Why is the Texas Instruments Digital Micromirror Device™ (DMD™) so reliable?

The remarkable Digital Micromirror Device

There are two remarkable things about the Digital Micromirror Device (DMD) from Texas Instruments. The first is that it works at all: the second is that it works so reliably.

The Digital Micromirror Device is at the heart of TI's Digital Light Processing technology. It allows images to be projected and displayed which are brighter, sharper and more realistic than has previously been possible with alternative technologies.

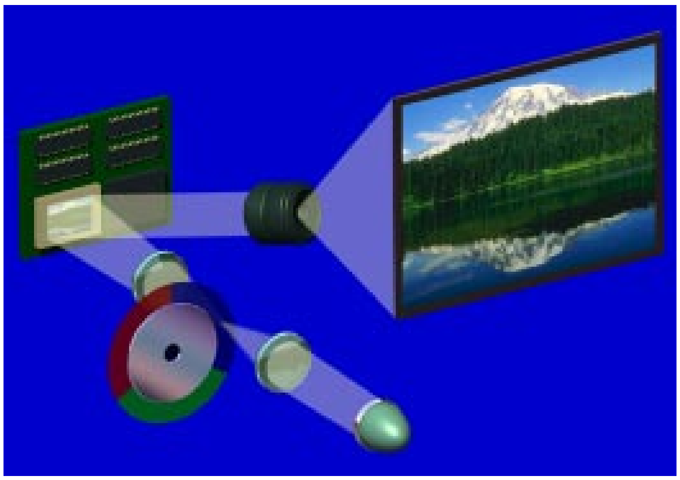


Figure 1*: Simplified schematic of the underlying principle of the Digital Micromirror Device*

Put simply, the DMD is an array of microscopically small, square mirrors - some half a million or more in a space no larger than a finger nail - each of which can be turned on and off thousands of times per second. Each mirror corresponds to a single pixel in the projected or displayed image.

Given that the DMD has half a million rapidly moving parts, it's easy to believe that it shouldn't be reliable. After all, it's a mechanical device as much as it's an electronic one - and don't mechanical things wear out and break down?

Yes - and no. Our experience of the mechanical world hasn't always been a positive one. On the other hand, mechanical devices today are typically far more reliable than they were ten - or even five - years ago. It wasn't that long ago that we took it for granted that a new car engine had to be 'run in': we were happy to accept that a mechanical device was bound to have rough edges, and needed time for the component parts to be bedded down. Not any more. The development of new materials, new manufacturing processes and new testing programs have enabled us to engineer mechanical products whose performance and reliability vastly surpasses that of their predecessors.

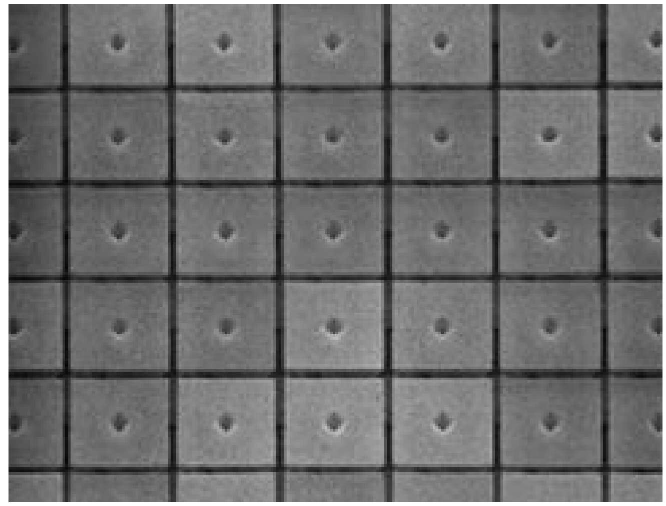


Figure 2: ***A close-up of the DMD array***

The DMD: changing the rules

And how many of the mechanical devices with which we're familiar (even today) have been the subject of a development program lasting close to twenty years - like the DMD? How many of them have been precision-engineered to tolerances of a micron or less, as the DMD is? (The average human hair is between sixty and eighty microns wide). How many of them have been manufactured using the same manufacturing techniques that are used to make the world's most powerful microprocessors and computer memories, as is the case with the DMD?

