

DESIGN AND DEVELOPMENT OF A HIGH PRECISION LENS FOCUSING MECHANISM USING FLEXURE BEARINGS

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Abstract

The emergence of multi-tier stacked die architecture in semiconductor devices has given rise to the need for multi-level interconnection between dies (bare IC chips) and the substrate. In the context of interconnection by wire bonding, this necessitates the use of a vision system, which has real time focussing capability. This paper presents the design and development of such a high precision Programmable Focussing Mechanism (PFM), which is used to move a lens relative to another fixed lens, thus altering the focus of the optical system. The device employs flexure bearings and is actuated by a voice coil motor (VCM).

Keywords: Machine vision, lens focus, wire bonder, flexure bearing, voice coil motor

1 Introduction

Wire bonding is by far, the most flexible and the most widely used semiconductor interconnection technology [1]. Fine gold wire is used to make connections between the “die” (bare IC chip) and its substrate, using a thermo-sonic bonding process. Modern-day wire-bonders are expected to bond on pads with a tight pitch of around 50 μ m or less, with an accuracy of $\pm 4 \mu$ m at their best. Status of art machines can attain bonding rates of 10-15 wires per second. The bond-head, which carries the ultrasonic transducer, is mounted on a X-Y table, which moves in a horizontal plane at peak accelerations of about 120 m/s² in each direction, possibly simultaneously.

Before the onset of bonding every device, a computerised machine vision system precisely locates the positions and orientations of the substrate and the die mounted onto it. This involves locating the leads on the substrate and bond pads on the die and then transforming and correcting the taught locations for each bond. The vision system is also used for post-bond inspection in monitoring bond placement accuracy and wire sweep.

2 Programmable Focussing Mechanism (PFM)

Traditionally, a wire bonder is equipped with a fixed focus vision system of two different magnification levels, high magnification for the die pads and low magnification for the substrate leads. The incessant push for miniaturisation of ICs has resulted in a stacked die architecture, wherein one die is bonded on a substrate and then one or more dies are mounted successively one above the other in a vertical stack. Wire bonding on such multi-tier die stacks needs a vision system with programmable focussing capability for die surfaces at different heights. This is achieved by motorising a relay lens in the high magnification optics [2].

The usable travel range of the PFM is 3 mm with the typical stroke response requirement specified as 0.5 mm in 30 ms with a position repeatability of 10 μ m. Although absolute de-centration of 50 μ m is allowable between the moving lens and fixed lens, the repeatability in image position and by implication, the repeatability in off-axis deviation of the moving lens is limited to a stringent 1 micron. The tilt excursion of the moving lens about any axis normal to motion has to be less than 12 arc minutes. The maximum “ON”-time during image capture on the largest of dies is specified as 5 seconds and a maximum process duty of 10 %.

Fig. 1a shows a schematic diagram of the PFM. The moving lens is affixed in a cylindrical tube, which is suspended on two flexure disc assemblies. The space between the flexures is utilized to house a small voice coil motor, which actuates the moving lens and precisely controls its axial position in closed loop servo mode using feedback provided by an LVDT. The position of the fixed lens can be adjusted and locked as and when required for different batches of packages to be bonded. This extends the overall focus range of the optics to the required 3mm, while keeping the stroke requirement of the moving lens to within ± 0.7 mm for any given package, leading to a compact design.

