Overview of Deformable Mirror Technologies for Adaptive Optics and Astronomy

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ABSTRACT

From the ardent bucklers used during the Syracuse battle to set fire to Romans' ships to more contemporary piezoelectric deformable mirrors widely used in astronomy, from very large voice coil deformable mirrors considered in future Extremely Large Telescopes to very small and compact ones embedded in Multi Object Adaptive Optics systems, this paper aims at giving an overview of Deformable Mirror technology for Adaptive Optics and Astronomy.

First the main drivers for the design of Deformable Mirrors are recalled, not only related to atmospheric aberration compensation but also to environmental conditions or mechanical constraints. Then the different technologies available today for the manufacturing of Deformable Mirrors will be described, pros and cons analyzed. A review of the Companies and Institutes with capabilities in delivering Deformable Mirrors to astronomers will be presented, as well as lessons learned from the past 25 years of technological development and operation on sky. In conclusion, perspective will be tentatively drawn for what regards the future of Deformable Mirror technology for Astronomy.

Keywords: deformable mirror, piezoelectric material, electrostrictive material, MEMS, bimorph mirror, membrane mirror, stacked array mirror

1. INTRODUCTION

The resolution of ground based astronomical telescopes is severely limited by the aberrations introduced by the atmosphere during optical beam propagation. To overcome this problem, H. W. Babcock first proposes in 1953 [1] the concept of adaptive optics. It consists in placing an optical corrector in a pupil image plane and in controlling in real-time its shape to compensate for the aberrations introduced by the atmosphere. The first optical corrector proposed by Babcock in his founding paper was the so-called Eidophor made of a thin layer of oil covering a reflecting mirror. Electric charges are deposited on the surface of the oil film and, through electrostatic forces, the oil film is distorted according to the charge spatial pattern. This was the first proposal of Deformable Mirror (DM). This component was slow, chromatic and very sensitive to environment.

Since then, following the invention of the laser and with the impetus given my military research, DM technology has been developed and has triggered the interest of many small to large size companies.

In the following sections, a review of the actual available DM technologies is proposed, focused on astronomical applications. In section 2, the main drivers for the design of DMs are recalled, not only related to atmospheric aberration compensation but also to environmental conditions or mechanical constraints. Section 3 details the different technologies available today for the manufacturing of DMs; pros and cons are also analyzed. Section 4 presents the Companies and Institutes having capabilities in delivering DMs to astronomers. Finally, section 5 concludes this review.

2. DEFORMABLE MIRROR REQUIREMENTS

The requirements set to the DM of an Adaptive Optics (AO) system come from the overall AO error budget. Depending on the final science requirements driving the design of the instrument, its associated AO module can be of different instances: Single Conjugate AO (SCAO), Laser Tomography AO (LTAO), Multi Conjugate AO (MCAO), Multi Object AO (MOAO) or Extreme AO (XAO). While it is (far…) beyond the scope of this paper to present comprehensively such error budgets, it is important to recall their main contributors and to show how they link with the DM requirements. This

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is the purpose of the section 2.1 where only SCAO, MCAO and XAO are considered for the sake of simplicity. In the sections 2.2 to 2.6, the main DM requirements flowing down from the AO error budget are presented and are finally summarized in the section 2.7. These requirements are defined for 8m and 40 m class telescopes.

2.1 AO (rough) error budget

The purpose of this section is certainly not to provide extensive error budgets for all the different flavors of AO systems, but to focus on the main contributors impacting on the DM specifications. Assumptions will be made and numbers will be given which do not reflect perfectly the actual status of instruments at use on sky or under development but have more to be considered as orders of magnitude to illustrate what could be the design of a DM.

In most of the cases, science instruments define a Strehl Ratio (S_R) as specification to their associated AO module. This translates into a residual phase variance that can be further broken down into different contributors. A very rough error budget can then be expressed following:

$$\sigma_{res}^2 = \sigma_{fitting}^2 + \sigma_{temporal}^2 + \sigma_{noise}^2 + \sigma_{tomo}^2 + \sigma_{miscel}^2 \quad (1)$$

where $\sigma_{fitting}^2$ represents the error due to the finite number of DM actuators, $\sigma_{temporal}^2$ the error due to the finite bandwidth of the DM, σ_{noise}^2 the error due to the measurement noise, σ_{tomo}^2 the error in the tomographic reconstruction of the turbulent volume above the telescope (in the case of SCAO this is simply the anisoplanatism error) and eventually σ_{miscel}^2 all the other contributors to the error budget (as for example the aliasing error, the chromatism error, etc…).

Amongst all these sources of errors, only the two first ones are of interest when specifying a DM.

The fitting error can be expressed following ([2], [3]):

$$\sigma_{fitting}^2 = k \left({}^{D}/_{r_0} \right)^{5/3} N^{-5/6} \quad (2)$$

with D the pupil diameter and r_0 the so-called Fried parameter. N is the maximum number of DM actuators and k is a factor which depends on the shape of the DM influence function. In this paper, a value of 0.3 is attributed to k.

