High Density Vertical Comb Array Microactuators Fabricated Using A Novel Bulk/Poly-Silicon Trench Refill Technology

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ABSTRACT

This paper reports the development of a new fabrication technology for the implementation of electrostatically-driven vertical microactuators. It combines bulk and surface micromachining techniques to produce thick (>10μm) polysilicon microstructures by depositing 1-2μm thick polysilicon films. Deep (10-15μm) and narrow (~4μm diameter) trenches are RIE etched in a boron doped silicon chassis and are then completely refilled with polysilicon. The polysilicon microstructure and the p++ chassis are both released using EDP. This technology can be used for the fabrication of a variety of microactuators with different electrostatic drive structures that can generate large vertical motion for the polysilicon microstructure out of the plane of the wafer. In addition to allowing the simultaneous formation of polysilicon and p++ silicon microstructures, the technology allows the creation of sub-micron gaps between these two structures, which in turn allows the generation of a large amount of force. Several bridge structures have been fabricated using this technique. Polysilicon fingers and beams as thick as 8μm, and as narrow as 2μm have been fabricated in 4μm-wide trenches in a p++ chassis. A vertical out-of-plane force of about 1μN can be generated using an array of 13, 100μm-long polysilicon beams driven with a 10V signal.

INTRODUCTION

Microactuators have been widely used in many different devices and applications like resonant sensors, micromechanical displays, micromotors, accelerometer feedback drives, micropumps, microvalves, switches, etc. [1]. With dimensions constantly being scaled down using micromachining technology, electrostatic drives are predominantly employed for their higher energy density [1]. The most widely used and practical electrostatic drive that many microactuators utilize are the parallel plate capacitive drive [2], and the lateral interdigitated comb drive [3,4]. The former can generate a substantial amount of force when the gap spacing between the two plates of the capacitor are small (≤1μm), however, the force that it produces is nonlinear with respect to both voltage and electrode separation, resulting in a limited range of motion (typically <2μm). The latter technique, lateral comb drive [3], produces an electrostatic force that is nearly independent of displacement, and hence permits much larger motion parallel to the wafer surface. Both of these actuation techniques have been used successfully in different devices, and both have been fabricated using either surface or bulk micromachining technologies [2,5].

Surface micromachined actuators are most suitable for devices where motion lateral to the wafer surface is desirable, and where large layer thicknesses are not required. For example, the lateral polysilicon comb drives developed by *Tang et. al* [2] can be moved over a fairly large distance lateral to the wafer surface. One shortcoming of polysilicon micromachined devices is the small thickness of the mechanical structure that can be achieved, which is primarily due to the limited thickness (typically a few microns) that can be deposited using CVD techniques. Bulk micromachining technologies do not suffer from this limitation and fabrication processes have been developed that can produce laterally driven microactuators as thick as 15μm [5]. These technologies, however, possess their own limitations, most important of which is their lack of flexibility in forming complex micromechanical systems. While laterally-driven microactuators have been fabricated using both of these technologies, vertically driven microactuating systems have so far been limited to those that utilize parallel plate capacitive drives. By combining bulk and surface micromachining techniques, one can produce more sophisticated micromechanical devices and develop alternative vertical actuation topologies.

This paper reports on the development of a new fabrication technology that combines bulk and surface micromachining techniques by utilizing silicon micromechanics formed from both bulk silicon and deposited polysilicon. The technology allows the fabrication of thick polysilicon microstructures (>10μm), without the need for large deposited layer thicknesses, by using a trench refill technique, and combining thick polysilicon and bulk micromachined microstructures to create three-dimensional micromechanical devices. Using this technology it is possible to form lateral comb drives, as well as *vertical comb arrays* that offer features similar to those produced by laterally-driven microactuators. The proposed vertical comb arrays can produce large deflections (several microns) vertical to and out of the plane of the wafer surface The moveable comb and microstructure is made from polysilicon, while the fixed drive electrode is made out of p++ silicon. In this paper we will discuss in detail the development of this new combined bulk-silicon poly-silicon technology that can be used for the development of a variety of devices, and will discuss its use in vertical comb array microactuators that can produce large motion *vertical* to the wafer surface, in much the same way that *lateral* comb drives can produce motion lateral to the wafer surface.