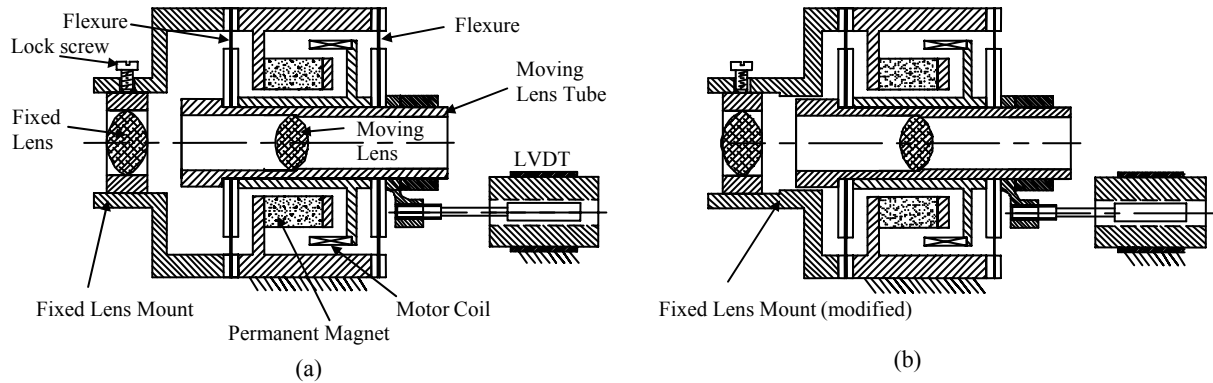


Fig. 1 Schematic diagrams of the Programmable Focusing Mechanism; (a) un-damped, (b) with integral air damper

Fig 1b shows a slightly modified version of the PFM in which the design of the fixed lens mount has been altered to surround the moving lens tube over a significant portion of its length such that a small radial clearance ($\sim 10\text{-}15\ \mu\text{m}$) exists between the two. This simple modification introduces substantial air damping in the system when air is driven through the annular gap, to and from the space between two lenses. The objective of this damping is to attenuate the residual vibrations at the end of the stroke, thus reducing the settling time and speeding up the process.

3 Design of flexure bearings

Stringent demands on the repeatability of lens position and orientation, call for the use of flexure bearings. Flexures offer incomparably high repeatability of motion since motion is enabled through elastic deformation of the material. Absence of relative motion between two contacting parts leads to frictionless, wear-free operation. Thus, if designed adequately to withstand fatigue, flexure bearings can easily outlast rolling element bearings and slider bearings. They are relatively inexpensive to produce and simple to assemble.

Fig. 2 shows elements and assembly of the flexure bearing. A flexure disc is photo-chemically etched out of a flat metallic sheet to give three flex-arms placed 120° apart. These flex-arms are partly straight and partly arc-shaped to best utilise the available space while minimising the axial stiffness. Boundary constraints for the flexures are defined by sandwiching them between spiders in the central moving portion and peripheral spacers on the outer section, which is stationary. As shown in Fig. 1, a pair of such flexure discs separated by a distance, forms the bearing.

3.1 Finite Element Analysis of the flexures

Simple analytical methods are inadequate in predicting the operating characteristics of the flexure bearing due to the mutual coupling effect between the three flexural arms making up the bearing. Use of finite element analysis (FEA) method in tackling such a geometrically non-linear problem thus becomes indispensable. FEA has been conducted with a view to examine, apart from the stress distribution, characteristics such as axial stiffness, radial stiffness and extent of parasitic rotation as a function of axial displacement. Fig. 3 shows the FEA results for a single flexure.