The temporal error is simply given by ([3]):

$$\sigma_{temporal}^2 = \left({}^{\tau}/_{\tau_0} \right)^{5/3} \quad (3)$$

where τ is the time lag in the AO loop and τ_0 represents the atmospheric coherence time ([3]) following:

$$\tau_0 = 0.314 \, {}^{r_0}/_{v} \quad (4)$$

with v the mean wind speed weighted by the turbulence profile along the line of sight of the telescope.

Before breaking down the error budget it is important to specify the expected S_R. This depends obviously on each specific science instrument to consider and no general rule can be given; this is why the following numbers have to be considered only as an educated guess used to define orders of magnitude for the DM requirements.

For SCAO systems, it is proposed to consider a S_R of 50% defined at 2.2 µm for a 0.7 arcsec seeing (defined at 0.5 µm). This gives a residual phase variance of 0.7 rad^2 which can be broken down into 0.15 rad^2 for the fitting error, 0.15 rad^2 for the temporal error and into 0.2 rad^2 for the two remaining terms. The miscellaneous error term is neglected here.

For MCAO systems, the same requirements are considered but within a 2 arcmin field of view; this also gives a residual phase variance of 0.7 rad^2 which can be broken down in the same way it is done for SCAO. It has to be noticed that in the case of MCAO, multiple DMs are used conjugated at different altitudes. To define the number of actuators required per DM, the total amount of actuators projected inside the pupil has to be considered.

For XAO systems, it is proposed to consider a S_R of 90% defined at 1.6 µm for a 0.6 arcsec seeing (defined at 0.5 µm). This gives a residual variance of 0.1 rad^2 which can be broken down into 0.05 rad^2 for the fitting error, 0.02 rad^2 for the temporal error, 0.01 rad^2 for the noise error and 0.02 rad^2 for the miscellaneous term. As XAO is always using the science target as reference source, the anisoplanatic error can be neglected. It has to be noted that for XAO systems, the error budget is not really driven by the S_R but by the contrast achievable in the close vicinity of a star. The different terms of the error budget are then defined from this criterion which at the end leads to a very demanding S_R.

2.2 Number of actuators

- *8m class telescopes*

For SCAO systems, considering a 0.15 rad^2 fitting error at 2.2 µm for a 0.7 arcsec seeing, equation (2) gives 190 useful actuators in the pupil which corresponds to a 16x16 actuator DM (cartesian geometry). This is pretty much matching the design of the NAOS DM on the VLT [4].

For MCAO systems, let's assume that three DMs are used: one conjugated to the ground, one at 5000 m and the final one at 10000 m. Let's also consider that these three DMs have the same number N of actuators. The diameter of the meta-pupil at 5000 m is equal to 11 m (2 arcmin field of view) while the one at 10000 m has a diameter of 14 m. The total number of actuators projected in the pupil is given by $N_{tot} = N\left(1 + \left({}^{8}/_{11}\right)^2 + \left({}^{8}/_{14}\right)^2\right) = 1.9\,N$ providing there is no overlap between the projections in the pupil of the different DM actuators. To account for such overlap, let's assume that $N_{tot} = 2\,N$. Considering a 0.15 rad^2 fitting error at 2.2 µm for a 0.7 arcsec seeing, equation (2) gives $N_{tot} = 190$ which in turn gives N=95 useful actuators for each DM (11x11 in case of a Cartesian geometry).

For XAO systems, considering a 0.05 rad^2 fitting error at 1.6 µm for a 0.6 arcsec seeing, equation (2) gives 1200 useful actuators in the pupil which corresponds to a 40x40 actuator DM (cartesian geometry). This corresponds to the actual design of the SPHERE DM [5].

- *40m class telescopes*

For SCAO systems, considering a 0.15 rad^2 fitting error at 2.2 µm for a 0.7 arcsec seeing, equation (2) gives 4700 useful actuators in the pupil which corresponds to a 80x80 actuator DM (cartesian geometry). This is less than what is foreseen for M4, the 2.4 m diameter deformable mirror located in the E-ELT optical path [6], but the order of magnitude is correct.

For MCAO systems, let's take the same assumptions than for the 8m class telescopes; this gives $N_{tot} = 2.6\,N$. Considering a 0.15 rad^2 fitting error at 2.2 µm for a 0.7 arcsec seeing, equation (2) gives $N_{tot} = 4700$ which converts to $N = 1800$ useful actuators for each DM (50x50 in case of a Cartesian geometry). This compares quite well to what is foreseen for MAORY, the MCAO module of the E-ELT [7].

For XAO systems, considering a 0.05 rad^2 fitting error at 1.6 µm for a 0.6 arcsec seeing, equation (2) gives 29000 useful actuators in the pupil which corresponds to a 200x200 actuator DM (cartesian geometry), as in the case of EPICS the XAO system of the E-ELT[8]

2.3 Actuator pitch

The actuator pitch requirement is mainly driven by the optical design of the AO module. Depending where the DM is located (post focal AO module or optical train of the telescope) this value can vary a lot. In both cases, the DM has to be located in a pupil plane, except for MCAO systems where only one DM is there.

The main interest to locate the DM in the telescope optical train is to reduce the number of optical surfaces through which the science photons have to go before reaching the science camera. The price to pay is the development of large DMs whose typical size ranges from 1 m diameter (LBT or VLT deformable secondary mirrors) to 2.5 m in the case of the E-ELT. The pitch size is then defined either by the required number of actuators or by technological constraints. In the case of LBT, VLT and E-ELT a typical value is 30 mm.

