would ultimately be 1 cm in diameter and 3 mm thick, and would be fabricated from SiC and theoretically produce 10 to 20 W of electrical power (using a coupled generator) while only using 10 g/h of H_2 fuel. Despite technical hurdles such as speeds as high as 2 million RPM, a key incentive driving this development is that the power densities of hydrogen or hydrocarbon fuels is far greater than that possible with any known batteries.

All of these mechanisms are severely limited by friction due to sliding contact at interfaces to the substrate and other members. Considerable research effort is being expended to mitigate this problem (as discussed below), but to some extent, this problem can be expected to remain. It is interesting to note that in nature, sliding contact mechanisms are virtually nonexistent at the microscale.

4.2 OUT-OF-PLANE MECHANISMS

The mechanisms described above are capable of moving only in the two-dimensional (2-D) plane of the wafer's surface. In order to provide access to the third dimension, Pister, et al. (1992) demonstrated the fabrication of movable hinges and "fold-up" structures, again using a very similar fabrication process.

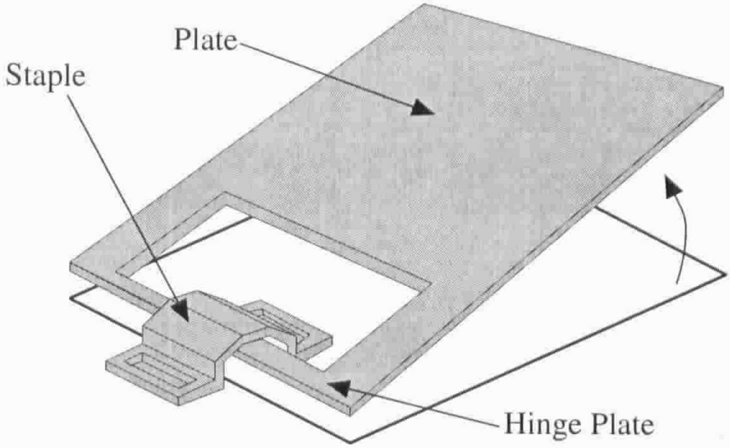
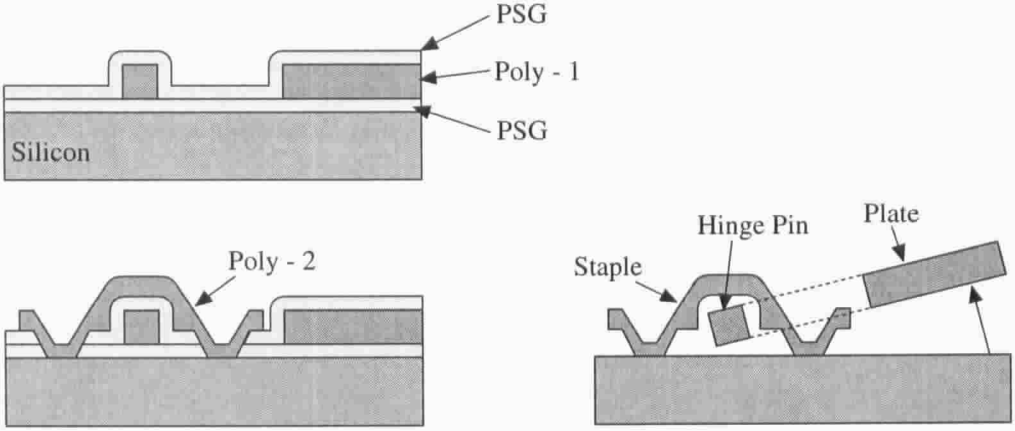


Illustration of a surface micromachined out-of-plane hinge that can be fabricated using a two-layer polysilicon micromachining process. After Pister, et al. (1992).

The hinges were fabricated using a two-polysilicon layer, sacrificial PSG process, which was very similar to those described above (however, it is described here since it represents a more recent process).

