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Design and Fabrication of Microelectromechanical Systems

An attempt has been made to summarize some of the important developments in the emerging technology of microelectromechanical systems (MEMS) from the mechanical engineering perspective. In the micro domain, design and fabrication issues are very much different from those of the macro world. The reason for this is twofold. First, the limitations of the micromachining techniques give way to new exigencies that are nonexistent in the macromachinery. One such difficulty is the virtual loss of the third dimension, since most of the microstructures are fabricated by integrated circuit based micromachining techniques that are predominantly planar. Second, the batch-produced micro structures that require no further assembly, offer significant economical advantage over their macro counterparts. Furthermore, electronic circuits and sensors can be integrated with micromechanical structures. In order to best utilize these features, it becomes necessary to establish new concepts for the design of MEMS. Alternate physical forms of the conventional joints are considered to improve the manufacturability of micromechanisms and the idea of using compliant mechanisms for micromechanical applications is put forth. The paper also reviews some of the fabrication techniques and the micromechanical devices that have already been made. In particular, it discusses the fabrication of a motor-driven four-bar linkage using the "boron-doped bulk-silicon dissolved-wafer process" developed at The University of Michigan's Center for Integrated Sensors and Circuits.

Introduction

Microelectromechanical systems (MEMS) is an emerging area of research that makes possible the integration of movable mechanical elements with electronic circuits and sensors at micron level. Petersen (1982), in his paper entitled "Silicon as a Mechanical Material," remarked that "the basis for micromechanics is that silicon, in conjunction with its conventional role as an electronic material, and taking advantage of an already advanced microfabrication technology, can also be exploited as a high-precision, high-strength, high-reliability mechanical material, especially applicable wherever miniaturized mechanical devices and components must be integrated or interfaced with electronics." Since the early eighties, many *movable* micromechanical structures such as cantilevers, diaphragms and bridges, have been widely used in microsensor related applications. However, the *movement* in those microstructures was by virtue of *elastic deformations* and *not rigid body motions*. Fan, Tai and Muller (1987) reported the fabrication of the first movable micromechanical elements with joints that allowed rotary or translatory motion between different links. This was considered to be a significant development as it demonstrated that relative rigid body motions are possible in the micron-scaled mechanical structures and became the harbinger of many other technological advances in the area of MEMS.

We begin with a brief overview of MEMS highlighting some aspects of their design and fabrication. It is then followed by a review of microfabrication processes and microactuators. Next, we describe a bulk micromachining process in detail, which is used in fabricating motor-driven micro four-bar linkage. Finally, we explain the importance of alternate physical forms and compliant mechanisms in enhancing the scope of MEMS.

Overview of MEMS

Many researchers have demonstrated the feasibility of their microfabrication technologies by building a variety of micromechanical elements (Fig. 1). They include rotary motors, linear actuators and resonators, springs, grippers and gears all of which are in the size range of few tens of microns to few hundreds of microns. The most attractive feature of these tiny devices is the fact that they are all batch-produced and the fabrication processes used to make them are compatible with the integrated circuit (IC) chip processing technology. This implies that micromechanical structures can be integrated with electronic circuits using the same processes and techniques. Although the applications of MEMS are not fully envisioned at this stage, many researchers believe that they can be used in numerous areas including optics, fluidics, material handling in electronic component assembly, microscopy with microprobes such as STM's (scanning tunneling microscopes) and AFM's (atomic force microscopes), microsurgery and in bioen-

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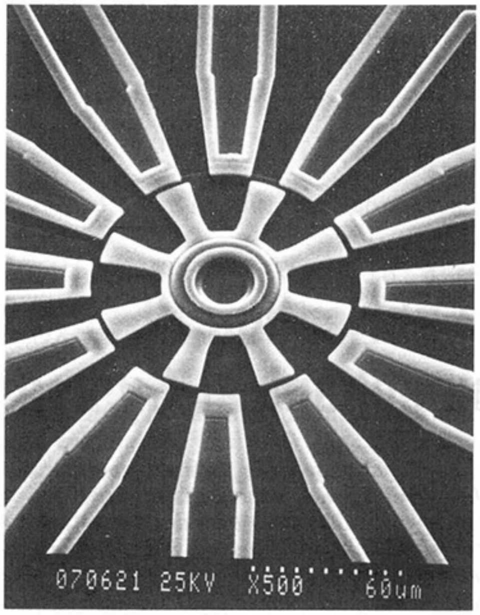

Fig. 1(*a*) Electrostatic rotary micromotor (Mehregany et al., 1992)