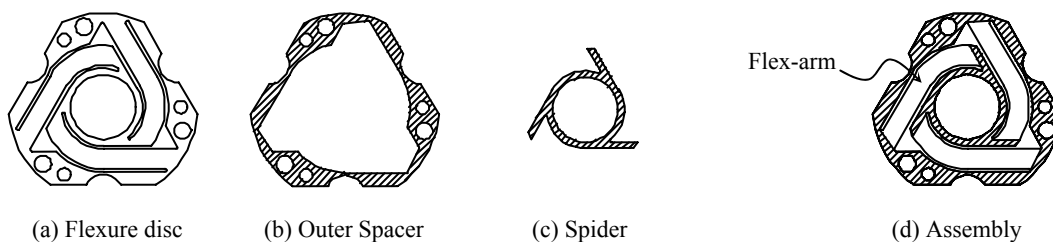


Fig 2. Flexure bearing components and assembly

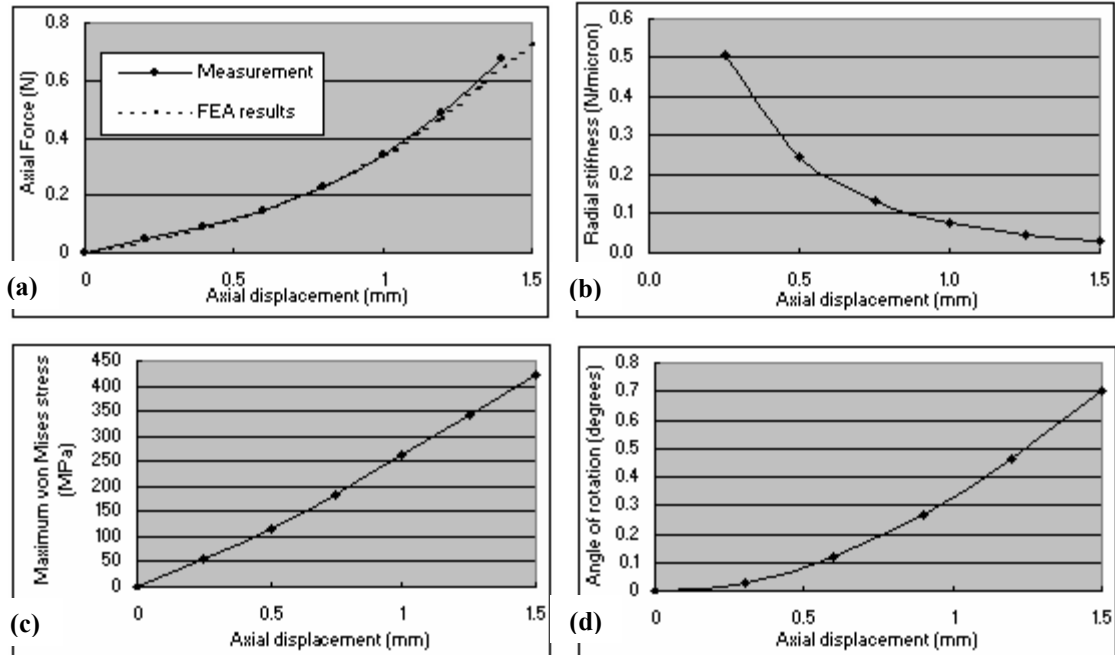


Fig. 3 FEA results for single flexure disc; (a) Axial force (b) Radial stiffness (c) Combined Stress (d) Parasitic rotation

As shown in Fig. 3a, the measured values of **axial force** corroborate well with those predicted by FEA. The restoring force due to the flexure bearing (a pair of flexure discs) for 0.7 mm axial displacement is about 0.4 N. This maximum axial force exerted by the flexure bearing, forms an input to motor design.

Radial stiffness of the flexure bearing (Fig. 3b) reduces rapidly as the flexures move out of plane. The maximum lateral force on the flexures is the inertial force on account of the high acceleration of the XY table, perpendicular to the flexure axis. In the present case, the suspended mass is only about 12 gm. At a maximum acceleration of 120 m/s^2 , the inertial force is 1.44 N. For a stroke of 0.7 mm, the effective radial stiffness of the bearing is about 0.31 N/ μm . Thus the worst-case lateral deflection of the bearing is about 4.6 μm . However this deflection is fully recovered as soon as the table comes to rest, since the equivalent stress is well within the elastic limit.

For a stroke of 0.7 mm, the maximum von Mises **stress** under combined axial and lateral loading is about 171 MPa, Since the maximum stress level is well below the endurance limit of the material, the flexures will have a virtually unlimited life even for completely reversed loading. This has been borne out in the accelerated reliability tests conducted on eight flexure discs which could sustain over 200 million reversed cycles without failure, even at +/- 1.5 mm (double the required stroke) giving strong confidence as regards the fatigue life of the flexure bearing.