DEVICE STRUCTURE

A typical microactuator structure is shown in Fig. 1, and is fabricated on a single silicon wafer. This device structure is only a representation of a range of devices that can be fabricated and is chosen because it contains all the main elements needed for different microactuators. It consists of an etch pit spanned by a two-part bridge made up of (i) a flexible mechanical polysilicon (MP) bridge which supports an array of thick polysilicon fingers (or beams), and is suspended over (ii) a rigid p++ chassis containing a number of holes (or slots) through which the fingers (or beams) pass . The MP bridge is the dynamic element of the actuator which deflects on the application of a driving signal applied between it and the p++ chassis. The MP bridge and its array of fingers (or beams) are made by refilling deep and narrow trenches etched in the p++ chassis. The gap between the MP and the p++ chassis on top and on the sidewall of the trench is defined by a LPCVD silicon dioxide and a sacrificial polysilicon (SP) layer which is removed later. Since the trenches are about 4μm wide, it is possible to completely refill and close the trench by depositing polysilicon thin films with a thickness of about 1-2μm. This will allow the formation of narrow (about 2-3μm) and thick (greater than 10μm) polysilicon fingers (or beams) buried within the p++ chassis. Since the thickness of the p++ boron-doped silicon chassis here (typically about 5μm) is smaller than the depth of the trenches (typically 10μm), when the bridge is undercut using a concentration-dependent etchant such as EDP, the polysilicon fingers (or beams) protrude below the lower surface of the chassis by several microns. The extent of this protrusion is defined by the depth of the trenches which can be controlled using the dry etching step that is used to form them. A protective oxide layer prevents MP from getting attacked by EDP while the chassis is undercut. The MP fingers (or beams) protruding below the p++ chassis and suspended through the holes in the chassis, are shown in the cut-away view in

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Fig. 1 (the bridge is shown undercut in the figure). It is also possible to partially remove the mechanical polysilicon over the fingers (or beams) and leave these portions open but connected on the side to the main MP layer at the edges (this will be discussed in more detail later in the paper). A control polysilicon (CP) electrode (not shown in the figure) is deposited on top of the p++ chassis, and is located between the chassis and the MP layer. It is insulated by a layer of oxide, and provides a means to shield the p++ chassis from the MP layer. This is important as will also be discussed in the paper. The above structure utilizes features offered by both surface and bulk micromachining. It allows the formation of thick microstructures made from polysilicon, and provides the capability to form vertical comb arrays that can be used in a vertical drive actuation scheme similar to that used in laterally-driven comb microstructures.

FABRICATION

The fabrication process requires seven masks, and involves both surface and bulk micromachining techniques, as illustrated in Fig. 2. On a standard, p-type <100> silicon wafer, using a thermal masking oxide, we perform deep boron diffusion at 1175°C for 2.5 hours to achieve a 5µm boron etch stop depth, which defines the thickness of the rigid p++ chassis. The boron diffusion is masked from the regions where the etch pit is to be formed to allow access to, and final etching of the undoped silicon needed for releasing the p++ chassis. This chassis functions as the skeletal frame for the refill process and as one of the two drive electrodes in the vertical comb arrays.

This is followed by the deposition of 1000Å of LPCVD silicon dioxide (#1), and 4000Å of polysilicon (which forms the control polysilicon, CP). The oxide insulates the polysilicon from the chassis. The CP layer is now doped with phosphorus, and a thin layer of oxide is grown in preparation for the second masking step. The CP layer is patterned using an RIE process to define only its outer boundaries; the RIE etch terminates on the silicon substrate below CP. Next, a thin layer of oxide is deposited on the CP layer, and the wafer is prepared for the deep RIE trench etching process. A 2500Å layer of aluminum is deposited on the wafer and patterned to expose those areas where the deep trenches are to be formed. RIE etching is now used to etch through the control polysilicon layer, the oxide layer, and the single crystal silicon underneath to form the deep trenches [5]. This RIE etch is done using 17.5sccm of SF_6 and 7.5sccm of O_2 at a pressure of 5mT, a power of 60W for about 100min; the etch rate is about 0.1µm/min. The RIE etches through the doped p++ silicon into the undoped silicon and forms a narrow (4µm wide) and deep trench (~10µm deep). Because all etching is done through the same mask and in one step, the control polysilicon is self-aligned with the deep trench. This ensures that CP covers the top surface of the chassis everywhere.