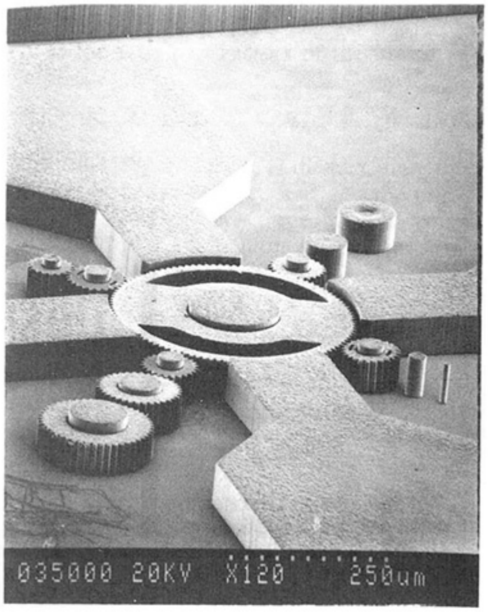

Fig. 1(*c*) Micro magnetic motor (Guckel et al., 1991)

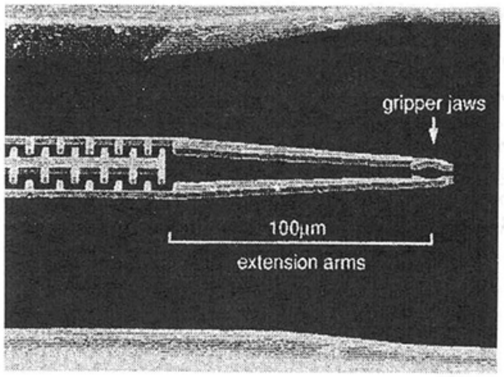

Fig. 1(*b*) Polysilicon microgripper (Kim et al., 1992)

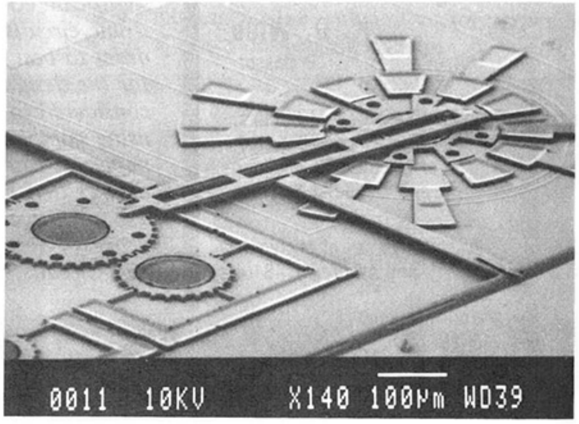

Fig. 1(*d*) Electrostatic rotary motor actuated micro four-bar mechanism (Gianchandani and Najafi, 1992)

gineering for handling cells and macro molecules (Fujita and Gabriel, 1991; Jara-Almonte, 1989) and microflight (Crary et al., 1992; Shimoyama et al., 1992).

The advantages and limitations of the microfabrication technologies suggest that the design and fabrication of MEMS is completely different from mere miniaturization of macro machines (Fujita and Gabriel, 1991). Considerable disparity exists in the design and fabrication of micro and macro mechanical systems. The reason for this is twofold. First, the limitations of the emerging microfabrication technologies give way to new exigencies that are nonexistent in the macro machinery. One such difficulty is the virtual loss of the third dimension because, most of the micro structures are fabricated by IC based micromachining techniques that are predominantly planar. The mechanical world, however, is essentially three-dimensional. Even the so called *planar mechanisms* need to be built in different parallel planes in order to avoid the interference among their different links while the mechanism is in motion. This difficulty can either be surmounted with further breakthroughs in microfabrication technology or circumvented with novel designs. Second, the batch-produced micromechanical devices that require no further assembly whatsoever, offer significant economical advantage over their macro counterparts. Furthermore, electronic circuits and sensors can be integrated with mechanical elements. In order to take full advantage of these features, it becomes necessary to establish new concepts for the design of MEMS. One way to obtain new designs is by transforming the designs of the macromachinery to suit the needs of the micro domain. The development of entirely new configurations for MEMS is also required. Before addressing the design issues, it is necessary to give an overview of microfabrication techniques.

