Actuators

The physical world is not still, but rather it is very dynamic and full of motion. If sensors extend our faculties of sight, hearing, smell, and touch, then actuators must be the extensions of our hands and fingers. They give us the agility and dexterity to manipulate physical parameters well beyond our reach. It is not surprising that the promise to control at a miniature scale is fascinating. Wouldn't the surgeon dream of electronically-controlled precision surgical tools? And what to do when our sensors tell us of a need to locally act and control on a microscopic scale? It is actuation that affords us the ability to apply this type of feedback.

The number of commercial systems or components with microactuators is limited, underscoring the nascency of this field. The following section first describes a novel display system capable of steering light on the scale of its constituent miniature mirrors, then three examples of micromachined valves. Collectively, they illustrate the current state of MEMS actuation.

Digital Micromirror Device™

The Digital Micromirror Device™—DMD™—is a trademark of Texas Instruments, Dallas, Texas, which developed and commercialized this new concept in projection display technology, referred to as Digital Light Processing™—DLP™. U.S. Patent #4,615,595 (Oct. 7, 1986) describes the early structure of the DMD™. The technology has since undergone continuous evolution and improvements. In 1996 Texas Instruments formally introduced its new product family of DLP-based projection systems.

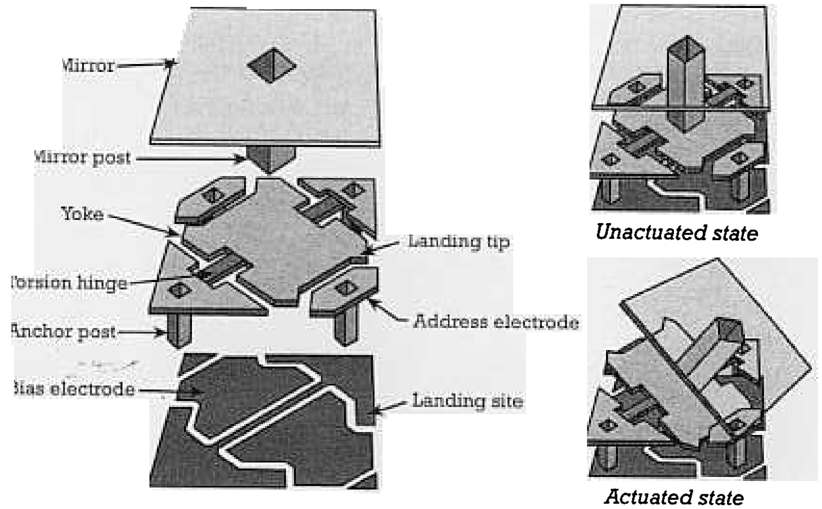


Figure 4.29 Illustration of a single DMD™ pixel in its resting and actuated states. The basic structure consists of a bottom aluminum layer containing electrodes, a middle aluminum layer containing a yoke suspended by two torsional hinges, and a top reflective aluminum mirror. An applied electrostatic voltage on a bias-electrode deflects the yoke and the mirror towards that electrode. A pixel measures approximately 17 μm on a side. Adapted from Van Kessel et al. [26].

The DMD™ consists of a two-dimensional array of optical switching elements (pixels) on a silicon substrate [26]. Each pixel consists of a reflective micromirror supported from a central post (Figure 4.29). This post is mounted on a lower metal platform—the yoke—itself suspended by thin and compliant torsional hinges from two stationary posts anchored directly to the substrate. Two electrodes positioned underneath the yoke provide electrostatic actuation. A 24-V bias voltage between one of the electrodes and the yoke tilts the mirror towards that electrode. The nonlinear electrostatic and restoring mechanical forces make it impossible to accurately control the tilt angle. Instead, the yoke snaps into a fully deflected position, touching a landing-site biased at the same potential—to prevent electrical shorting. The angle of tilt is limited by geometry to ±10° (the direction of the sign is defined by the optics). The restoring torque of the hinges returns the micromirror to its initial state once the applied voltage is removed. CMOS static-random-access-memory (SRAM) cells, fabricated underneath the micromirror array, control the individual actuation states of each pixel and their duration. The OFF state of the memory cell tilts the mirror by −10°, whereas the ON state tilts it by +10°. In the ON state, off-axis illumination reflects from the micromirror into the pupil of the projection lens, causing this particular pixel to appear bright. In the other two tilt states, 0° and −10°, an aperture blocks the reflected light, giving the pixel a dark appearance (Figure 4.30). This beam-steering approach provides high contrast between the bright and dark states. Each micromirror is 16 μm square, and is made of aluminum for high reflectivity. The pixels are arrayed in