A thin LPCVD oxide (#2, ~2500Å) is now deposited to conformally cover all the exposed silicon regions (polysilicon as well as the trench sidewall), and is followed by the deposition of a 1µm-thick sacrificial LPCVD polysilicon (SP) layer. The SP layer thickness together with the oxide #2 and oxide #3 thicknesses (oxide thicknesses are negligible) determines the finger to chassis gap distance, and can be changed easily to accommodate different gap separations between the polysilicon fingers and the p++ chassis. The fourth masking step is used to pattern the SP layer (Fig. 2b). After the SP layer is patterned and removed in the areas where anchors for the MP layer are to be created to the substrate, a 2500Å LPCVD oxide (#3) and 1.5µm LPCVD polysilicon layer (MP) are deposited. This third polysilicon layer (MP) refills the trenches and planarizes the wafer for subsequent processing. This layer when patterned forms the dynamic bridge-component of the actuator as shown in Fig. 2c. It is also possible to selectively remove part of the MP layer over the regions where the fingers or beams are located (as shown in Fig. 2c). Note that this is required for the fabrication of vertical comb arrays. In order to do this, a high pressure isotropic RIE etch is performed through a mask. This etch will remove the top part of the MP layer and part of polysilicon refill in the trenches to achieve the desired height for the polysilicon beams and fingers.

The ensuing and final furnace step is the deposition of an LPCVD oxide layer (#4) which will serve to protect the MP layer from the EDP etch. This oxide is patterned to (i) provide access through etch windows for the EDP to undercut the structure; (ii) remove the sacrificial layer, (Note that oxide layers #2 and #3 are patterned to provide a passage for EDP to etch SP and to protect MP and CP from being attacked); and (iii) provide contact openings for the metal lines and pads. After the oxide patterning step, Cr/Au is deposited and patterned to form bonding pads and make connections to the three layers (i.e. p++ silicon, MP, and CP). The final step of the process is the removal of SP and undercutting of the bridge (Fig. 2c,d). Undercutting of the bridge is possible because it is aligned 45° to the major flat of the wafer. The etch pits 'V' outward from each side of the bridge till the bridge is completely undercut which takes 3.5 hours. The SP layer is also etched in the same step, which results in releasing the MP bridge and fingers which are encapsulated by the protecting oxide shell. This oxide shell is removed by a brief BHF dip to release the final structure as shown in Fig. 2d.