When located in a post focal AO module, optical designers have more freedom to define the clear aperture of the DM. To reduce the size of the instruments, it is of great interest to limit the size of the pupil as much as possible. During the last decades, this was limited by the DM technological constraints preventing to have pitches smaller than 4 to 5 mm. Typical DM diameters for few hundreds actuators were in the range of 150 mm (5 to 8 mm pitch).

In the mean time MEMS technology made progress in the field of DM, and pitches in the range of 0.5 mm are now accessible (see section 3.4). This opens the door for compact multi 10k actuator DMs required for ELTs' XAO but cannot be exploited for all AO systems. For wide field AO systems of 40m class telescope, it is not possible to set the pupil magnification below a certain threshold. The main reason for that has to do with the Abbe equation. In case the pupil magnification is too small, the associated field of view at the level of the pupil image becomes too large and cannot be managed in a proper way by the pupil imaging optical system: pupil aberrations become too large. For a 2 arcmin

field of view AO system, the size of the DM cannot be smaller than 200 mm. In most of the cases, a final diameter of 300 to 400 mm reduces the risks on the complete optical design. Considering a 400 mm diameter pupil image, the pitch for the SCAO DM is in the range of 5 mm while it goes to 7 mm for MCAO DMs. For XAO systems the diameter of the pupil image can go down to 200 mm which gives a 1 mm pitch for the DM.

2.4 Actuator mechanical stroke

The mechanical stroke required for a DM is defined not only by the amount of turbulence to compensate for, but also by the request to flatten the DM optical surface itself, to compensate for the telescope residual aberrations and very often for the telescope vibrations.

The mechanical stroke requested by the atmospheric aberrations is given by:

$$\delta = \frac{3\,\lambda}{2\,\pi}\,\sqrt{l}\,\left(\frac{D}{r_0}\right)^{5/6} \tag{5}$$

where $l = 1.03$ if the DM compensates for the total amount of aberrations and $l = 0.134$ in case the DM does not compensate for the tip-tilt. In this equation, λ is the wavelength at which r_0 is defined; r_0 being proportional to $\lambda^{6/5}$ the DM stroke is achromatic.

In the ideal case, it is preferred to have the DM also taking care of the tip-tilt compensation but very often the technology does not allow getting enough mechanical stroke for that. The use of an additional tip-tilt mirror is then required.

To specify the DM mechanical stroke, AO engineers shall not consider only the nominal operational seeing. It is well known that the seeing can have quite strong short term evolution (burst of turbulence) and it cannot be accepted to lose an observation because the AO loop crashes due to DM saturation. To improve the robustness of AO systems, the DM stroke is specified for large seeing values considered as a worst case. In the following, a worst case seeing of 2.5 arcsec is used to specify the stroke.

- *8m class telescopes*

Using equation (5), the stroke required to compensate for the turbulence excluding tip-tilt is equal to 7 µm. Adding one extra micron for flattening the DM and another one to compensate for telescope aberrations gives a grand total of 9 µm. This corresponds to the stroke specified for the DM of NAOS.

- *40m class telescopes*

Using equation (5), the stroke required to compensate for the turbulence excluding tip-tilt is equal to 28 µm.

In the case of a secondary DM, it is necessary to add 5 µm for flattening the DM, 5 µm to compensate for telescope aberrations and also a provisional 10 µm to correct the aberrations coming from the mechanical flexures of the DM itself (2.5 m diameter mirror). For the E-ELT the DM (M4) is also asked to compensate for the residual tip-tilt left uncorrected by the tip-tilt mirror (M5). This additional term amounts to almost 40 µm in the worst case; summing up quadratically these 40 µm with the 28 µm requested for the high order atmospheric aberrations, one ends up with a 50 µm stroke for time evolving aberrations. Accounting eventually for the correction of static aberrations gives a grand total of 70 µm.

For MCAO, altitude DMs will have to compensate neither for telescope aberrations, vibrations nor for residual tip-tilt. Only high altitude turbulence has to be corrected for. Assuming two altitude DMs and that 40% of the full atmospheric stroke is provided by the pupil DM, each additional DM needs an 8.5 µm stroke. Accounting for an extra 1 µm to flatten each DM, final required stroke is close to 10 µm.

For XAO, the small pitch does not allow to get large mechanical strokes. The idea is to work in a woofer-tweeter mode where a first DM is used to compensate for large stroke “low” order aberrations while the tweeter exhibits a large number of actuators but only little stroke. For the E-ELT the woofer could be M4. This means that the tweeter has only to correct for the residual high order aberrations. A stroke of 2 to 3 µm is enough.

2.5 Temporal response

The temporal response of the DSM is driven by the AO loop frequency requirements. Associated to the allocated temporal error, the equations (3) and (4) define the maximum time lag of the AO loop which in turn gives the AO loop frequency keeping in mind that in most of the cases, an AO loop exhibits a two frame time lag. Assuming a simple

integrator term in the loop, the open-loop cut-off frequency is equal to 0.08 times the AO loop frequency [3]. To avoid slowing down the AO loop and impacting its temporal performance, the DSM temporal transfer function shall not show any resonance and shall exhibit a phase lag smaller than 5 degrees within the AO control bandwidth.

