MEMS-based flexible reflective analog modulators (FRAM) for projection displays: a technology review and scale-down study

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Abstract. A MEMS based technology for projection display is reviewed. This technology relies on mechanically flexible and reflective microbridges made of aluminum alloy. A linear array of such micromirrors is combined with illumination and Schlieren optics to produce a pixels line. Each microbridge in the array is individually controlled using electrostatic actuation to adjust the pixels intensities. Results of the simulation, fabrication and characterization of these microdevices are presented. Activation voltages below 250 V with response times below 10 µs were obtained for 25 µm x 25 µm micromirrors. With appropriate actuation voltage waveforms, response times of 5 µs and less are achievable. A damage threshold of the mirrors above 8 kW/cm² has been evaluated. Development of the technology has produced projector engines demonstrating this light modulation principle. The most recent of these engines is DVI compatible and displays VGA video streams at 60 Hz. Recently applications have emerged that impose more stringent requirements on the dimensions of the MEMS array and associated optical system. This triggered a scale down study to evaluate the minimum micromirror size achievable, the impact of this reduced size on the damage threshold and the achievable minimum size of the associated optical system. Preliminary results of this scale down study are reported. FRAM with active surface as small as 5 µm x 5 µm have been investigated. Simulations have shown that such micromirrors could be activated with 107 V to achieve f-number of 1.25. The damage threshold has been estimated for various FRAM sizes. Finally, design of a conceptual miniaturized projector based on 1000x1 array of 5 µm x 5 µm micromirrors is presented. The volume of this projector concept is about 12 cm³.

1. Introduction
More than ever, displays are omnipresent in our societies. HD televisions, cell phones, MP3 players, projectors, all rely on advanced display technologies based on LCD, PDP, OLED or MEMS to list just a few. Many applications make use of projection displays and associated technologies have received particular attention over the years. This paper reviews the effort devoted by INO and partners for the development of one such technology for projection display based on MEMS. The active element of

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this technology is a linear array of microbridges acting as flexible micromirrors. This mirror array is illuminated with a laser source and produces an image line at the output of an optical relay. Each pixel of the image line corresponds to one flexible micromirror which modulates the pixel intensity in an analog fashion with switching times in the range of 5 µs. The light modulating scheme shown in figure 1 employs Schlieren optics [1] which translate the micromirror curvature into light intensity at the Schlieren relay output. Micromirror curvature is controlled by electrostatic actuation. A complete 2-D image is obtained by a scanning mechanism that displays each image column sequentially. Projection optics is used to tailor the final image.

One force driving the development of many display technologies is miniaturization. Such requirement for low weight and compactness is obviously essential for many applications. The projection display platform described herein is no exception. Results describing a preliminary study aiming at decreasing the size of the developed prototypes will be presented. In addition, this paper first provides a review of the technology including simulation results, a description of the micromirror fabrication process and characterization results for these microdevices and associated projection engines developed for principle demonstration.

2. FRAM simulation
In order to limit the parameter design space for the micromirrors, electromechanical static simulations and dynamic simulations were performed with the MEMS simulation software Intellisuite™. The software ANSYS™ was also used for thermal simulations to estimate the micromirror damage threshold. The simulated micromirror structure (see figure 2) consists of a reflecting flexible area supported by two legs a few microns above an electrode located on the substrate underneath the mirror. Aluminum with a low residual tensile stress of about 10 MPa was set as the micromirror material.

![Figure 1. Light modulation approach using flexible micromirrors.](image-url)
As an additional requirement, the optical design of the display engine assumes a maximum micromirror curvature corresponding to f-number of 2. The maximum mirror sag or deflection is therefore approximated by the following expression:

$$
\delta_{\text{max}} \approx \frac{L}{16f#} \approx \frac{L}{32}
$$

(1)

where $$\delta_{\text{max}}$$ is the maximum mirror sag, $$f#$$ is the micromirror f-number at maximum curvature and $$L$$ is the mirror length as defined in figure 2.