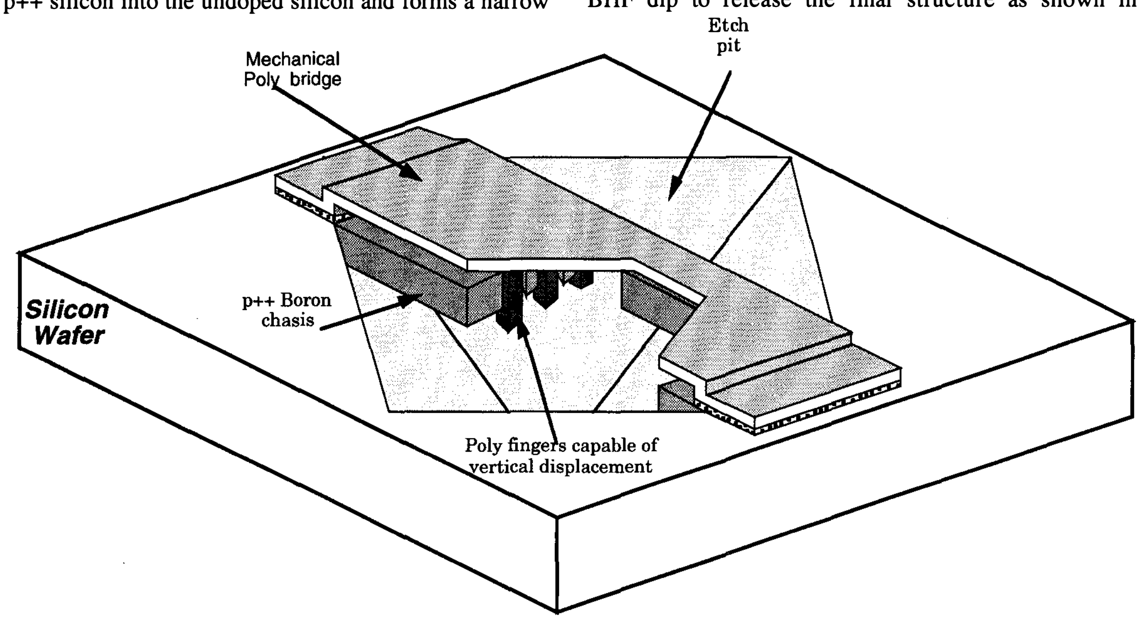

Figure 1: Three-dimensional view of a microactuator structure. It contains a p++ chassis with holes and slots through it, a mechanical polysilicon layer that is supported on the p++ chassis and fills up the holes, and a control polysilicon which shields the p++ chassis and the MP layer for proper device operation.

FABRICATION RESULTS

The above fabrication process has been used to fabricate a number of prototype microstructures. Figure 3 shows a SEM photograph of a bridge structure fabricated using this technology. One can see the etch pit, which is about 400μm deep, and the combined polysilicon/p++ silicon bridge spanning the etch pit. The bridge is about 300μm long, 200μm wide. Figure 4 shows a close-up SEM view of the MP polysilicon bridge, which is about 1.5μm thick, and the p++ bridge which is about 5μm thick. One can observe the array of polysilicon fingers on the underside of the polysilicon bridge. Figure 5 shows a close-up view of one of the polysilicon fingers; note that the p++ chassis is broken to reveal the polysilicon finger. The finger is about 7μm high, and has a bottle-like shape. The shape is determined by the fact that the deposition of the sacrificial polysilicon is not quite conformal around the top edges of the trench and tends to build up there. Therefore, the neck is somewhat narrower than the body of the finger. This figure also shows the sidewall of the p++ chassis. Figure 6 shows a view from the underside of the p++ chassis. One can easily see the protruding fingers of polysilicon from this angle. These fingers extend below the lower side of the chassis by about 1.5μm. Deeper RIE etch can be used to form a deeper trench and a thicker polysilicon finger or beam.

APPLICATIONS

The above technology allows the fabrication of a number of different actuator topologies and structures. The polysilicon finger shown in Fig. 6 can be driven electrostatically by applying a voltage between the MP layer and the p++ chassis. The control polysilicon plays an important role in any of these actuator structures. It serves as a shield between the p++ chassis and the MP layer. When the MP layer is to be attracted to the p++ chassis (Mode 1), a voltage can be applied between the CP and MP layers, thus pulling the MP bridge down (as in a parallel plate capacitive drive).

When the MP bridge is to be pushed away from the p++ (that is pushed away from the substrate), then a different actuator structure will be needed, as illustrated in Fig. 7. In this microactuator, after the MP is deposited, a portion of it is selectively removed, using an isotropic dry etching process, in areas where actuator beams are to be formed. The actuating polysilicon beams are connected to the main body of the MP bridge at their ends. The gap between the beam and the p++ chassis is defined by the thickness of the sacrificial layer. To create repulsion between MP and the p++ chassis (Mode 2), a voltage is applied between MP and the p++ chassis with CP being shorted to MP. The electric field between the chassis and the MP layer pulls the MP layer up till the top surface of the polysilicon beam is aligned with the top surface of the p++ chassis. The operation is similar to that of laterally-driven combs [3]. However, this structure can generate a much larger force per unit area than lateral actuators because: i) the polysilicon beams can be made to be several hundred microns long, and therefore provide a much longer edge between the p++ chassis and the ploysilicon beam; and ii) the gap between the two layers can be easily made to be much smaller (<1μm) than practical with the surface micromachined lateral combs. Analytical calculations and electrostatic simulations using FASTCAP [6] have shown that a force of about 1μN can be generated using only an array of 13, 100μm long beams with 10V drive signal.