For a 0.7 arcsec (resp. 0.6 arcsec) seeing and a 15 m/s wind speed, τ_0 is equal to 3 ms (resp. 3.6 ms) at 0.5 µm.

For SCAO and MCAO systems, the temporal error is allocated 0.15 rad^2 at 2.2 µm. Equation (3) gives a maximum time lag of 6 ms which in turn corresponds to a 340 Hz AO loop frequency. This is pretty much comparable to the specifications of [4]NAOS. 340 Hz control frequency leads to a 27 Hz open-loop cut-off frequency: the phase lag introduced by the DM transfer function has to stay below 5 degrees at least up to 30 Hz. It has to be noticed that in the case of the E-ELT, the control frequency of M4 has been set to 1 kHz; this is justified by the need to compensate for the residual wind shake and vibrations of the telescope. This corresponds to an 80 Hz open-loop cut-off frequency, and requires the M4 transfer function phase lag to be better than 5 degrees up to 80 Hz.

For XAO systems, the temporal error is allocated 0.02 rad^2 at 1.6 µm. Equation (3) gives a maximum time lag of 1.4 ms which in turn corresponds to a 1.4 kHz AO loop frequency. This is quite close to the control frequency of the AO loop of SPHERE [5]. The phase lag of the associated DM transfer function has to stay below 5 degrees up to 110 Hz.

2.6 Miscellaneous

Besides these major requirements, some other important DM features have to be specified. Most of them are related to environmental conditions and reliability.

The DMs have to be fully operational for temperature ranging from -10C to +20C.

They have to be very reliable, with a MTBF better than 3 to 5 years; it has to be noted that the failure of a single actuator cannot be considered as a failure of the DM as long as the remaining ones are still fully operational and the closed-loop optical figure of the DM is not degraded significantly. It is generally admitted than less than 5% of failed actuators are acceptable providing they are randomly distributed over the clear aperture of the DM. The capability to replace any faulty actuator is certainly an asset.

Even if it is not planned in this paper to discuss the issues related to the DM drive electronics, technologies based on low voltage DM are very much appreciated, allowing for compact and low dissipation drivers and reducing the size of the cable bundles which will become a serious practical issue for the high order DMs required in the ELTs era.

2.7 Summary

The outcome of previous sections is summarized in the Table 1.

Table 1. Specifications of DMs depending on their field of application

	8m class telescope			40m class telescope		
	SCAO	MCAO	XAO	SCAO	MCAO	XAO
number of actuators	200	100	1200	5000 - 6000	2000	30000
pitch (mm)	30[i)] / -[ii)]	-[ii)]	- [ii)]	30[i)] / 4 to 5	6 to 8	1
mechanical stroke (µm)	10	6 to 10	10	70 to 80	10	2 to 3
control bandwidth[iii)] (Hz)	30	30	110	80	40 to 80	110

i) 30 mm pitch is given for a 1m class secondary deformable mirror
ii) there is no particular requirement for this parameter: it depends on the system design and constraints
iii) within this bandwidth, the phase lag of the DM transfer function has to be smaller than 5 degrees

3. DEFORMABLE MIRROR TECHNOLOGY

The development of deformable mirrors for AO systems started in the early 1970s mainly driven by military contracts. Many different concepts were proposed and studied at that time; the most popular ones were based on the use of ferroelectric (piezoelectric or electrostrictive) materials: capability to deliver high force, high accuracy, fast response time, low power dissipation. This was the case for continuous face sheet stacked array DMs and for bimorph DMs which are nowadays widely used in AO for astronomy.

In the early 1990s, thanks to the technological progresses made in the field of real-time computers and optics, the concept of large secondary DMs has been introduced; it is based on the use of voice coil actuators controlling the shape of a thin optical shell. The MMT and the LBT are already equipped with such secondary DMs and so will be the VLT.

Latter in the 1990s a new category of DMs appeared following the advent of MEMS technology: very compact, light weighted, low drive voltage hardware which can take advantage of economies-of-scale to bring significant cost reductions.

And finally more recently, first prototypes of optically addressed DMs were manufactured and few test results reported in the literature. The main interest of this new concept is to allow for wireless high degrees of freedom DMs.

These different kinds of DMs are described in the following sections.

3.1 Stacked array DMs

Stacked array DMs are using ferroelectrics actuators made of stacks of individual plates or disks (see Figure 1). The ferroelectrics material can be either of piezoelectric or electrostrictive form. Lead zirconate titanate $Pb(Zr, Ti)O_3$ (PZT) and lead magnesium niobate $Pb(Mg_{1/3}Nb_{2/3})O3$ (PMN) are respectively the most commonly used piezoelectric and electrostrictive materials The physics of the piezoelectric or electrostrictive effects is beyond the scope of this paper and will not be recalled; the reader is invited to refer to the chapter 4.2 of [5] for more details.