Fabrication of MEMS

Excluding a few specialized techniques such as diamond point micromachining (Trimmer and Jebens, 1989), micro-EDM (Masaki et al., 1990), etc., many other microfabrication techniques can be grouped into two major categories: *bulk micromachining* and *surface micromachining*. In bulk micromachining, the desired features are carved out of a bulk piece of material using reagents such as acids or bases. The reagents work in conjunction with a protective resist layer that masks the areas that are to be left uncarved. On the other hand, in surface micromachining, the desired features are formed by selective deposition and removal of material in alternating layers (Jara-Almonte, 1989). Both of them are compatible with IC processing techniques.

Polysilicon thin-film technology is perhaps the most popular surface micromachining process. In this method, polysilicon is used as the structural layer and *phosphosilicate glass* (PSG) as the sacrificial layer. For instance, to make a revolute joint, the pin and the second member that has a matching hole and rotates around the pin, are both formed by selectively depositing polysilicon in two separate layers with a dissolvable *sacrificial* layer in between. The same technique can be used to fabricate gears, springs, flat links and electrostatic rotary and linear actuators (Fan et al., 1987; Kim et al., 1990). Using this technique Fan et al. (1987) built the first micro four-bar linkage. The linkage, however, was not equipped with any actuation. The maximum vertical thickness possible with this technology is approximately 2 μm per layer.

The boron-doped bulk silicon dissolved-wafer process is a versatile bulk macromachining process using which microstructures of thickness 1 μm to 25 μm with any lateral shape can be manufactured. This process also allows the stacking of multiple layers of silicon microstructures. Recently, the mechanical coupling between an electrostatic motor and a gear has been achieved with this technology (Gianchandani and Najafi, 1992).

Another important method for the fabrication of microstructures is based on *deep-etch synchrotron lithography and high precision replication processes* known under the acronym of "LIGA" (in German: Lithographie , Galvanoformung, Abformung) (Mohr et al., 1990). The LIGA process allows the fabrication of microstructures of any lateral shape with structural heights of more than one hundred microns (Mohr et al., 1991). This process allows the use of different materials including plastics, metals and ceramics. The LIGA process is a combination of deep-etch X-ray lithography, electroforming and molding techniques. By combining the original LIGA process with a sacrificial layer technique, it is possible to fabricate micro structures partly fixed and partly movable on top of a substrate (Mohr et al., 1991). This process requires sophisticated X-ray equipment and is expensive. It also requires assembly of fabricated structures. By fabricating such microstructures with nickel and its alloys and by exploiting their property of ferromagnetism, Guckel et al. (1991) have produced magnetically driven micromotors.

The majority of the micromachining techniques described above have been used to build microactuators. A brief discussion of microactuators follows.

Microactuators

Microactuators are important components of MEMS. Unlike the macroactuators which most commonly use electromagnetic force, a majority of the existing microactuators are governed by electrostatic force. The electromagnetic forces do not scale well into the micro domain, since it becomes difficult to obtain the current needed in very small electromagnetic motors (Trimmer and Gabriel, 1987). However, some efforts to use magnetic force have been reported (Wagner and Berscke, 1991; Kim et al., 1990; and Guckel et al., 1991). Few other microactuators employ different energy sources including piezoelectricity, shape memory alloy and thermal energy. A microbubble powered actuator (Lin et al., 1991), an array-driven ultrasonic microactuator (Furuhata et al., 1991) and several other types have been proposed, but they can only be used in specific applications. A detailed account of various microactuators is reported by Fujita and Gabriel (1991). The generic actuators, rotary and linear types, which are most useful in building micromachines are discussed next.

Rotary Actuators. There are two kinds of electrostatic rotary motors: *side-drive* motors and *wobble* or *harmonic* motors. Side-drive motors are comprised of a rotor with poles which resembles a gear, and stator poles placed on a circle surrounding the rotor and are connected in two or more phases. The successive excitation of each phase makes the rotor spin in synchronization. The rotational speeds of these motors range from 3–15000 rpm and the motors can deliver a torque of a few pNm (Mehregany et al., 1990). The operational principle of the other type of micromotor is the same as that of the harmonic motor. The advantages of this over the side-drive motor are the reduction in friction as a result of point contact and higher torque due to the reduced gap between the rotor and the stator. Several variations of this motor are developed and reported by Jacobsen et al. (1989), Trimmer and Jebens (1989), Mehregany et al. (1991) and others. Although a wide variety of micromotors have already been built, the mechanical coupling of the actuators with the mechanisms has been achieved only in a few cases (Gianchandani and Najafi, 1992; and Guckel et al., 1991). One such motor and its fabrication process will be described later in this paper.