![Flexible micromirror structure](image)

Figure 2. Flexible micromirror structure (W: mirror width, L: mirror length, G: mirror/substrate gap size, t: membrane thickness).

2.1. Static simulations

Electromechanical static simulations have been performed to evaluate the micromirror deflection as a function of the applied voltage for various FRAM configurations. These response curves are of particular interest to estimate actuation voltage required to reach the mirror sag corresponding to $$f#$$ of 2 and to verify that a particular design presents a safe margin between the maximum actuation voltage and the pull-in voltage. Pull-in phenomenon is well-known [2] and occurs for a wide variety of electrostatic MEMS. In the particular case considered here, pull-in is caused by nonlinear variation of electrostatic force with mirror curvature. At some point, the restoring force caused by the membrane curvature cannot counterbalance the electrostatic force; the mirror either stops as it touches the substrate or it collapses. It is therefore critical that the designed micromirror exhibits control range sufficient to reach the required maximum curvature without approaching too closely the pull-in threshold. Another important design issue is minimizing the activation voltage while maintaining the feasibility of the structure by surface micromachining. This was also considered within this simulation phase.

The influence of various parameters including membrane length (L), membrane width (W), membrane thickness (t) and gap size between the membrane and the underlying electrode (G) (see figure 2 for definitions) was studied. Preliminary fabrication tests indicated that the membrane thickness should be 0.1 µm or more to keep the structure reliable and rugged. Gap size had to be a few micrometers only (1.5 to 4.5 µm typically) to maintain a reasonably low maximum activation voltage. Due to this small gap size, membranes with length of 30 µm or more exhibited a maximum activation voltage very close to the pull-in threshold. For this reason, the study considered mainly membrane lengths shorter than 30 µm. Membrane width was not found to have a significant impact on static performance.

Detailed results of these simulations have been presented elsewhere [3]. Typical results are shown in figure 3 for 25 µm x 25 µm micromirror with a thickness of 0.15 µm. The horizontal line in this figure indicates the required deflection corresponding to $$f#$$ 2 for a mirror length of 25 µm. As
expected, the actuation voltage increases with the gap value. The margin between actuation voltage and pull-in threshold (the voltage at which the curve becomes vertical) also increases with the gap size. Similar results were obtained for thinner membranes with $t = 0.1 \mu m$ but with the actuation voltages shifted toward lower values. Simulations also investigated the behavior of shorter membranes with $L = 15 \mu m$. Shorter membranes are stiffer but require smaller deflection to achieve a $f$-number of 2. Simulations showed that, for the selected parameters, these effects combine to result in actuation voltages similar to the ones for 25 $\mu m$ long membranes. However, due to the reduced gap, activation of these structures produces electric field higher than for the 25 $\mu m$ long membranes. These microstructures are therefore more prone to electrostatic discharges which must also be taken into account when optimizing the device design.

![Figure 3. Simulation of the micromirror static response for a membrane thickness of 0.15 $\mu m$. Structure dimensions: L: 25 $\mu m$, W: 25 $\mu m$, t: 0.15 $\mu m$, G: 2.5 to 4.5 $\mu m$](image)

2.2. Dynamic simulations
Since resolution of a projection engine based on linear FRAM array depends critically on the fast response of the micromirrors, dynamic simulation of these microdevices were performed to verify that response times within the required range could be achieved. Dynamic simulations included structural and squeeze film damping effects [4]. The MEMS simulation software used for these simulations required that the non uniform electrostatic pressure field acting on the membrane and varying in time with the mirror deflection to be converted into a uniform pressure field. This uniform field was a function of time but did not include the influence of the mirror curvature variations. The uniform pressure waveforms used for these simulations stabilized at a value corresponding to the required final micromirror deflection. The correspondence between voltage and pressure was obtained by determining what uniform pressure would produce the same static deflection as a given voltage. This was considered an acceptable simplification for this preliminary study of dynamic performance of the microdevice. The dynamic simulations were performed for various FRAM structures and different pressure variations with time. Of particular practical interest were pressure waveforms corresponding to a voltage step function or to an exponentially varying voltage. For performance characterization, the time required by the micromirror to oscillate within $\pm 5 \%$ of the maximum deflection value was used as a definition of response time.