But still, we carry with us preconceptions about what should and what should not work - and these preconceptions have given rise to a number of myths. Like many myths, we tend to believe them, because they sound plausible - they accord with what we think we know. The DMD changes the rules about what we think we know.

DMD: the questions

So what do we think we know? What are the questions we ask ourselves about the DMD?

We wonder whether the hinge - which allows the micromirror to tilt back and forth - will eventually break under the strain of constant twisting?

We ask ourselves whether the micromirrors are likely to stick in one position, causing defects in the projected image?

We ask whether such microscopically small components aren't so fragile that they'll break if handled roughly?

We wonder if the enormous speed at which the micromirrors must switch will, over time, cause them to become damaged and inoperative?

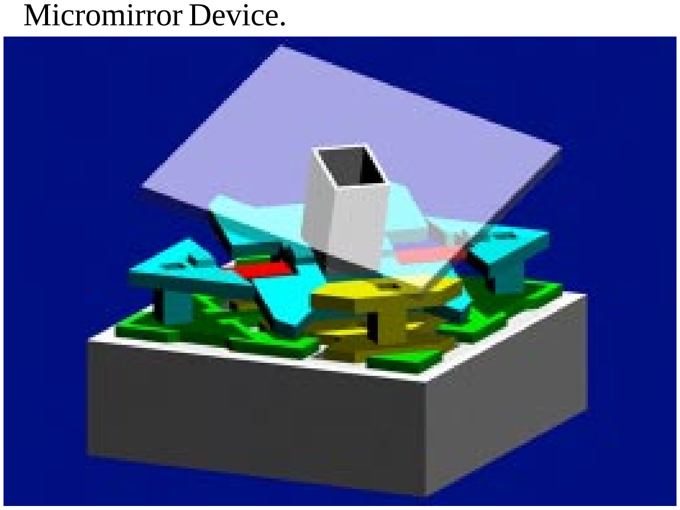
And we ask ourselves about the effect of dust: after all, if a human hair could cover five micromirrors, wouldn't a piece of dust in the DMD surely cause one or more mirrors to become inoperative?

DMD: the answers

Each of these questions seems entirely reasonable, based as it is on our preconceptions. What follows is an explanation of what's different about the DMD that helps us to understand why the answers to the above questions aren't what we might expect.

Question 1: won't the hinges bend or break?

Each micromirror is hinged, allowing it to rotate on its diagonal axis. Given that each mirror will be switched through twenty degrees thousands of times per second, it seems to many people that it must, sooner or later, break. In fact, "hinge fatigue" has never been a problem for the Digital Micromirror Device.



The mirror hinge is manufactured using 'thin-film' technology. Thin films have distinctly different properties from the general macroscopic concept of bending metal. A thin-film material is said to be more 'compliant'; in other words, it has less stiffness. Stiffness is the property of a material that causes the material to resist bending. The more the material resists, the greater the likelihood of its breaking.

Consider, for example, a bar of aluminum which is repeatedly bent against itself: it will ultimately snap. Few of us have not at some time bent and re-bent a soft drink can until the metal has torn. But how many of us have taken a sheet of aluminum foil and attempted to cause it to break by bending it back and forth?

The important relationship is between the size of the crystals - or 'grains' - which comprise the material of the item and the size of the item in question. When a material breaks, it is because of dislocations caused to the crystal structure within it. These dislocations migrate to, and accumulate at, joints between the grains. This has the effect of concentrating mechanical stress until the yield point of the material is exceeded - at which point, breakage occurs.

In something as microscopically small as a DMD hinge, there is, in effect, no internal crystal structure - all crystals are at the surface of the material. What this means is that the stresses caused by crystal dislocations are relieved immediately on the hinge surface - before the hinge's crystalline structure can be damaged.