Linear Actuators. A simple linear electrostatic motor has a pair of parallel plate capacitors differentially misaligned in the longitudinal direction. When a voltage is applied to the misaligned plates, a force is exerted to bring the plates back into the alignment. This is the operational principle of all the electrostatic linear actuators (Trimmer and Gabriel, 1987). To obtain large forces, several sets of misaligned plates are arranged in the form of two comb-like structures so that the teeth of one comb slide between the gaps of the other. Both resonating and nonresonating linear actuators have been made (Guckel et al., 1989; Tang et al., 1989; and Hirano et al., 1991). The measured displacements of linear actuators range from a fraction of a micron to 10 μm. Such actuators are useful in applications involving very fine positioning. Kim et al. (1990) report the fabrication of an electrostatic, comb-driven polysilicon microgripper which is a natural application of the linear actuators with small displacements. The challenge lies in using the linear actuators to drive other mechanisms carrying load over a long range like the hydraulic and pneumatic cylinders of the macro world.

Coupling of Motors and Mechanisms

Neither the four-bar mechanism fabricated by Fan et al. (1987) using a surface micromachining technology, nor the three degree-of-freedom planar mechanism of Behi et al. (1990) was equipped with an actuating device, although the micromachining techniques used in both cases permit the fabrication of a micromotor. The reason for this can be explained as follows. Most of the micromachining techniques limit all the mechanical elements to one layer due to the inherent difficulties in the processes. Furthermore, in all electrostatic micromotors the rotor is surrounded by the stator poles, which are in the same layer. Thus, the mechanical coupling of the rotor with other movable elements becomes impossible unless the separate components are assembled afterwards. Post-assembly of micromechanical elements is very difficult, time consuming and expensive due to the lack of automated *microtools*. Hence, the ability to fabricate individual micromechanical elements is not sufficient to build a micromachine that can be used to accomplish a useful task. By the same token, the ability to build a microactuator is not sufficient unless it can be coupled with mechanisms to actuate the latter.

A few micromachining techniques, however, are amenable for the mechanical coupling between motors and mechanisms. Guckel et al. (1991) used a LIGA-based technique to fabricate a magnetic micromotor made of nickel and its alloys which are ferromagnetic. In this case, the gaps between the stator poles were wide enough to attach a small gear externally to the rotor. However, this technique requires assembly to some extent. Gianchandani and Najafi (1992) have integrated a motor and a gear with a link using a bulk micromachining process.

Design Building Blocks for MEMS

The ability to fabricate a few arbitrarily selected joints and mechanisms does not ensure the potential to build a complete micromechanical system. The processes used to fabricate the varied elements should be compatible with each other and the combined process should satisfy the requirement of batch production without manual assembly. It is hence necessary to identify some generic mechanical components and processes using which a wide variety of micromechanical systems can be designed and manufactured with *inter-process compatibility*. But, the available micromachining techniques are so diverse that a component made using one method cannot possibly be integrated with components of another method. Future enhancements to the microfabrication processes should pay more attention to this aspect.

Improving an existing process to fabricate arbitrarily chosen mechanisms might become repetitive, if the selected mechanisms are not distinct enough to encompass different varieties of motions. A systematic identification of a set of joints and mechanisms will lead to a comprehensive set of building blocks for MEMS. If an existing microfabrication process is improved further so that it is possible to fabricate all the identified building blocks, it will then allow the construction of a multitude of micromachines. The bulk micromachining technology developed at The University of Michigan is being investigated to identify manufacturable joints. A brief description of the process follows.

Fabrication Process. The bulk silicon technology of The University of Michigan's Center for Integrated Sensors and Circuits allows for the fabrication of mechanical structures of thickness from 0.5 μm to 15 μm and of any shape in the plane normal to the direction of the thickness. Therefore, the technique allows for the fabrication of revolute and prismatic joints, levers, gears, cams, etc. in a single layer. The technique also permits, in batch fabrication, the stacking of such layers, one on top of the other, a capability that is necessary for the proper functioning of a mechanism without interference among the links, while the mechanism is in motion and to facilitate *mechanical transmission* of motion among various links. This technology is based on a "boron-doped bulk silicon dissolved-wafer process," which is briefly described below.

Boron-doped Bulk Silicon Dissolved Wafer Process. The process consists of fabricating two types of patterned wafers, one made of *standard p-type (100) silicon wafer* and the other is of *#7740 Corning glass.* The silicon wafers are processed to obtain the shapes of moving links of the mechanism, while the glass wafer serves the purpose of a ground link. The adjacent moving links need to be arranged in different parallel planes in order to avoid interference between them. Thus, one or more silicon wafers may be necessary depending on the complexity of the planar mechanism being made. The patterned silicon wafers are bonded to the glass wafer. Therefore, some parts of the silicon wafer, such as the pins of the revolute joints, which involve a connection with the ground link, get bonded to the glass wafer and thus become a part of the ground link.