CONCLUSIONS

We have reported the development of a new fabrication technology for the implementation of electrostatically-driven vertical and lateral microactuators. It combines bulk and surface micromachining techniques to produce thick (>10μm) polysilicon microstructures by depositing 1-2μm thick polysilicon films. Deep (10-15μm) and narrow (~4μm diameter) trenches are etched in a boron doped silicon chassis and are then completely refilled with polysilicon. The polysilicon microstructure and the p++ chassis are both released using EDP or KOH. This technology can be used for the fabrication of a variety of microactuators with different electrostatic drive structures that can generate large vertical motion for the polysilicon microstructure out of the plane of the wafer. In addition to allowing the simultaneous formation of polysilicon and p++ silicon microstructures, the technology allows the creation of sub-micron gaps between these two structures, which in turn allows the generation of a large amount of force. Analytical and electrostatic simulations using FASTCAP have shown that a force of about 1μN can be generated using only an array of 13, 100μm long beams.

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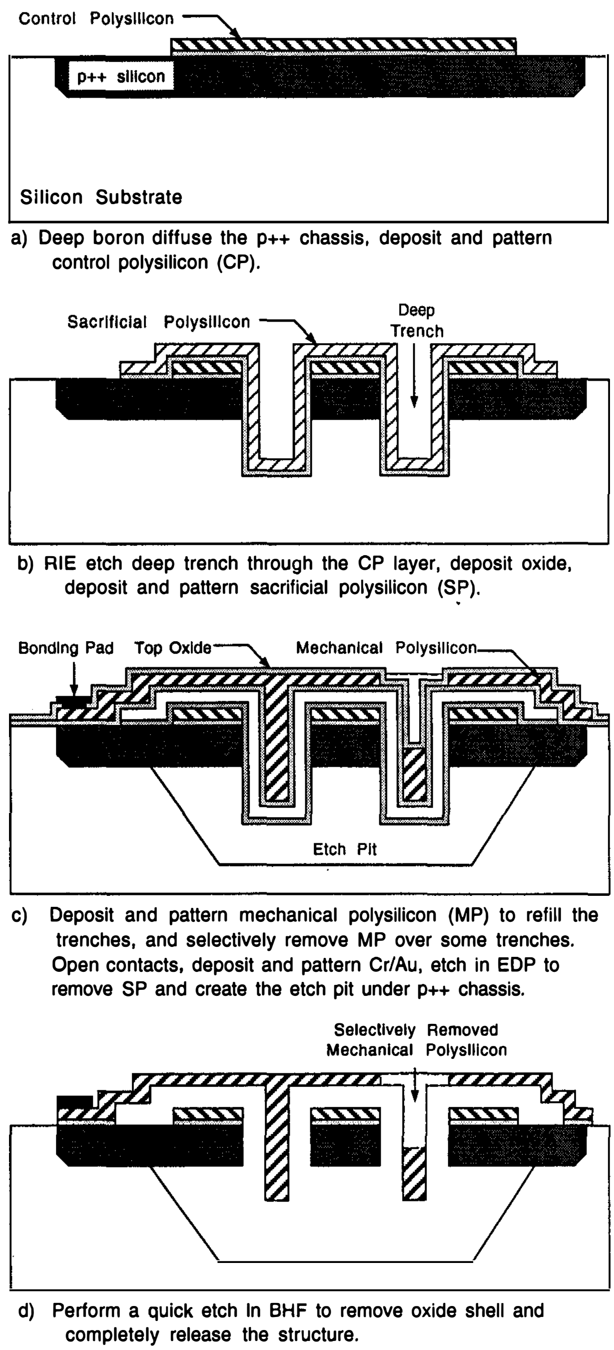

Figure 2: Fabrication process for a typical microstructure.