To demonstrate this concept, sets of devices were tested through 1 trillion cycles, well in excess of the requirement for a 'normal' commercial lifetime. No broken hinges were observed.

In this case, the DMD 'changes the rules' because of the microscopic physical size of its mechanical parts: the laws that apply to the everyday objects in our lives work differently at this level of miniaturization

Question 2: are the mirrors likely to stick?

When the micromirrors are switched between their 'on' and 'off' positions, they are held in place by electrostatic forces. It is true that during early DMD prototype development, some mirrors tended to stick to the underlying surface due to large (in sub-micron technology terms) adhesive forces. This, in turn, caused the mirrors to fail to switch.

What would be the cause of such an adhesive force? There are two phenomena at work. The first phenomenon is the relatively straightforward one in which capillary water condensation will cause the landing tip and the landing surface to become 'stuck'.

To understand better how this happens, consider the case of two glass plates stuck together with water - an extreme example of the adhesive force of capillary condensation. By wetting the common interface of the two plates, a partial vacuum is produced at this interface due to the surface tension of the water on the glass. As a result, enormous forces are required to pull the plates apart.

The second phenomenon, which is probably familiar to those with an advanced education in physics, is the phenomenon known as 'van der Waals forces'. Van der Waals forces are short range forces which cause materials to become attracted at the molecular level.

In order to prevent the mirrors from sticking, three actions are taken in the design and manufacture of the DMD. First, the effect of van der Waals forces is significantly mitigated by the application, during the fabrication process, of a thin anti-stick layer which lowers the surface energy of the contacting parts.

Second, the mirror was redesigned in 1995 to improve the ability of the mirror to overcome the remaining forces. The redesign added miniature springs to the mirror landing tips, as can be seen in Figure 4. These springs store energy upon landing and push the mirror away from the surface upon release.

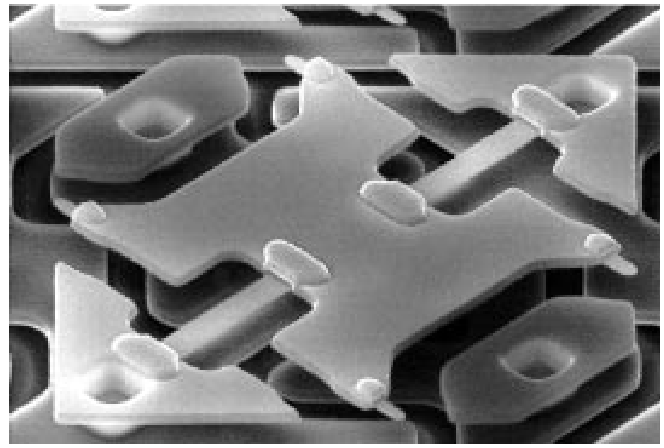


Figure 4: ***The addition of the 'spring tip' has further improved the reliability of the Digital Micromirror Device***

And third, to minimize the effect of capillary condensation of water, the DMD is sealed in a dry environment using special hermetic packaging designed to ensure that it stays dry throughout its lifetime.

Thus the forces which would otherwise cause the DMD to stick were eliminated - and to improve the DMD's operating margin, its ability to "bounce back" was dramatically improved.

Question 3: will the mirrors fall off if the DMD is treated roughly?

Most people find it hard - if not impossible - to imagine a device in which over half a million individual moving parts are arrayed in an area measuring less than 1.5 sq. cms. What they *can* imagine, however, is how fragile such a device must be. Surely it must be true that only the smallest shock or vibration will be enough to cause severe dislocation of the micromirrors when subjected to, for example, the robust treatment a projector will typically receive during its working life?

Again, our thinking is conditioned by the phenomena we observe during everyday life. However, the objects with which we are familiar, and which exhibit such characteristics, have very different profiles in terms of their modes of vibration.

Why are 'modes of vibration' important? Simply, because it's vibration that causes fracture and breakage. A simple illustration of this is the classic example of a wine glass shattered by an opera singer's voice. The sound waves - at the appropriate frequency - cause the glass to vibrate, and it is the vibration which causes the glass to break.