Fig. 2(*a*) Processed silicon wafer (upright) (*b*) bonding of silicon wafer (inverted) to glass

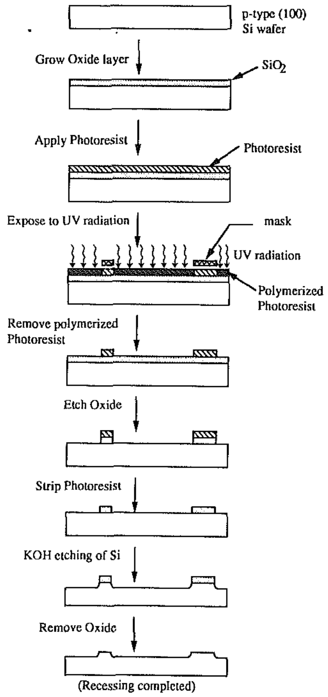

Fig. 3 Recessing of the silicon wafer

Processing of Silicon Wafers. The processing technique facilitates the fabrication of any planar shape and any single wafer can consist of a step, i.e., in a wafer, there can be two different thicknesses, t_1 and t_2, as shown in Fig. 2(*a*). However, the overall thickness ($t_1 + t_2$) cannot exceed 15 μm. Holes and empty spaces can be provided in the silicon wafer wherever they are necessary. Another important thing to be noted is the flipping of the patterned silicon wafer upside down, when it is bonded to the glass wafer. Hence, the silicon wafer in Fig. 2(*a*) will be bonded to the glass as shown in Fig. 2(*b*). Many mechanical elements, such as gears, cams, pin jointed bars etc., can be made in the same way as the stepped part shown in Fig. 2(*a*). The patterning method is described with regard to obtaining a representative structure shown in Fig. 2(*a*). In the discussion ahead, many details regarding the chemical reagents used are deliberately omitted and the terminology has been simplified for the sake of clarity.

The process consists of two stages: *recessing with KOH etch* and *boron diffusion* into the silicon. Recessing is done in those portions of the silicon wafer where projected parts of thickness t_1 are needed. Boron diffusion is performed to obtain the remaining part. Both steps use *photolithographic masks* to selectively remove the material in the unwanted portions. These two stages are explained below and are illustrated in Figs. 3 and 4.

Recessing. First, on a silicon wafer of about 0.4 mm thickness, an oxide layer is grown in a *pyroletic* steam and *tricloroethane* ambient. The layer of oxide is then patterned for recessing, which involves etching away the oxide layer everywhere except in the places where we want projections. This is done by applying a layer of *AZ-1811 photoresist* on top of the oxide layer and polymerizing the photoresist in all the places where there are no projected parts. Polymerizing is done by exposing the photoresist to ultraviolet radiation under a mask. The mask determines the locations of the projected parts. After removing the polymerized portion of the photoresist layer, the oxide is etched by using proper chemical reagents. The oxide under the remaining, nonpolymerized photoresist is, however, not etched away. The remaining photoresist is then stripped completely.

After patterning the oxide as described above, the next step is to etch silicon with a mixture of *KOH, deionized water* and *isopropanol.* Because of the presence of the patterned oxide