Their process began with the deposition of the lower sacrificial PSG (0.5 to 2.5 µm) on bare silicon by LPCVD. This was followed by the deposition of the lower, undoped polysilicon (1 to 2 µm) by LPCVD and another temporary doped PSG layer. The combination was annealed at 950°C in an N_2 ambient not only to remove stress in the polysilicon, but also to dope it using the phosphorus in the PSG. The top (doped) PSG layer was then removed in 5:1 buffered HF and the polysilicon was patterned using a CCl_4, O_2 and He_2 plasma to form most of the movable structures. The second sacrificial PSG layer was then deposited, and both sacrificial PSG layers were patterned using a CCl_4, CHF_3 and He_2 plasma to define contacts between the top polysilicon layer (deposited next) and either the substrate or the lower polysilicon layer. A second temporary doped PSG layer was then deposited and used in a subsequent annealing/doping step for the top polysilicon, which was then patterned using a plasma process as above. The final step was the release of the mechanisms in 49% HF (1 min), followed by a rinse in deionized (DI) H_2O and air drying.



Cross-sectional illustration of the formation of a hinge structure using a two-level polysilicon process. After Pister, et al. (1992).

Only three masks were used to form a rich variety of structures, which were manually rotated (a time-consuming serial process) into position after release. Some structures could be "locked" in place either by locking structures or by depositing an overcoating of PECVD SiO_2. As illustrated below, three basic hinge types (based on whether or not they were anchored to the substrate or to other polysilicon members, and on their direction of rotation) could be fabricated, being defined simply through the layout of lithographic masks.

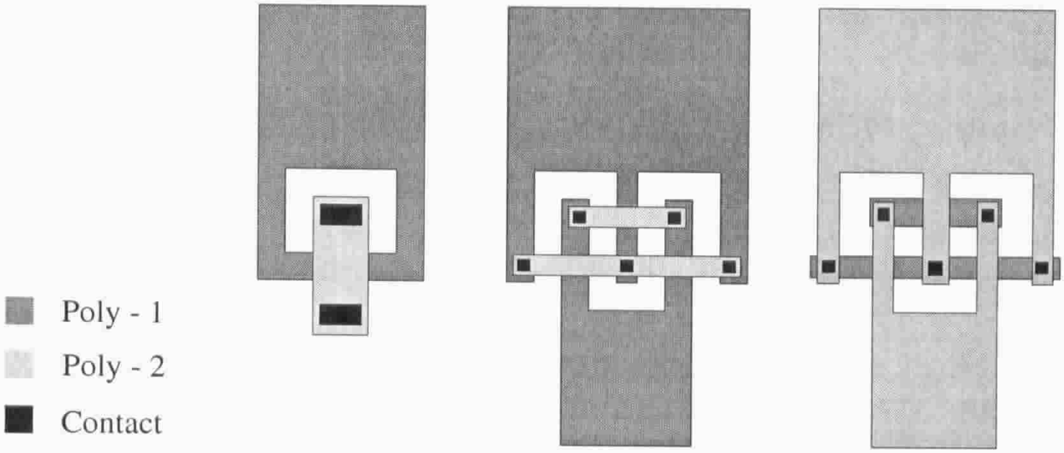


Illustration of three basic hinge types available in a two-level polysilicon surface micromachining process. After Pister, et al. (1992).

They demonstrated a variety of demonstration devices, including hot-wire anemometers (200 µm long, 2 µm wide polysilicon "hot wires" with electrical contacts through serpentine springs), a conformal micro-probe, a "tissue growth dynamometer" (for measuring forces exerted by growing embryonic tissues), and a parallel-plate gripper (pulling the "handle" in turn pulled on 1 mm long "tendons" that pulled the normally closed gripper plates apart). More recently, Yeh, et al. (1995) demonstrated a variety of more complex "fold-up" structures for exploratory work in fabricating articulated manipulators for miniaturized robotic systems.

4.3 STRUCTURAL MEMBERS

While not strictly considered mechanisms by themselves, structural members are critical in connecting between mechanisms, supporting other structures, etc. In the processes discussed above, such members can readily be fabricated from lengths of polysilicon. They can be made using one or both layers of polysilicon (the latter being possible if a contact cut is made in the inter-polysilicon sacrificial layer prior to deposition of the upper layer).

Rather than using solid polysilicon, however, Judy and Howe (1993a, 1993b), developed a process for fabricating hollow polysilicon beams. Their process is more complicated than the "typical" single-layer polysilicon processes often used for electrostatic actuators, but offers a significant advantage: increased "stiffness-to-mass ratio," leading to higher resonant frequencies for a given geometry (allowing for higher-frequency operation). The basic process (details covered in Judy and Howe (1993a, 1993b), and illustrated below) was essentially to pattern a polysil-