The DMD superstructure has modes of vibration with frequencies which are at least two orders of magnitude above the frequency of vibration generated during normal handling and operation (the lowest frequency mode of the device is about 100kHz: all of the other resonant modes are measured in MHz). As such, there is virtually no vibration coupling from the environment to the DMD array: the DMD has a much higher vibration frequency than can be generated with conventional shock and vibration sources.

This is the theory: the fact is that laboratory testing has shown that the mirrors do not fall off as a result of shock or vibration. Much to many peoples' surprise, dropping a DMD on the floor does not cause thousands of tiny mirrors to start rattling around behind the transparent enclosure!

Question 4: as the mirrors move so rapidly, surely they must eventually become damaged?

To achieve the high quality image for which Digital Light Processing is renowned, the individual micromirrors - each of which corresponds to a single pixel in the projected image - must be switched on and off thousands of times per second. As such, each mirror is subjected to (relatively) enormous forces.

To understand why the speed at which the mirrors switch does not cause them to fail, it must be understood that the size of the mirrors and the air gap are fantastically small (the weight of an individual micromirror is measured in millionths of a gram!) and that the mirrors rotate through only twenty degrees. In fact, in 5 microseconds, the mirror's tip moves through just 2 micrometers: as such, the average velocity of the micromirror is just 40 cm/second. By comparison, the terminal velocity of an oak leaf falling from a tree is of the order of 100 cm/second - which makes the landing of the DMD mirror a relatively gentle event!

Knowing this, it's easy to understand why the speed with which the mirrors move will not cause them to break.

Question 5: surely, tiny particles of dust could cause mirrors to fail?

Yes, they could. So small are the dimensions of the DMD that even the smallest particle of contaminant could cause one or more micromirrors to become non-functional. The single most significant potential problem in fabricating a DMD is the existence of particles in the manufacturing environment (just as it is in the manufacture of microprocessors and other sophisticated electronic devices).

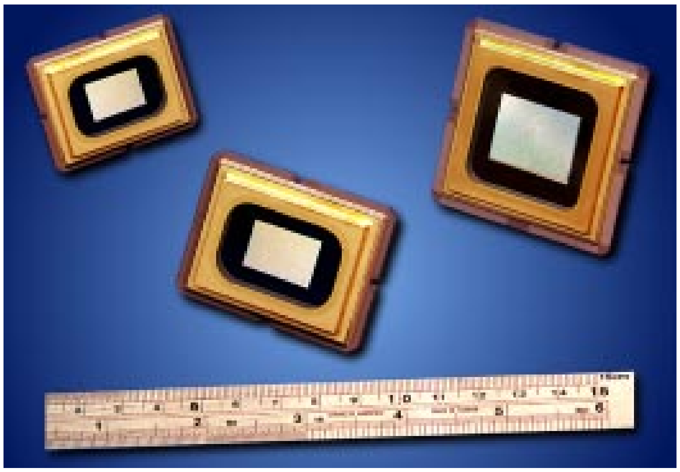
The DMD is manufactured in exactly the same way, using exactly the same facilities, as the world's most sophisticated semiconductor devices (Texas Instruments is a world leader in this field). As such, the DMD manufacturing process - which occurs in a world-class wafer fabrication clean room facility - can take advantage of the huge amount that has been learned about contaminant particle elimination.

In the manufacture of any sophisticated semiconductor device, initial yields are expected to be low. Process improvements are identified and implemented, and, over time, yields increase substantially. It is this "yield curve" which gives rise to the significant reductions in price that we have become accustomed to during the lifetime of, for example, a memory chip or a microprocessor. We are seeing the DMD making its expected progress up the yield curve since the effort to reduce the impact of particles began in the autumn of 1994. Naturally, the effort is continuing.

Today, Texas Instruments is able to meet the demand for DMDs which are 100% defect free at the time of manufacture, thus surpassing a specification which is already extraordinarily rigorous (the specification allows a maximum of one defective micromirror/pixel per 100,000 - significantly more demanding than is often found elsewhere).