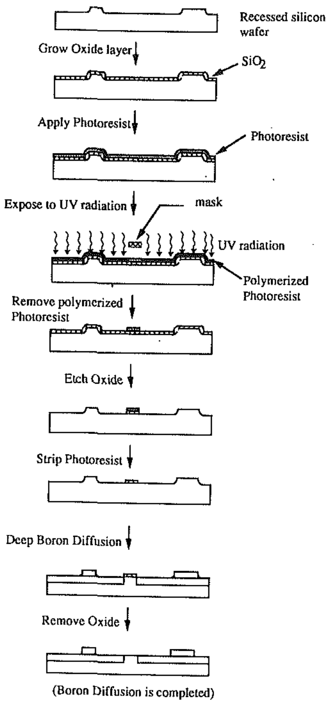

Fig. 4 Boron diffusion of the silicon wafer

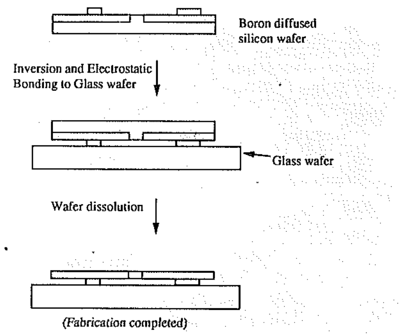

Fig. 5 Bonding of silicon wafer to glass and wafer dissolution

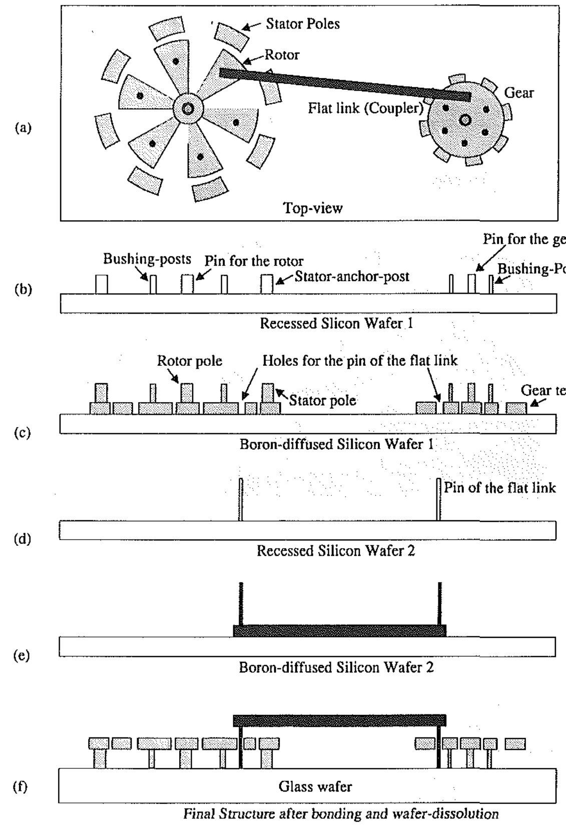

Fig. 6(*a*)-(*f*) Fabrication steps of the motor-driven micro-four-bar mechanism

layer, the silicon under the oxide is protected from the KOH etch and thus, projected parts of the silicon wafer take shape. The process of recessing is completed with the removal of the patterned oxide layer.

Boron Diffusion. The second stage in processing the silicon wafer is the "deep boron diffusion" of the silicon wafer. The processing steps of this stage are illustrated in Fig. 4. As in recessing, the oxide layer is grown and then patterned with the help of a second layer of photoresist, exposure to ultraviolet radiation under a mask and subsequent etching of oxide in the unwanted portions. The second mask used in this patterning defines the planar contours of all the mechanical elements. After patterning the oxide layer, the photoresist is stripped and boron diffusion is performed. The depth of diffusion determines the thickness of the structure. The remaining oxide layer is then removed.

Bonding to the Glass Substrate. A *glass* (#7740 Corning) wafer of approximately 0.8 mm thickness is patterned to form metallic interconnections for lead transfer between silicon and glass and also to provide a proper seating plane upon which the mechanical elements can rest. After patterning the glass wafer, the processed silicon wafer is inverted and electrostatically bonded. Thus, all the top portions of the silicon wafer get bonded to the glass and bottom parts face up. The silicon wafer is then dissolved using *ethylenediamene pyrocatechol.* The boron diffused portion of the silicon wafer remains undissolved and becomes the final fabricated structure. Figure 5 illustrates the final steps of this fabrication process.

Fabrication of a Motor-Driven Four-Bar Mechanism

The four links of the mechanism are: the rotor of the electrostatic motor, the ground link (glass substrate), a gear attached to the ground link with a revolute joint, and a flat link attached to the rotor and the gear links. The rotor is the input link, the gear is the output link and the flat link is the coupler. The rotor and stator poles constituting the micromotor and the output gear link are in one layer. The flat link attached to the rotor and the gear with revolute joints is in the second layer. Hence, two silicon wafers and one glass wafer are needed to fabricate this mechanism. The top view of the fabricated mechanism is shown in Fig. 6(*a*). (The reader may please note that Figs. 6(*a*) through 6(*f*) are schematic diagrams and do not correspond to the mask-patterns of the actual mechanism shown in the subsequent micrographs). It can be seen that bushing action for the rotor and the output gear is achieved by providing six posts below the rotor and the gear. The revolute joint between the rotor and the flat link is obtained by providing a hole in the rotor and a pin under the flat link. The revolute connection between the flat link and the gear is achieved in the same way.