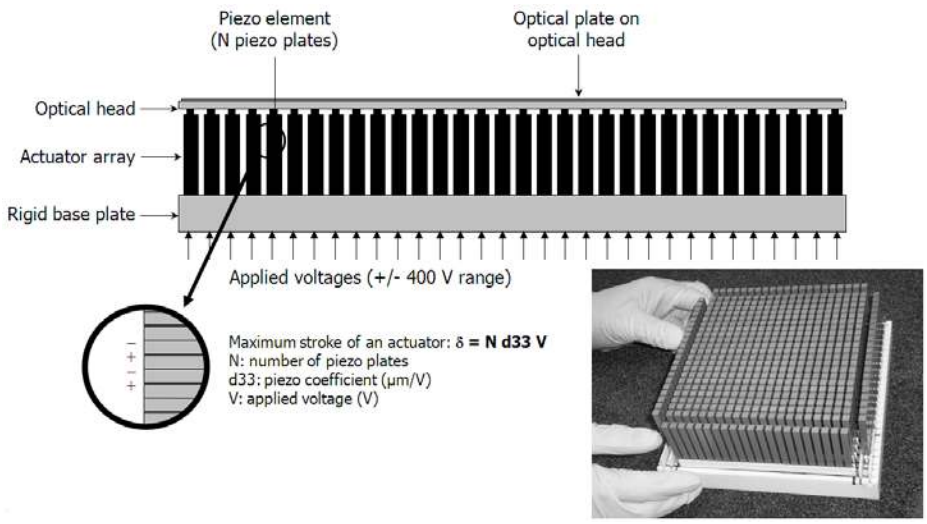

Figure 1. Stacked array DM concept. An optical head is assembled on top of an array of ferroelectric actuators. Each actuator is made of a stack of plates. Electrodes are deposited between each plate. The array of actuators is glued on a rigid base plate (courtesy CILAS).

When applying an electric field to a ferroelectric plate, it is possible to change its dimension. Elongation in the direction of the electric field is known as the longitudinal effect when the electric field is parallel to the poling axis of the material while the transverse effect is referring to an electric field perpendicular to this poling direction. For stacked array mirrors, the longitudinal effect is at play.

PZT is a poled ceramic whose longitudinal elongation is proportional to the applied voltage following $\Delta e = d_{33}V$ where V is the applied voltage and d_{33} is the longitudinal piezoelectric coefficient. For hard piezoelectric materials which show a small hysteresis, d_{33} is of the order of 0.3 µm/kV. Using stacks of PZT plates amplifies the elongation as a function of the number of plates used. For example, PZT actuators made out of 40 plates can provide a ±5 µm stroke for a ±400 V control voltage. Piezoelectric properties of PZT are almost insensitive to temperature, within the usual observatory temperature range.

PMN is a non-poled ceramic whose longitudinal elongation is proportional to the square of the applied voltage and is inversely proportional to the thickness of the plate following $\Delta e = a\left({V^2}/{e}\right)$ with a the electrostriction coefficient and e the thickness of the plate. By designing properly the drive electronics, it is possible to "linearize" the behavior of the

PMN. One interesting feature of the PMN material is that stacked actuators can be manufactured using a process similar to the one employed in the multilayer capacitor industry, allowing massive production of actuators and reducing dramatically their cost. Individual equivalent plate thickness can be as small as 150 µm leading to very compact actuators. Usually, PMN actuators are driven between 0 and 150 V and can deliver up to a 10 µm stroke. Electrostrictive properties of PMN are well known to be temperature sensitive; for example the PMN is almost hysteresis free at 20°C while it can go up to 10% at 0°C.

Stacked array DMs are made of a reflective optical plate assembled on an array of stacked actuators lying on a rigid base plate (see Figure 1). The actuator pitch is linked to the actuator stroke: the more the stroke, the longer the actuator, the larger its section (shear stiffness) and the larger the pitch. Typically, pitches down to 5 mm can be safely obtained for 10 µm strokes. Once assembled, the DM is very stiff thanks to the individual stiffness of the actuators. This allows polishing its reflective surface following classical optical shop processes. This is also why the first eigen frequencies are far above 10 kHz, allowing for very short response times very often limited by the associated drive electronics. By carefully selecting the optical plate and the rigid base plate materials, DM athermalization can be obtained.

The design of stacked array DMs can be tuned to almost any need of the customer (very large number of actuators, small pitches, rectangular or hexagonal geometry…) making them suitable to any AO system. The main drawbacks of this technology are the high driving voltages requiring bulky electronics racks and large bundles of cables in case of multi thousands actuators, the creep inherent to the ferroelectric material, a long lead time and the cost. However, their high stiffness, high reliability, large stroke, excellent accuracy, high resonant frequencies and flexibility in actuator geometry are making this technology the most attractive for AO applications including ELTs to date.

3.2 Bimorph DMs

Bimorph DMs are based on the transverse piezoelectric effect. The bimorph concept is described in Figure 2.

When a control voltage is applied to one electrode, it creates locally an electric field which in turn induces a local transverse elongation in one wafer while the second one shows a corresponding contraction. This creates locally a bimorph effect giving rise to a curvature. Applying a given set of voltages to the bimorph DM allows controlling the shape of its optical surface.