As mentioned above, various FRAM configurations were considered with different gap, thickness, length and width. All studied structures typically exhibited response times well below 10 $\mu s$ when actuated with the proper pressure waveform. Detailed results were discussed elsewhere [3]. This necessity of using an appropriate waveform is particularly critical and one of the most important
information resulting from this dynamic study. Using step functions to actuate the micromirrors caused large overshoots and made the device oscillate for relatively long time. These microsystems were clearly underdamped. It was therefore necessary to modify the actuation waveforms to minimize the mirror oscillations. Good results were obtained with pressure waveforms corresponding to exponentially varying voltages. Figure 4 shows an example of such improvement in response time obtained when passing from a step function to an exponential voltage waveform to activate a given micromirror structure.

Another interesting observation obtained from the dynamic simulations is related to the effect of the mirror width. As mentioned in section 2.1., micromirror width is not an important parameter when considering the static membrane performance. However, the situation changes significantly when dynamic response is considered. In this case, for FRAM with different widths and all other parameters being the same, simulations showed that response time can be strongly increased for narrower structures. This demonstrates, as expected, that squeeze film damping is significantly reduced for narrow membrane. This is another important information that must be taken into account when designing this type of micromirror.

Figure 4. A) Simulation of the micromirror dynamic response to a 158 V step function. Structure dimensions: L: 25 µm, W: 25 µm, t: 0.15 µm, G: 4.5 µm B) Simulation of the micromirror dynamic response to an exponential voltage variation with a time constant of 0.43 µs. Structure dimensions: L: 25 µm, W: 25 µm, t: 0.15 µm, G: 3 and 4.5 µm.
2.3. Damage threshold estimate
Thermal and stress analyses have been performed with ANSYS™ software to estimate the damage threshold for 25 x 25 µm micromembranes. These simulations indicate that a membrane initially at 20°C could absorb up to 6750 W/cm² before reaching 450°C that is about 75% of the melting point of the Al alloy. Assuming optical absorption of 10 % for the alloy, this means that an optical power density of 67.5 kW/cm² could illuminate the membrane before its temperature reached 450 °C. However, stress analysis revealed that the Al alloy yield – about 190 MPa – is reached in some points of the structure when absorbed power density is 885 W/cm². Still assuming absorption of 10%, membrane damage threshold is then estimated to correspond to an incident optical power density of about 8850 W/cm². Most importantly, the damage threshold for the studied micromirror structure is not limited by the Al alloy melting temperature but by the Al alloy mechanical yield.

3. Micromirror array fabrication
Over the years, micromirror linear arrays with various sizes have been fabricated within development activities, going from 480 x1 mirrors for VGA format to the demonstration of 4000x1 FRAM. These arrays have been fabricated using surface micromachining techniques. The micromirror design rules resulted either from simulations described briefly above or from practical considerations linked to the developed fabrication process. As part of the technology development, micromirrors presenting various dimensions and structures have been built. This allowed investigation of the actual microdevice performance variation within the design parameter space. Table 1 below presents a representative set of parameters that has been used over the years for the fabrication of FRAM.