Deflection of a simple cantilever flexure through a certain distance is always associated with a second order **parasitic error** in an orthogonal direction towards the fixed end of the flexure. In the present design, the parasitic errors of all the three flexures are so coupled that the resultant error motion is a small rotation about the translation axis. Fig.3d shows the variation of this angular motion with axial displacement of the lens tube. The rotation being very repeatable and only a small fraction of a degree, does not have any adverse impact on the imaging process since the moving optical component is an axi-symmetric lens.

4 Voice Coil Motor (VCM) design

Since the travel range of the PFM is only +/- 0.7 mm, a voice coil motor of cylindrical topology has been adopted. This consists of an axially magnetised NdFeB ring-magnet of high energy density (48 MGOe) and soft iron poles forming a working gap with a radial magnetic field. A copper coil suspended in the working gap (see Fig. 1) develops the axial actuating force, the direction of which depends on the direction of coil current.

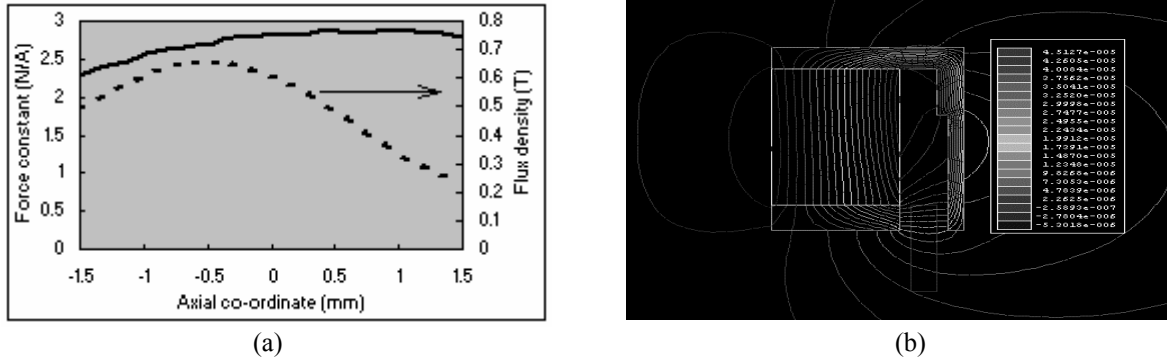


Fig. 4 Electromagnetic FEA results, (a) Gap flux density and force constant variation and (b) flux distribution

4.1 Electromagnetic FEA

The VCM has been optimised using electromagnetic FEA, the results of which are summarised in Fig.4. The maximum flux density of 0.65 T occurs at a location about 0.5 mm from the middle towards the outer end of the working gap. However, the force constant increases from 2.3 N/A at the outer extreme of the stroke to a maximum of about 2.9 N/A close to the inner end. This is because as the coil moves inside the gap, it can also utilise the substantial leakage flux emanating from the magnet as seen in Fig. 4b. In the region of interest, i.e. ± 0.7 mm, the variation in force constant is only about $\pm 4\%$.

Assuming a conservative average force constant of 2.3 N/A, the maximum holding current was expected to be 0.17 A. In actual practice, the current was measured to be 0.2 A and the corresponding temperature-rise in the coil was less than 1 °C for the specified maximum “ON”-time of 5 s. The worst-case r.m.s. force is a time weighted average of the maximum flexure force and the inertial force in the axial direction. For a 10% duty cycle, the estimated worst-case r.m.s. force is only about 0.09 N. Hence the thermal test is sufficiently conservative and safe.

5 Conclusion

The combination of voice coil motor and flexure bearing has resulted in a very compact and robust motion stage for the lens focussing application, giving very high position repeatability and overall reliability than would be possible using conventional rolling element bearings and/or rotary-to-linear actuator. Tests aimed at evaluating the dynamic performance have been conducted on several prototypes of the PFM, using a dedicated, auto-tuneable FPGA-based controller board [2]. The lens can be moved from its home position to either end of the stroke range of ± 0.7 mm in less than 14 ms, well within the required specification. Imaging tests have also yielded satisfactory results [2]. Patents have been filed in several countries [3]. The PFM has been successfully deployed in the field.

References

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