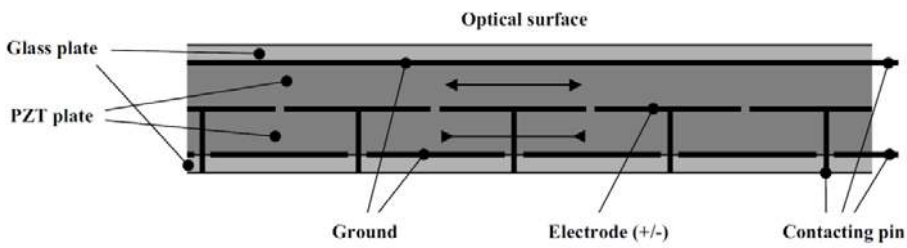

Figure 2. Bimorph DM concept. Two disks of polarized piezoelectric material are bonded together; an array of control electrodes is placed in between. On top and bottom of this sandwich, a glass plate is glued; one is used as a reflective surface, the other one is there to athermalize the DM. A ground electrode is deposited between the top/bottom of the sandwich and the glass plates (courtesy CILAS).

Let's call l the length of the electrode and t the thickness of one individual wafer, the transverse elongation in each wafer is given by $\Delta l = \pm V d_{31} \, {}^{l}/_{t}$ with d_{31} the transverse piezoelectric coefficient. This corresponds to a radius of curvature $R = {}^{tl}/_{2\Delta l} = {}^{t^2}/_{2Vd_{31}}$. The radius of curvature does not depend on the electrode size, while the stroke depends on the diameter d of the considered area following $\delta = {}^{d^2}/_{4t^2} V d_{31}$. This bending effect is competing with the local PZT induced variation of the wafer thickness and it can be shown (section 4.2.5 of [5]) that the diameter of each electrode has to be at least four times the wafer thickness to get an efficient bimorph effect.

It is worth noting that the spectrum of a bimorph deformation decreases as k^{-2} matching pretty well the one of the atmospheric aberrations ($k^{-11/6}$), making bimorph DMs excellent candidates for AO applications.

Bimorph DMs manufacturing process is much simpler than stacked array ones. There is no need to manufacture rows of actuators; one "simply" has to deposit an electrode pattern on a PZT wafer, to glue it to another one, to deposit a ground

electrode on both sides of the sandwich and eventually to glue a thin optical plate on both sides. As very often, Devil is in the details which will not be described there… Bringing the wires to the electrodes is one of these details as well as the polishing process of such thin optical device.

From a mechanical perspective, a bimorph DM is a thin circular plate that needs to be supported at its periphery by only three points to avoid introducing constraints and degrading its deformation capabilities. The first eigen frequencies of a bimorph DM are not given by the plate itself (typically few kHz) but by its mechanical mount. Resonances in the range of few hundreds Hz are very often observed.

The diameter of a bimorph DM has to be small enough to avoid resonance frequencies within the AO control bandwidth. This limits to a few hundreds the total number of electrodes within the clear aperture.

The main drawbacks of this technology are the high driving voltages requiring bulky electronics racks, the creep inherent to the ferroelectric material, low resonant frequencies and an actuator number smaller than 200 to 300; this technology is not suited to 40m class telescopes. However, their high reliability, large stroke, excellent accuracy, reasonable lead time and moderate cost are making this technology very attractive for up to 10m diameter telescopes.

For more details about the bimorph technology, the reader is invited to refer to the chapter 4.2.5 of [5].

3.3 Voice-coil actuator DMs

Voice-coil actuator technology is used to build large secondary DMs (see Figure 3). It is based on the use of a thin (less than 2 mm) optical shell "floating" on a magnetic field created by a dense array of voice coil actuators. This is made possible by gluing permanent magnets on the rear face of the thin shell. The actuators are attached on a thick metallic plate (cold plate) which is also used to dissipate the heat generated by the voice coil to a cooling circuit. The actuators are going through a thick and very stable glass plate (reference body) and are facing the magnets glued on the thin shell.

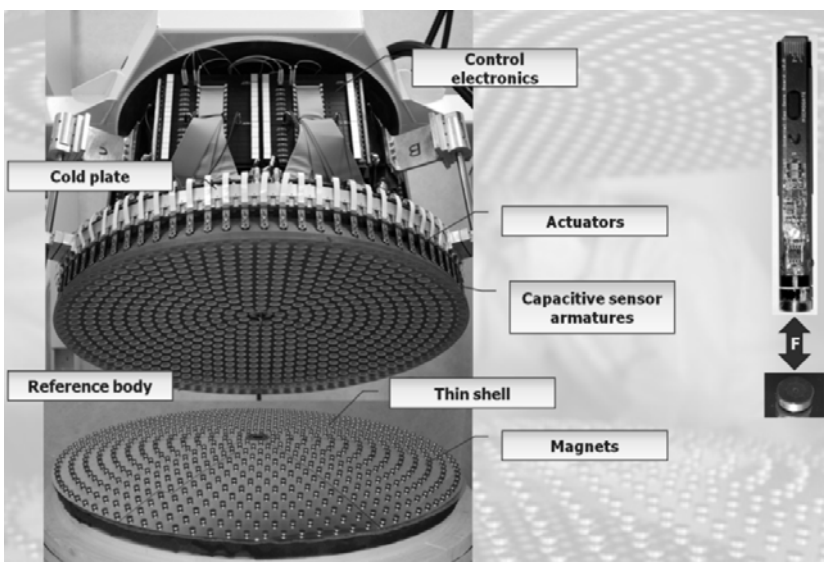

Figure 3. Voice-coil actuator DM. The concept is based on the use of a thin optical shell "floating" on a magnetic field created by a multi voice-coil actuator array. On the left-hand side a picture of the LBT secondary DM is presented, with the thin shell lying on its supporting tool. On the right-hand side, a cut-off of a voice coil actuator is shown (courtesy Microgate and ADS)