3.1. Fabrication process
The developed fabrication process uses 3 to 4 photolithographic masks. The devices are built on silicon substrates on which a silicon nitride (SiN) film has been deposited for electrical insulation. A first metallic layer is deposited and patterned to produce the bottom electrodes (see figure 5). This metallic layer material is typically aluminum or aluminium alloy. The electrodes are then passivated using a SiN layer and windows are opened in the SiN to produce bonding pads. This passivation step is optional, i.e., it is not absolutely required to achieve functional micromembranes. The membrane fabrication begins with the definition of the gap in a relatively thick sacrificial polyimide layer. The thickness of this polyimide determines the gap size between the mirror and the electrode. The next step comprises the deposition and patterning of an aluminum alloy thin film. The aluminum alloy layer is deposited using Physical Vapor Deposition (PVD). This aluminum alloy film is patterned using a photosresist mask and reactive ion etching based on chlorine chemistry. This produces the micromembrane itself. Finally, the sacrificial polyimide layer is isotropically removed using a plasma ash which releases the microstructures by generating a gap between membrane and substrate.

3.2. Some fabrication results
Many micromirror array fabrication runs have been completed using the process described above. The obtained FRAM exhibit a smooth reflecting surface and are relatively flat (see figure 6). At the mirror
level, the structures show typically a membrane width which is narrower than the nominal width. Moreover, the legs supporting the mirror are found to be slightly wider at the substrate level than at the mirror level. These small defects come from the fact that the photoresist used to mask the Al alloy for the etching step does not cover the wafer topography in a perfectly conformal manner. This results in a photoresist mask which does not match perfectly the photomask pattern. This difference, combined with some slight undercut occurring during the Al alloy etching, caused the observed geometrical imperfections. The texture on the leg surface reproduces surface topography of the sacrificial polyimide which supported the leg before being finally etched away. In addition, small defects can be observed at the membrane edges. The characterization performed on the membranes indicates that these defects do not distort the mirror profile significantly.

4. Micromirror characteristics
Three main aspects characterizing the micromirror performance have been measured: the static response, the dynamic response and the damage threshold. The static response was characterized by
measuring the mirror deflection as a function of the voltage applied to the FRAM. This was done using an interferometric microscope equipped with a 10 x Mirau objective with a numerical aperture of 0.25. The wavelength of the light illuminating the mirror under test was 548 nm. This produced an interference pattern in which two consecutive dark or light fringes are generated by mirror regions separated by a vertical distance of 0.27 µm. The voltage was increased gradually across the FRAM and the corresponding mirror deflection was measured by recording the number of fringes between the mirror centre and the mirror edges.

An optical method (see figure 7) has been used to characterize the micromirror dynamic response. The micromirror under test was illuminated with a laser beam and the reflected diffraction pattern was observed through a microscope. When the micromirror curvature was changed, the observed diffraction pattern was modified and some regions of the intensity profile showed an important intensity variation. A photodetector was positioned at the microscope output to measure the intensity corresponding to such high contrast regions. The photodetector response time was short enough (about 10 ns) to provide intensity measurements resolved in time. The voltage waveform applied to the micromembrane and the photodetector signal were recorded simultaneously using an oscilloscope. The analysis of recorded signals allowed the evaluation of the micromirror response time and overall dynamic performance.

![Set-up for the micromirror dynamic response characterization](image)

Figure 7. Set-up for the micromirror dynamic response characterization

Finally, a doubled YAG laser source was focussed on groups of micromirrors to evaluate damage threshold. The micromembranes were illuminated with a fixed laser intensity. After each illumination session of a few minutes, the micromirrors were examined with a microscope to verify if visible damage had occurred. Laser intensity was then increased and the procedure repeated until the mirrors were damaged.

4.1. Static response characterization

The micromirror curvature at rest (no voltage applied) depends on the residual stress in the membrane. A compressive residual stress causes a convex initial curvature while a tensile residual stress results in a downward membrane deflection. The residual stress can be modified, to some extent, by varying the aluminum alloy deposition parameters. Using such deposition parameter variation, it has been possible to fabricate micromirrors exhibiting various initial curvatures.