Figure 5: *The architecture of the DMD has continued to evolve over time, to the point where its reliability for commercial applications is assured.*

The DMD is, of course, hermetically sealed so that once the manufacturing process is complete, no contaminants can enter the enclosure.



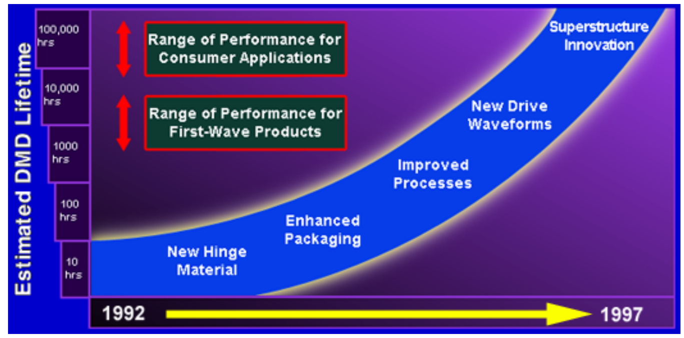
By early 1996, exhaustive tests (120,000 operating hours, which is approximately equivalent to 120 years in the life of a typical portable business projector) on 150 DMDs revealed only nine - 6% - which exhibited an increase in the number of nonfunctional pixels/mirrors.

Detailed examination of each particle which had caused a failure allowed its source to be identified and eliminated. This effort has seen particulate contamination improved by over 80%.

The very small possibility that a microscopic particle of dust was sealed into the DMD package during manufacture is now the only potential factor which might affect the operation of the DMD during its lifetime - all others having been progressively eliminated during its development. The Digital Micromirror Device has now reached a level of reliability which is the envy of competing technologies.

The DMD: confounding our preconceptions

So why does the reliability of the DMD appear to defy and contradict everything which we hold to be true about mechanical devices? Intuitively, it should not work: the fact is, though, that laboratory testing has thus far shown that it is capable of 100% reliable operation for periods of time measured in decades (and, in fact, testing has not yet revealed the point at which failure might be expected under normal operating conditions).



Testing has put each micromirror through hundreds of billions of cycles - of being switched 'on' and 'off' - yet there has been no sign of sticking or of fracture. Moreover, the DMD has been put through comprehensive shock and vibration tests - tests which exert far more significant forces on it than could be expected in normal commercial operation - and, despite its apparent fragility, micromirrors haven't broken off or become misaligned as a result.

There are three key reasons for the DMD's ability to confound our preconceptions.

The first relates to the microscopic size of the mechanical parts. Many of our preconceptions are based on our experience with objects that are readily observed by the naked eye. The microscopic size of the DMDs mechanical parts is therefore a part of the explanation for the way in which the DMD apparently contradicts those truths which we hold to be self-evident.

The second reason is that the DMD is the first commercially produced
mechanical technology based upon conventional semiconductor techniques. As such, DMD technology derives significant benefit from building on the past experience and the current knowledge base of the semiconductor industry.

Finally, while Digital Light Processing products featuring the Digital Micromirror Device only came to market during 1996, the DMD itself had been under development for twenty years in TI's laboratories. Much of that development effort was spent in progressively refining the design, architecture and manufacture of the DMD such that its reliability to commercial standards could be assured.

The Digital Micromirror Device is an astonishing phenomenon. That it works, and works reliably, is almost beyond belief. It challenges our preconceptions about what should and should not be achievable in much the same way that seeing moving pictures did a hundred years ago, that seeing television pictures did fifty years ago and that seeing television pictures of a man walking on the moon did twenty-five years ago. The DMD defies - and redefines - our understanding of what is possible.

For more information about Digital Light Processing by Texas Instruments, visit our World Wide Web site at http://www.ti.com/dlp. Alternatively, in the USA, call 1-888-DLP-BY-TI xtn 2930. In Europe, call the TI DLP Hotline on +44-1604-663066, email ian@msg.ti.com or fax +44-1604-663099.