Figures 6(*b*) and 6(*c*) show the first silicon wafer after the completion of recessing and boron diffusion. In Fig. 6(*c*), it can be seen that the holes are provided around the two pins, in between the rotor and the stator poles and on the rotor and the gear in the place where the pins of the flat link go through. Figures 6(*d*) and 6(*e*) show the second silicon wafer after re-

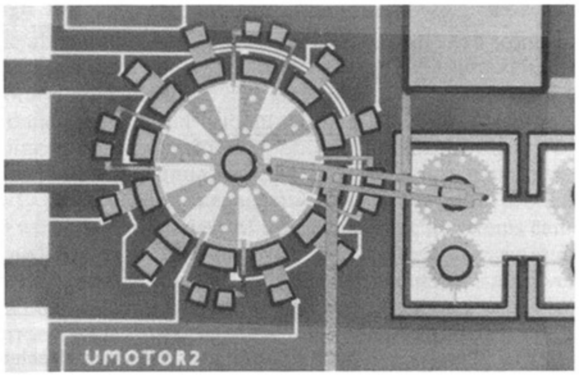

Fig. 7(*a*) Optical photograph of the motor-driven micro-four-bar mechanism fabricated by Gianchandani and Najafi (1992)

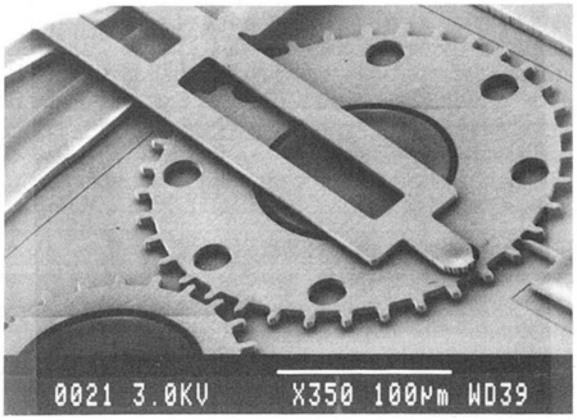

Fig. 7(*b*) SEM view of the micromechanism in close-up

cessing and boron diffusion. The final step is to bond the two inverted silicon wafers to the glass wafer, one after the other, and then dissolving the undoped portions of the silicon wafers. Figure 6(*f*) shows the final structure after bonding the two inverted silicon wafers to the glass wafer, which is patterned with metallic contacts and seating planes.

Figure 7(*a*) is an optical photograph of the micro-four-bar mechanism that has been fabricated by Gianchandani and Najafi (1992) using the process just described. It can be seen that it is a parallelogram linkage in the dead-center position. It needs to be reassembled in a different configuration. The process, however, is capable of fabricating any four-bar mechanism with the exception of those in which the length of the fixed link is exceeded by the sum of the lengths of the two revolving links. The diameter of the rotor is 250 μm and that of the gear is 150 μm. The rotor, stator poles and gear are 5 μm thick. The length of the bushings is about 3 μm. The pins of the coupler link are 12 μm long, thus permitting considerable clearance between the two layers of the mechanism. Figure 7(*b*) is a scanning electron micrograph (SEM) of the connection between the coupler link and the output gear. The two layers of the mechanism are clearly visible in this picture.

New Designs for MEMS

So far the research on MEMS has been concentrated upon building a few planar joints and mechanisms. Hence, the mechanical tasks that can be accomplished with the existing micromechanisms is limited. To make the micromachines more versatile, future developments should aim for microdevices that could give spatial motions. The first step towards that

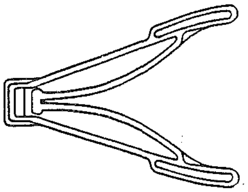

Fig. 8 An example of compliant mechanism (Midha, 1993)

objective is to build an *out-of-plane hinge*, i.e., a revolute joint whose axis of rotation is parallel to the ground plane. The following two joints are proposed to extend the domain of micromachines to three dimensions. The inclusion of spherical joint, bevel gears, camoids, etc., is thought to be premature until the fabrication process acquires the ability to fabricate two basic joints: (*i*) Out-of-plane revolute joint (*ii*) Out-of-plane wedge. Obtaining a precise out-of-plane revolute joint using a planar microfabrication is difficult. Pister et al. (1991) have proposed one form of this joint, but it can neither be attached to the other links, nor can actuation be provided at the joint.

Alternate Physical Forms

Usually the shapes of the contacting portions of the two links, called *elements of the kinematic pairs*, determine the relative motion permitted by the joint between them. These elements decide the *physical form* of the joint. Thus, each joint is associated with a pair of characteristic shapes for its elements, which constrain the relative motion of the links in the desired manner. It is, however, not required to strictly adhere to the prescribed shapes of the elements if one is only interested in approximate, but very similar relative motion between the links. Hence, for instance, an out-of-plane revolute joint can be substituted by a thin flexible cantilever beam. By employing alternate physical forms, the manufacturability can be improved for micro applications.