Typical static responses for micromirrors exhibiting residual compressive and tensile stresses are presented in figure 8. In the case of the membrane with a compressive stress, a voltage bias is necessary to bring back the mirror curvature to a minimum value corresponding to a deflection of 0 µm. In the present example, this offset voltage is about 136 V and a deflection of 0.8 µm
corresponding to f/2 is reached with 233 V. The membrane with a tensile residual stress exhibits a downward deflection at 0 V. In the example shown, this deflection is 0.25 µm which represents a significant portion of the required deflection range. A deflection of 0.8 µm corresponding to f/2 is obtained with 158 V.

From these examples, it is clear that a membrane with a tensile residual stress has the advantage of reaching the maximum required deflection at a lower voltage than a membrane with a compressive residual stress. However, this reduced actuation voltage for membranes with a residual tensile stress is obtained at the expense of a significant decrease in the useful deflection range. This is an important drawback. The larger deflection range available for membranes with a compressive residual stress and the corresponding larger pixel intensity change are key features for projection applications. Although they typically require a higher activation voltage, these micromirrors seem a better choice for projection engines than FRAM with tensile stress.

![Graph A]

**Figure 8.** A) Static response of a micromirror with compressive residual stress  B) Static response of a micromirror with tensile residual stress. Nominal micromirror dimensions are L: 25 µm, W: 25 µm, t: 0.15 µm and G: 4.7 µm for both cases.
4.2. FRAM dynamic response
The dynamic responses for micromirrors with a compressive or a tensile residual stress were measured. Results are presented in figure 9 for membranes moved from the minimum to the maximum deflection and then back to the minimum deflection. The voltage waveforms used to control the membranes are also shown. In the compressive residual stress case, the activation voltage waveform is added to the voltage offset which is required to achieve an initial membrane deflection of 0 µm. In this case, the membrane stabilizes in about 10 µs. With the voltage waveform used, the stabilization time is even longer when the micromembrane is deactivated. These relatively long settling times indicate that the transient times of the voltage waveform (less than 2 µs) were not correctly adjusted for activation of the micromirror under test. Based on the simulation results presented above and on the observed response, it is clear that the settling times of the tested mirror could be improved by increasing the voltage transient times to 3 or 4 µs.

In the case of a membrane with a tensile residual stress, no voltage offset is applied to the membrane under test. A voltage waveform with a transient time of 3 µs has been used to control the micromirror. When activated, the micromembrane stabilizes in 4 µs and the settling time required to bring it back to its minimum deflection position is less than 5 µs.

Figure 9. A) Dynamic response of a micromirror with compressive residual stress. B) Dynamic response of a micromirror with tensile residual stress. Nominal micromirror dimensions are L: 25 µm, W: 25 µm, t: 0.15 µm, and G: 4.7 µm in both cases.
4.3. Damage threshold evaluation
The tests performed to estimate the membrane damage threshold demonstrated that no visible damage is produced on the micromirror for incident laser intensities up to 8000 W/cm\(^2\). However, permanent membrane deformations are observed for a laser intensity of 16000 W/cm\(^2\). Although the actual damage threshold was not precisely pinpointed, these experimental results still agree with the simulations reported in section 2.3 which evaluated a damage threshold higher than 8000 W/cm\(^2\). These simulations also predicted that thermally generated stresses exceeding the material yield would cause the device failure.

5. Projection engine prototypes
As part of the technology development, two projection engines have been built to demonstrate the principle. These engines include control software and electronics driving packaged FRAM linear arrays. They were integrated with illumination systems based on doubled YAG lasers. A line of light produced by these systems illuminates the micromirror arrays. For each setup, the light reflected by the micromirror array is collected by an optical relay which produces an image of the modulator array. A stop is positioned in the Fourier plan of the relay to block part of the collected light. The intensity of a given modulator image at the optical relay output depends on the amount of light coming from this modulator and not blocked by the stop (see figure 1). This amount of light is controlled by the curvature of the micromirrors. A galvanometer and projection optics located at the optical relay output produce the final 2-D image.