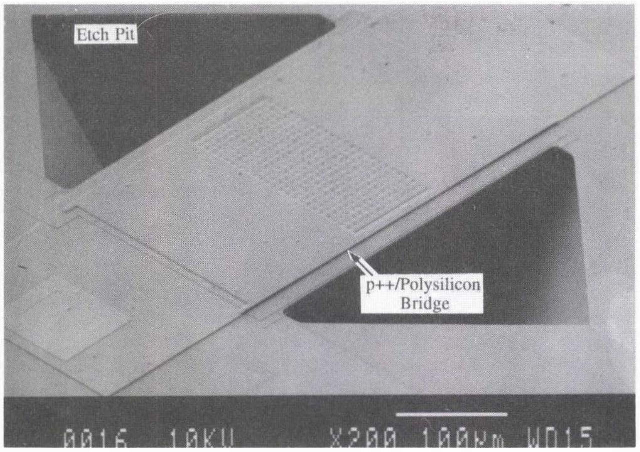

Figure 3: SEM photograph of a fabricated bridge structure, showing the 400µm deep etch pit, and the 300µm long, 200µm wide polysilicon/p++ silicon bridge spanning the etch pit.

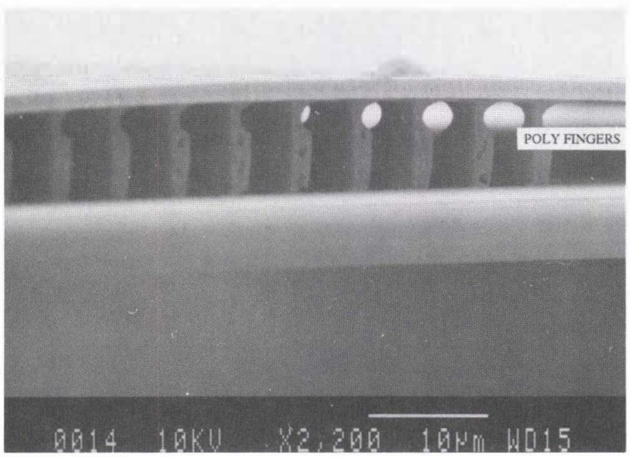

Figure 4: Close-up SEM view of the MP polysilicon bridge, which is about 1.5µm thick, and the p++ bridge which is about 5µm thick. One can observe the array of polysilicon fingers on the underside of the polysilicon bridge.

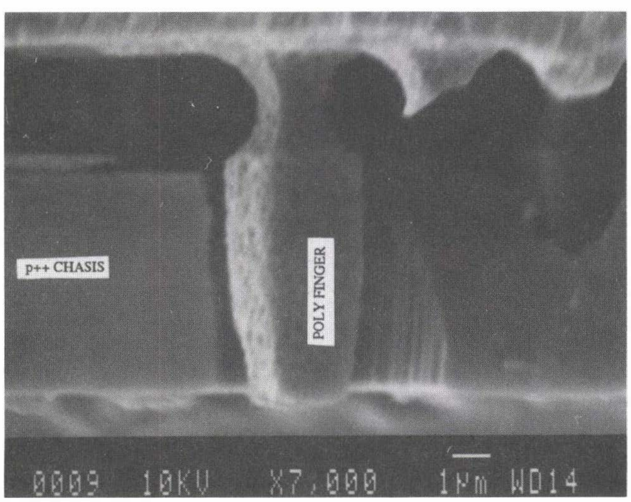

Figure 5: Close-up view of one of the polysilicon fingers; note that the p++ chassis is broken to reveal the polysilicon finger. The finger is about 7µm high, and has a bottle-like shape.