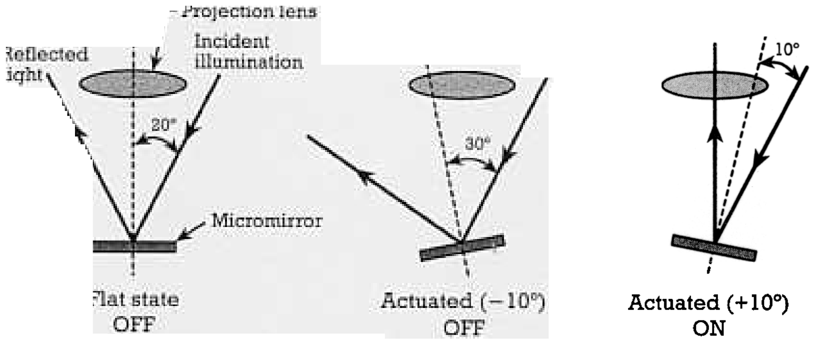
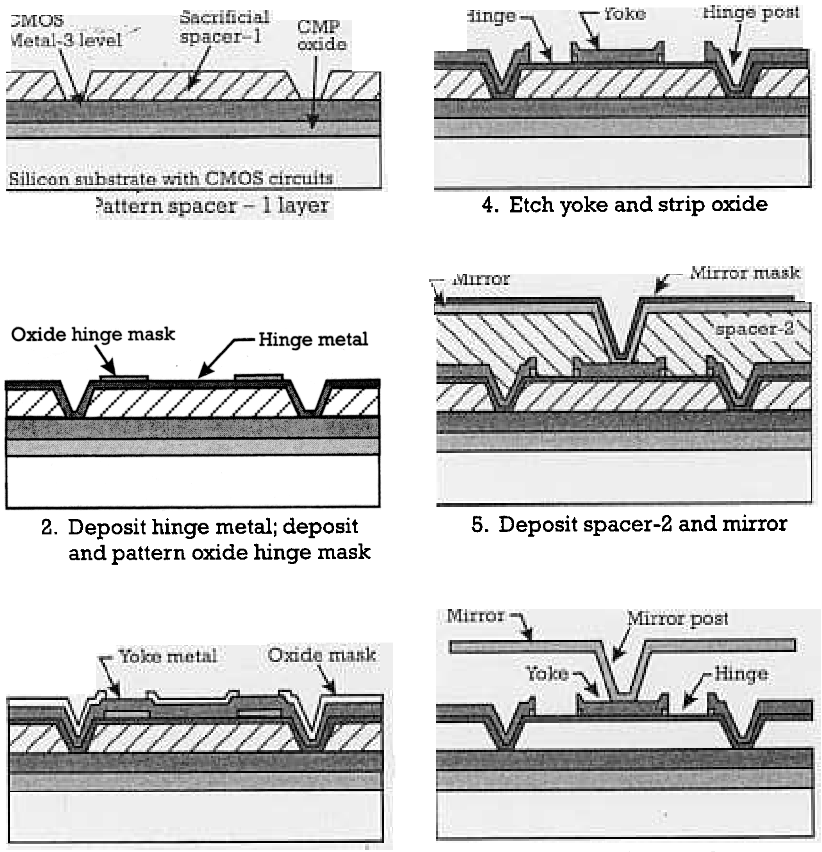


Figure 4.30 Illustration of optical beam-steering using the switching of micromirrors. Off-axis illumination reflects into the pupil of the projection lens only when the micromirror is tilted in its +10°-state, giving the pixel a bright appearance. In the other two states, the pixel appears dark [26].

two dimensions on a pitch of 17 μm to form displays, with standard resolutions from 800 × 600 pixels (SVGA) up to 1280 × 1024 pixels (SXGA). The fill factor, defined as the ratio of reflective area to total area, is approximately 90% allowing a seamless (continuous) projected image free of pixelation.

While the operation of each mirror is "only digital," in other words, the pixel is either bright or dark, the system is capable of achieving gray shades by adjusting the dwell time of each pixel—the duration is bright or dark. The mechanical switching time, including settling time, is approximately 16 μs, much faster than the response of the human eye. At these speeds, the eye can only interpret the amount—not the duration—of light it receives in a pulse. This, in effect, is equivalent to the impulse response of the eye. Modulating the duration of the pulse, or the dwell time, gives the eye the sensation of gray by varying the integrated intensity. Since the pixel switching speed is approximately 1,000-times faster than the eye's response time, it is theoretically possible to fit up to about 1,000 gray levels, equivalent to 10 bits of color depth. In actuality, full-color projection uses three DMD™ chips, one for each primary color (red, green, and blue), with each chip accommodating 8-bit color depth, for a total of 16 million discrete colors. Alternatively, by using filters on a color wheel, the three primary colors can be switched and projected using a single DMD™ chip.