Characterization of these prototypes has revealed contrast values up to 300. The contrast is defined as the ratio between the intensity for a fully on pixel and the intensity for a fully off pixel, the intensity being measured at the optical relay output. For these measurements, a CCD camera combined with a commercial beam analyser were used. A 10 X objective magnified the image at the relay output prior recording by the CCD camera. In addition, the temporal response of pixels has been studied with a high speed photodetector recording pixel intensity variations at the relay output. It has been verified that the speed at which the pixel intensity can be modulated is in good agreement with response time measurements described in section 4.2.

Figure 10 shows the most recently built projection engine. This engine can display monochrome VGA video streams at the rate of 60 frames/sec. The software developed for this engine allows image data transfer compatible with DVI protocol. It also features a built-in look-up table (LUT). The default LUT used by the software includes 14-bit voltage input data varying linearly with the grey level data for all FRAM of the array. Using this LUT, the voltages applied to the FRAM are proportional to the grey levels of the original images to be displayed by the projection engine. Alternatively, the user can modify the LUT to adjust the Pixel Intensity vs Grey Level relation for each FRAM. This feature is very useful to optimize the Pixel Intensity vs Grey Level curve to match the eye response. It also allows correction of the pixel-to-pixel non uniformity if necessary. In addition, contrast, brightness and gamma correction can be performed on the images before data conversion by the LUT. It is also possible for the user to manually adjust frame synchronization and the number of displayed columns.

The architecture of the controls electronics built for the projection engine of figure 10 includes a FPGA board, a high-voltage digital-to-analog converter (HV DAC) board and a high-voltage DC power supply board. The FPGA board is dedicated to locking to the incoming video stream received from the host PC through a DVI port, management of the line-wise/column-wise addressing scheme for read/write accesses in a double-buffer memory and generation of frame synchronization for the DAC board. These tasks are controlled by a VHDL application programmed in the FPGA (Xilinx Virtex-2 Pro). Images are sent from the FPGA board to the DAC board through a CameraLink port.
The CameraLink port provides 24 independent data channels and each channel is used as a serial data link to access the serial input port of each of 24 multi-DAC chips installed on the DAC board. The DAC board makes use of 480 individual 14-bits DAC from 24 AD5535 Analog Devices chips populating a printed circuit board. A common voltage reference is connected to each AD5535 chip. This signal allows adjustment of the maximum output voltage from 50 to 200 V. As mentioned above, the number of 480-pixel columns that is written into the DAC for each image frame is defined by the user and can vary from 480 to 640. If desired, this allows the adjustment of the time available for the HV DAC to display each image column. The DAC board also provides a signal available to drive a galvanometer which is the scanning device typically used to produce a 2-D image. This signal is a periodic triangular waveform synchronized with the frame rate of the incoming video stream. In addition, the rising time, falling time and amplitude of the triangular waveform can be set with potentiometers part of the galvanometer driver circuit located on the DAC board. More details on this control electronics can be found in reference [5].

![Figure 10. The projector engine and part of the optical test bench.](image)