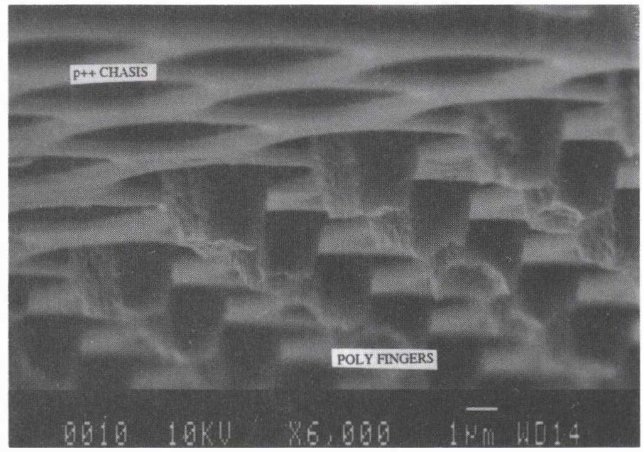

Figure 6: SEM view from the underside of the p++ chassis, showing the protruding fingers of polysilicon. These fingers extend below the lower side of the chassis by about 1.5µm.

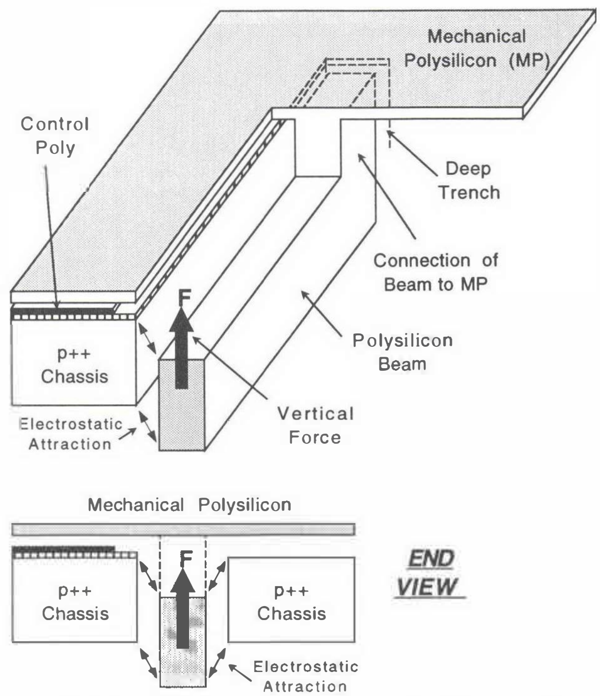

Figure 7: 3-D and end views of a vertically-driven comb array actuator. The polysilicon beam can be pulled up when a voltage is applied between it and the p++ chassis. Note that the beam has a slight overlap with the chassis, and that it is connected to the main body of the MP bridge at the ends.

REFERENCES

[1] H. Fujita, and K.J. Gabriel, "New Opportunities for Micro Actuators," Proceedings, Transducers '91, p. 14, San Francisco, June 91

[2] M.W. Putty, S.C. Chang, R.T. Howe, A.L. Robinson, and K.D. Wise, "Process Integration for Active Polysilicon Resonant Microstructures," *Sensors & Actuators*, 20(1989), p.143

[3] W.C. Tang, T-C.H. Nguyen, and R.T. Howe, "Laterally Driven Polysilicon Resonant Microstructures," *Sensors & Actuators*, 20(1989), p.25

[4] W.C. Tang, M.G. Lim, and R.T. Howe, "Electrostatic Comb Drive Levitation and Control Method," *IEEE/ASME J. MEMS*, Vol. 1, No. 4, p. 170, Dec. 92

[5] Y. Gianchandani, and K. Najafi, "A Bulk Silicon Dissolved Wafer Process for Microelectromechanical Systems," *IEEE/ASME J. MEMS*, Vol. 1, No. 2, p. 77, June 1992

[6] J.R. Gilbert et. al, "Implementation of a MEMCAD System for Electrostatic and Mechanical Analysis of Complex Structures from mask Descriptions," *Digest. MEMS Workshop*, Ft. Lauderdale, Florida, p. 207, Feb. 1993