Texas Instruments uses surface micromachining to fabricate the DMD™ on wafers incorporating CMOS electronic address and control circuitry (Figure 4.31). The basics of the fabrication process are in some respects similar to other surface-micromachining processes: the etching of one or more sacrificial layers releases the mechanical structures. But they differ in that they must address the reliable integration of close to one million micromechanical structures with CMOS electronics. All micromachining steps occur at temperatures below 400° C, sufficiently



Pattern spacer – 1 layer

2. Deposit hinge metal; deposit and pattern oxide hinge mask

3. Deposit yoke and pattern yoke oxide mask

4. Etch yoke and strip oxide

5. Deposit spacer-2 and mirror

6. Pattern mirror and etch sacrificial spacers

Figure 4.31 Fabrication steps of the Texas Instruments DMD™ [26].

low to ensure the integrity of the underlying electronic circuits. Standard 0.8 μm, double-metal level, CMOS technology is used to fabricate control circuits and SRAM memory cells. A thick silicon dioxide layer is deposited over the second CMOS metal layer. Chemomechanical polishing (CMP) of this silicon dioxide layer provides a flat starting surface for the subsequent building of the DMD™ structures. A third, aluminum-metal layer is sputter-deposited and patterned to provide bias and address electrodes, landing pads, and electrical interconnects to the underlying electronics. Photoresist is spin-deposited, exposed, developed, and hardened with ultraviolet (UV) light to form the first sacrificial layer. A sputter-deposition of an aluminum alloy defines the hinge metal layer. The mechanical integrity of the DMD™ relies on low stresses in the hinge. Naturally, the exact composition of the alloy remains proprietary to Texas Instruments. A thin, silicon dioxide mask is then deposited with PECVD, and patterned to protect the torsion hinge regions. The aluminum is not etched after this step. Retaining this silicon dioxide mask, another sputtering step deposits a thicker, yoke-metal layer, also made of a proprietary aluminum alloy. A thin layer of silicon dioxide is subsequently deposited and patterned in the shape of the yoke and anchor posts. An etch step removes the exposed aluminum areas down to the organic sacrificial layer. But in the regions where the oxide hinge mask remains, only the thick yoke metal is removed, stopping on the silicon dioxide mask and leaving intact the thin, torsional hinges. Both silicon dioxide masking layers are stripped before a second sacrificial layer, also made of UV-hardened photoresist, is deposited and patterned. Yet another aluminum alloy sputter-deposition defines the mirror material and the mirror post. A silicon dioxide mask protects the mirror regions during etch of the aluminum alloy.

The remaining fabrication steps address the preparation for sawing and packaging, made difficult by the delicate micromechanical structures. A wafer saw cuts the silicon along edge scribe lines to a depth that allows breaking the individual dice apart at a later stage. An oxygen-plasma etch step removes both sacrificial layers and releases the micromirrors. A special passivation step deposits a thin, antistiction layer to prevent any adhesion between the yoke and the landing pads. Finally, a singulation process breaks apart and separates the individual dice. The packaging of the DMD™ is discussed in Chapter 6.

Reliability is the *sine qua non* of the commercial success of DMD™ technology. The designs described above are the result of extensive efforts at Texas Instruments aimed at understanding the long-term operation of the pixels, as well as their failure modes. The DMD™ micromirrors are sufficiently robust to withstand normal environmental and handling conditions, including 1500-G mechanical shocks, because the weight of the micromirrors is insignificant. The major failure and malfunction mechanisms are surface contamination and hinge memory. The latter is the result of "metal creep" in the hinge material, and causes the mirror to exhibit a residual tilt in the absence of actuation voltages. Advancements in the hinge metal-alloy and fabrication processes have yielded a mean time between failure (MTBF) of more than 100,000 h.

Micromachined valves

A new generation of miniature valves with electronic control would be desirable among both manufacturers and users of valves. For example, recent trends in home appliances indicate a shift towards total electronic control [27]. Electronically programmable gas stoves, currently under development, require low-cost, electronically controlled gas valves. Moreover, miniature valves are important for the control of fluid-flow functions in portable biochemical analysis systems [28].

The field of micromachined valves remains nascent and in its infancy. In order for silicon micromachined valves to gain a substantial foothold in the market, they must effectively compete with the relatively mature, traditional valve technologies. These cover a broad range of media, pressures, flow rates, and price. It is unlikely that micromachined valves will displace traditional valves; rather, they will complement them in special applications where size and electronic control are beneficial (Table 4.4).

The following sections describe three micromachined valves. Two devices from Redwood Microsystems, Inc., Menlo Park, California; and TiNi Alloy Company, San Leandro, California, illustrate the efforts of two small companies in commercializing this technology. A third micromachined valve developed for internal use at Hewlett-Packard Laboratories, Palo Alto, California, was put on display at the San Jose Tech Museum, San Jose, California, after the company decided to halt further development. All three valves operate on the principle of blocking