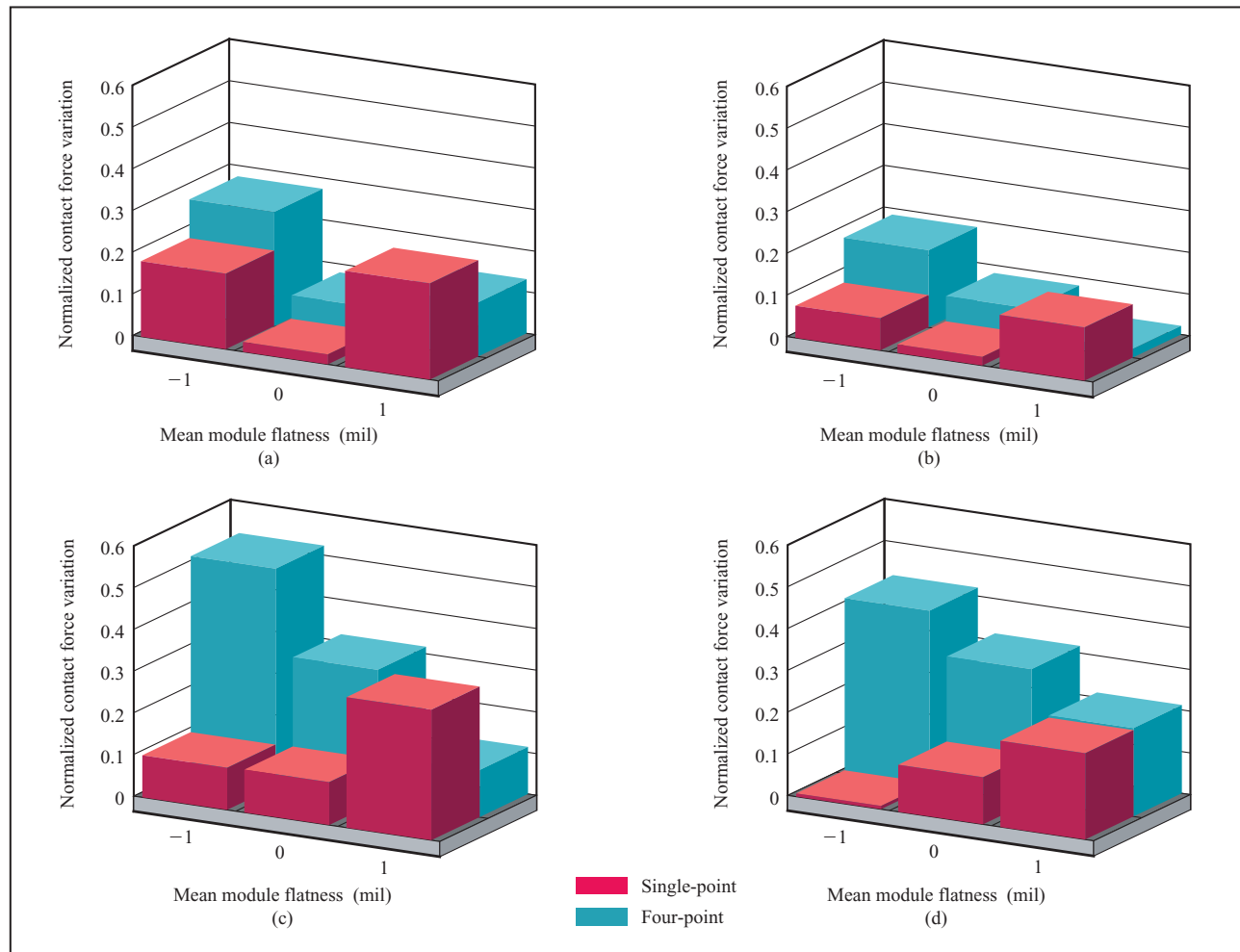


Figure 12

Factorial results for (a) low contact stiffness and low compression range; (b) low contact stiffness and high compression range; (c) high contact stiffness and low compression range; (d) high contact stiffness and high compression range.

can be particularly exacerbated at high values of contact stiffness, and that four-point actuation provides better performance only for cases of convex mean module camber. Finally, single-point actuation provides especially superior performance for the combination of high values of contact stiffness and flat-to-concave mean module camber.

Summary

The advantages offered by LGA sockets are significant, and this technology is well suited to meeting the needs of high-performance server system designs. Along with these cost, performance, and flexibility advantages, LGA sockets pose significant mechanical challenges. In order to realize the potential of LGA socket technology in a reliable socket system design, considerable attention must be

directed to the means of applying preload to the contact array. Structural concerns include ruggedness of the assembly, the means to apply sufficient force to actuate the socket, and techniques to account for sources of compression force variation in the design. Traditional means of clamping the socket system together are incapable of providing uniform compressive force across the array, and can be both bulky and difficult to assemble.

A design for an LGA socket system that uses a single-point back-side loading scheme promotes matched flexure between the LGA module and the stiffener. This, in turn, reduces the variation in individual contact compression within the contact array and permits a reduction in the structural stiffness (and its associated bulk) required to maintain an acceptable range of contact compression. Successful commercial application of this type of design

confirms the analytical results presented, which show that such LGA socket designs can be both efficient and reliable.

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