When a current is sent through a voice coil, a magnetic field is generated and creates a force which interacts with the associated thin shell magnet: the thin shell is deformed locally. To control the shell in position, a local contactless capacitive sensor is associated with each actuator; it measures locally the distance between the rear face of the thin shell and the front face of the reference body. These measurements are processed at frequencies in the range of 80 kHz thanks to a real-time computer based on on-the-shelves DSP boards. The average operating distance between the thin shell and the reference body is of the order of 50 to 70 µm. These local control loops increase the axial stiffness of the actuators, damping the resonance frequencies of the DM. Additionally, a global force feedforward allows fast response without

impairing system stability. This control scheme allows achieving a typical 1 ms response time for the position control. With this kind of technology, not only the actuators and the thin shell are critical components, but also the reference body; it is the one insuring the mechanical and thermal stability of the DM during operation. Actuator pitch is quite large, in the range of 30 mm, to avoid mutual interaction of neighboring magnets; this prevents using this technology for post focal AO systems.

Thanks to highly efficient voice-coil actuators, it is possible to get a stroke in the excess of 50 µm opening the door to atmospheric tip-tilt compensation on top of high order aberrations. The associated power consumption for 8m class telescopes is ranging from 1.5 to 2.5 kW and requires bringing coolant to the top of the telescope.

Another interesting property of this contactless actuator technology is that in case of failure of a single actuator, the surrounding ones take over the control of the shell without introducing any print-through effect in the pupil.

These nice features are not coming for free: the manufacturing process is long and risky. The thin shell on the one hand and the reference body on the other hand are delicate and fragile piece of optics. Handling procedures are at high risks (cleaning, recoating, transport), but experience shows that once in operation the safety of the thin shell is well under control thanks to the software running in the embarked real-time computer and to the hardware safety systems.

The main drawbacks of this technology are the overall complexity, the power consumption, the operation risks due to the thin shell brittleness, the manufacturing risks, a very long lead time and the cost; to be fair the lead time and the cost should be compared to the one of a classical secondary mirror. However, their reliability and maintainability (capability to replace one faulty actuator), large stroke allowing for tip-tilt correction, excellent accuracy and long term stability (no creep effect) offered by the internal metrology , short response time and athermalization have demonstrated to be very well suited to large secondary deformable mirror applications.

More details can be found in [9].

3.4 MEMS

During the 1990s, the advent of the Micro Electro-Mechanical System (MEMS) technology on the one hand and the imperious request from the customer to reduce the cost of DMs and to provide high actuator count solutions on the other hand accelerated the development of a new generation of DMs.

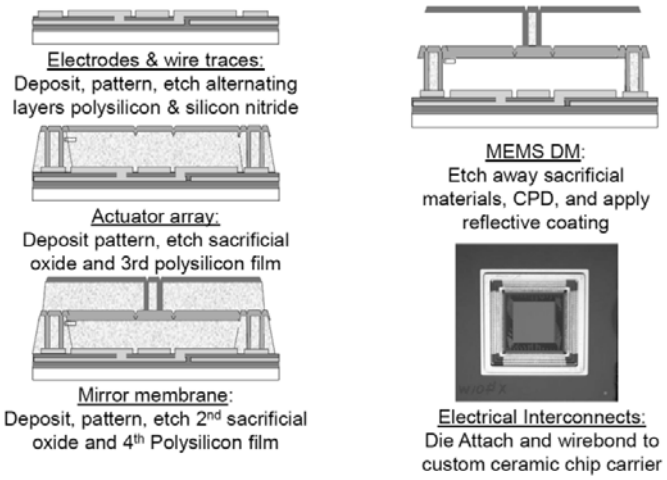

Figure 4. MEMS DM manufacturing process. Conducting and insulating layers are deposited and selectively etched to build up the electrodes, the actuator structure and the mirror membrane. The final DM is package into a ceramic chip carrier which can be sealed by an optical window to avoid the oxidation of the polysilicon membrane (courtesy Boston Micromachines Corporation)

MEMS DM manufacturing process is based on silicon computer industry technology (see Figure 4) which allows not only reducing the manufacturing cost and the delivery time but also opening the path to many different electro-mechanical concepts (see Figure 5). Most of these concepts are based on the use of a thin mirror membrane attached to

an intermediate flexible support actuated by electrostatic or electromagnetic fields. They all share the characteristics of sub millimeter pitch, low power consumption, capabilities to very high number of actuators and low mass.