The developed engine relies on a 480x1 FRAM array for light modulation. Due to the large number of inputs for this chip, a custom package and packaging procedure were developed to connect all 480 micromirrors of the array to the control electronics. The selected packaging approach is a modified die-on-board packaging method. A flex board exhibiting rigid central and external portions is used for this approach. Standard high pin count connectors are soldered to the external rigid portions of the board. A hermetic enclosure with an optical window is clamped to the central portion of the board. The micromirror array is mounted in this enclosure filled with a dry nitrogen atmosphere. The central rigid portion of the flex board exhibits bonding pads to which the FRAM are connected. The hermetic enclosure has been designed to allow easy rework of the package and regeneration of the dry nitrogen atmosphere, if necessary. The main purpose of the flexible portions of the board is to provide some degree of freedom during optical alignment of the FRAM array. Resulting packaging assembly is shown in figure 11. As can be seen in figure 10, this assembly is connected directly to the DAC board which completes the projection engine. All components of the projector engine have been assembled within an existing test bench (figure 10). This test bench provides the required optical setup to produce images with the fabricated projector engine. Tests confirmed functionality of all features of the engine and projection of VGA video streams at a frame rate of 60 Hz.
6. Preliminary scale down study
Initial development of the technology was triggered by identified needs linked to flight simulation for jet fighter pilots. For such application, size and weight of the projector were not such a concern. Therefore, until recently, no effort had been devoted to minimizing the size of the projection engine based on FRAM. This resulted in the test bench shown in figure 10 which has a volume of about 0.2 m³. However, for some applications, it is essential to strongly reduce this size. As a preliminary target, the possibility of decreasing the FRAM active area from 25 µm x 25 µm to 5 µm x 5 µm has been investigated. As a starting point, electromechanical simulations have been performed with Intellisuite™ to assess the performance of such micromirror. For these simulations, the FRAM material was an aluminum alloy with a density of 2.7 g/cm³, Young’s modulus of 70 GPa and Poisson’s ratio of 0.36. The membrane surface (active area) and the actuation electrode dimensions were set to 5 µm x 5 µm. The mirror/substrate gap was fixed to 1.5 µm. For a membrane thickness of 40 nm, a mirror deflection of 0.25 µm corresponding to f/1.25 was obtained of an actuation voltage of 107 V. Due to the small mirror size and optical design requirements, the f-number at maximum deflection was set at 1.25 instead of 2 (see section 2 above) to insure sufficient reflected beam divergence. For this mirror thickness, activation at full deflection generates a relatively high stress above 250 MPa in the structure. From these preliminary results, feasibility of a 5 µm x 5 µm FRAM seems possible although optimization of the structure is still required to reduce the stress at maximum deflection.

Figure 11. Packaging assembly for a 480x1 FRAM array.

Another interesting characteristic of these micromirrors is their capability to withstand high incident power density. This is of particular interest for various applications and it was important to estimate the damage threshold for FRAM with reduced active area. The approach used for this evaluation is the same that produced the results presented in section 2.3. As previously, the damage threshold was defined as the incident power density generating maximum stress in the structure corresponding to the yield stress of aluminum alloy. Results of this study are presented in table 2 below.

As can be seen in table 2, the damage threshold increases for smaller micromirrors since the effective thermal resistance is lower for these shorter structures and heat is more readily evacuated toward the substrate. Within the assumption underlying these simulations, the damage threshold is driven by the stress generated by the temperature increase. As can be seen, aluminum alloy yield stress is reached for fairly low temperatures. This is due to the relatively high structure stiffness and to the mismatch of coefficient of thermal expansion (CTE) between the mirror and the silicon wafer covered with a silicon nitride layer used as substrate. The maximum total power illuminating a 1000x1 FRAM array decreases for smaller micromirrors. This is due to the decrease in total array area which cannot
be fully compensated by the damage threshold increase. For applications requiring higher incident power, approaches have been identified to further improve the micromirror damage threshold. One possibility would be the addition of buffer layers of appropriate material at strategic locations to decrease the stress due to CTE mismatch. Another approach would involve the improvement of mirror reflectivity to decrease the amount of light absorbed by the mirror. As for previous simulations, the results of table 2 were obtained assuming mirror absorption of 10%. It is believed that this absorption could be reduced to 5% or less by using proper reflective coating on the FRAM. This would result in significant improvement of the damage threshold and substantial increase of the maximum incident power.