Compliant Mechanisms

The replacement of the rigid joints by flexible elements greatly enhances the manufacturability of micromechanisms. Further, this idea can be extended to emulate the overall performance of rigid link mechanisms with flexible structures without any rigid joints whatsoever. Such structures called *compliant mechanisms* (Midha, 1993) are described below. Figure 8 shows a compliant mechanism.

The concept of compliant mechanisms was initiated by Midha (1991). Compliant mechanisms, as interpreted here, are single-piece flexible structures that deliver the desired motion by undergoing elastic deformation as opposed to the rigid body rotations and translations of conventional mechanisms. A variety of short-range motions are possible as there is absolutely no limitation on how a properly shaped and sized continuum of material should deform. As these mechanisms are comprised of just one flexible continuum of material (Fig. 8) without any rigid joints (hinges, sliders, etc.), their manufacture becomes extremely simple. If they are properly designed, the task of assembly does not even arise. By virtue of elastic behavior, they can restore to the original configuration upon the release of applied loads, thus eliminating the need for accessories such as springs. The absence of rigid joints also helps in the reduction of friction, wear, the need for lubrication, inaccuracies due to backlash and noise. As flexure is permitted in these mechanisms, they can be equipped with nonmechanical actuation such as thermal, fluid pressure, piezoelectric and even shape-memory alloys (Midha et al., 1992).

From the above description of compliant mechanisms, it is clear that such mechanisms are best suited for micromechanical applications. It was mentioned in the beginning that the earliest micromechanical structures were comprised of mainly cantilevers and diaphragms. The flexibility to perform general mechanical tasks using such devices is hence very limited. Compliant mechanisms are capable of performing many more types of mechanical tasks than simple cantilevers and diaphragms could do, and they can be fabricated as easily as the latter.

While analysis of these mechanisms can be accomplished by means of finite element analysis or the more recently developed *chain algorithm* (Her, 1986), the synthesis is not straightforward. Synthesis, in this context, means obtaining a suitable topology, shape and size of the compliant mechanism which is capable of performing a specified mechanical operation. As yet, there is no systematic method to synthesize compliant mechanisms except that they can be synthesized iteratively with designer's intuition, by imitating by rigid link mechanisms that perform the same desired function. The development of a systematic method of synthesis for compliant mechanisms is part of our ongoing research. The basis for this new method is the *homogenization theory* (Bendsøe, 1992) which enables us to generate valid, if not optimal, *topology, shape* and *size* for compliant mechanisms when forces and displacements are prescribed. The homogenization method is briefly described below.

Homogenization Method. Bendsøe and Kikuchi (1988) developed a novel method to obtain optimal designs for structures starting only with the available space and loading conditions based on homogenization theory. Homogenization theory, originally developed for modeling composite materials, is a mathematical theory for obtaining average elastic moduli of material with periodic micro structures. The essence of Bendsøe and Kikuchi's method lies in the transformation of structural optimization problem into a material distribution problem by the introduction of two material constituents: *substance* and *void*, thus making it a composite material. The highlight of this method is the exclusion of dependence on designer's intuition from the formidable task of synthesis of optimal structures. The synthesis of compliant mechanisms, as stated above, has close resemblance to the synthesis of optimal structures. Yet, they differ significantly because of the additional requirement of desired displacement. The preliminary results of modifications to the existing homogenization method indicate that it is a promising approach to the systematic synthesis of compliant mechanisms (Ananthasuresh et al., 1993).

Closure

The design and fabrication of MEMS is significantly different from those of macrosystems. This is due to the new constraints brought in by the emerging microfabrication techniques. The IC-based micromachining techniques are predominantly planar and therefore limit the micromechanical structures to one or two layers. Consequently, the mechanical power transmission among micromotors and other links of the mechanism becomes difficult. Furthermore, the lack of spatial motions restricts the domain of the microsystems in accomplishing useful mechanical tasks. To exploit the batch-production capability of microfabrication techniques and also to achieve economic feasibility, micromachines are to be batch-produced without assembly. The fabrication processes used to manufacture various micromechanical elements and actuators should be compatible with each other to be able to realize a complete microsystem as per the aforementioned constraints. In view of this, the existing micromachining techniques are to be improved further in a systematic way. Finally, it is noted that by employing compliant mechanisms at micro level the manufacturing difficulties can be bypassed without sacrificing the flexibility in performing a wide variety of micromechanical tasks.

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