Table 2. Thermal simulation estimates for damage threshold

| Mirror size (µm) | Gap size (µm) | Thickness (µm) | Damage threshold (W/cm²) | Total powera (W) | Maximum temperatureb (°C) |
|------------------|--------------|----------------|-------------------------|------------------|--------------------------|
| 25 x 25          | 4.5          | 0.15           | 8 850                   | 55               | 76                       |
| 15 x 15          | 2.8          | 0.1            | 13 400                  | 30               | 69                       |
| 5 x 5            | 1.5          | 0.04           | 25 600                  | 6.4              | 54                       |

aTotal power: power incident on a 1000x1 mirror array at estimated damage threshold. bMaximum temperature reached at damage threshold, substrate kept at 20 °C.

The results presented above give preliminary indications that functional micromirrors exhibiting an active surface as small as 5 µm x 5 µm should be feasible. Another interesting aspect of this scale down study was to determine the minimum dimensions for a projector based on FRAM arrays presenting a reduced size. The optical design of this concept of miniaturized projector is based on a 1000x1 array of 5 µm x 5 µm micromirrors. The maximum deflection for these mirrors is assumed to be 0.25 µm which corresponds to f/1.25. Illumination of the array is performed with a focused laser line with a width of 2 µm. Generation of this line is based on f/3 cylindrical optics and requires a source with good optical quality to achieve the required line narrowness. The targeted throw distance is 15 cm. The resulting design is depicted in figure 12.

![Conceptual design of a miniaturized projector based on a 1000x1 array of 5 µm x 5 µm micromirrors. A) General view of the system showing the throw distance. B) Enlarged view of the projector showing details of the optical system.](image)

**Figure 12.** Conceptual design of a miniaturized projector based on a 1000x1 array of 5 µm x 5 µm micromirrors. A) General view of the system showing the throw distance. B) Enlarged view of the projector showing details of the optical system.

This projector concept exhibits a volume of about 12 cm³. This volume does not take into account the generation of the collimated beam at the input of the system. Preliminary evaluation of this non
optimized design shows some image distortion. The estimated resolution is about 40 µm at the centre of the image plane and about 400 µm in periphery. In practice, aberrations will limit the contrast of the designed system. It is likely that correction of these aberrations will be difficult due to the limited number of optical components that can be used for this miniaturized projector. Custom aspherical components would possibly be needed.

7. Conclusions
INO and partners have been working on a MEMS based technology for light modulation and projection display. This technology relying on flexible reflective analog modulators has been reviewed in this paper. Typical results have been provided regarding simulations of these microdevices and their fabrication. Characterization of the fabricated micromirrors has revealed activation voltages below 250 V with response times below 10 µs. With appropriate actuation voltage waveforms, response times of 5 µs and less are achievable. A damage threshold of the mirrors above 8 kW/cm² has been evaluated. Projector engines based on the FRAM have been built to demonstrate the technology principle. The most recent of these engines is DVI compatible and displays VGA video streams.

In addition, preliminary results of a technology scale down study have been reported. FRAM with active surface as small as 5 µm x 5 µm have been investigated. Electromechanical simulations have shown that such micromirrors could be activated with 107 V to achieve f-number of 1.25. However, the stress level generated in the structure at full actuation is high and further optimization is necessary to decrease this stress. The damage threshold has been estimated for various FRAM sizes. The damage threshold increases with decreasing active areas due to improved thermal coupling with the substrate. However, this increase cannot fully compensate for the decrease in active area when smaller micromirrors are used. Therefore, the maximum incident power allowed for illuminating an array of a given size increases with the micromirror dimension. Augmenting the available incident power is possible by further reducing the damage threshold. Possible approaches to do so have been suggested. Finally, design of a conceptual miniaturized projector based on FRAM array has been presented. The optical design is based on a 1000x1 array of 5 µm x 5 µm micromirrors for which the f-number reaches 1.25 at maximum deflection. The throw distance specified for the projector is 15 cm. This projector concept exhibits a volume of about 12 cm³. Although not optimized and still exhibiting some performance problems, this preliminary design and other results related to the scale down study provide interesting insights and suggest directions for a significant miniaturization of the technology. This is encouraging considering the importance of such miniaturization for most display and light modulation technologies.

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