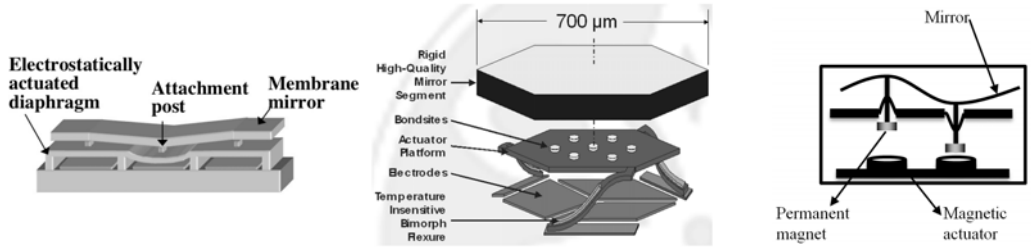

Figure 5. MEMS DM electro-mechanical concepts. Left: a continuous face sheet membrane is attached to an intermediate diaphragm whose local radius of curvature is controlled through an electrostatic field created by electrodes (courtesy Boston Micromachines Corporation). Center: the DM is made of individual segments, each of them being bonded to a platform supported by three flexures; three electrodes located beyond each platform can create three independent electrostatic fields allowing controlling the tip-tilt and the piston of each segment (courtesy Iris AO, Inc). Right: a continuous face sheet membrane is attached to intermediate flexures supporting a permanent magnet in front of which magnetic actuators are located (courtesy ALPAO).

Depending on the electro-mechanical concept at play, the internal features of the DM can be different. When actuation is based on electrostatic fields, the displacement of the membrane is proportional to the square of the applied voltage and requires applying up to 200 V to get a 5 to 8 µm stroke. Linearization of the control can be included in the DM drive electronics. If magnetic fields are used to deform the membrane, the displacement of the reflective surface is proportional to the applied voltage and low order mode strokes as high as 50 µm can be obtained for ±1 V control voltage. In both cases, there is no hysteresis and the overall mechanical behavior of the DM is insensitive to external temperature within the usual observatory thermal range.

Besides cost reduction and compactness, one important interest in MEMS technology is the scaling capability to multi thousands of actuators. Thanks to the photolithographic manufacturing process, increasing the number of actuators "simply" requires repeating the CAD generated mask. However, increasing the number of actuators also means increasing the number of control wires. In most of the cases wirebonding techniques are used to interconnect the DM wafer to its ceramic chip carrier; this requires to trace all the wires to the periphery of the substrate whose size has to grow very fast. At the end of the day, only few wafers can be manufactured in a single batch, which make them more sensitive to microscopic defects of the substrate. The yield is reduced and the associated cost of a single device increases. It is worth noting that the development time and associated cost also increases.

The main drawbacks of this technology are the small interactuator pitch, the limited stroke and the presence of an optical window in front of the DM; it has to be noted that depending on the electro-mechanical concept of the DM, not all the drawbacks are present at the same time. However, their large number of actuators, reliability, excellent accuracy, long term stability (no creep effect), short response time and reasonable price make this technology a very good candidate for XAO and MOAO in a woofer-tweeter arrangement; sub mm pitch DMs are well suited to up to 10m class telescope, while electro-mechanical design allowing for more than 1 mm pitch can be used for ELTs.

For more details about the MEMS technology, the reader is invited to refer to [10], [11], [12].

3.5 Optically addressed DMs

One of the major problem DM manufacturers have to deal with when talking about multi thousands actuators is the cabling. Actual status is that connectorized wire bundles are now close to be larger than the DMs themselves which is a nightmare for the AO module opto-mechanical designers. One solution to solve this issue is to optically address the DM. This was initially proposed [14] and patented [13] in the early 1990s.

This concept first found an application in the field of large screen displays or infrared scene projectors. In the mid of last decade, thanks to the advent of ELT projects and to the strong interest in XAO systems, a new kick was given to using this technology for the development of high degrees of freedom DMs.

This concept is based on the coupling between a micromachined membrane DM and a photoconductive substrate. When illuminated, the substrate converts incoming photons into electrical charges which in turn deflects the thin membrane

thanks to induced electrostatic fields or capacitor effects (see Figure 6). This opens the door to multi thousands actuators wireless DMs.

Figure 6. Optically addressed DMs concepts. Left (extracted from [15]): an InGaAs photodetector is coupled to a micromachined thin membrane mirror; a picture of a multi-detector prototype is represented, each detector having a different diameter. Right (extracted from [16]): a photorefractive BSO crystal is coupled to a micromachined thin membrane mirror; a bias AC voltage is applied across the DM; illumination spatial variations convert into spatial control of the membrane deflections.

The technology is clearly still in a very early development phase. Many issues have to be solved, the major ones being certainly the manufacturability and the sensitivity of these devices. At a system level, one will have also to solve the problem of the optical conversion of the wavefront measurements. Anyway, this new technology seems to be quite promising, as was the MEMS one few years ago.

For more details, the reader is invited to refer to [14], [15] and [16].

4. DEFORMABLE MIRROR PROVIDERS

4.1 CILAS

CILAS (Compagnie Industrielle des LASers, formerly Laserdot - www.cilas.com) is a medium size company located in Orleans (France) 100 km south of Paris. Together with Xinetics, CILAS is the pioneering company in the field of DM development. Over the past 35 years, CILAS has developed stacked array and bimorph DMs based on the use of hard PZT material and has equipped some of the world largest telescopes (VLT, Subaru, GTC and Gemini).

The CILAS commercial offer covers mainly all the potential needs for 8m class telescope post focal AO DMs (see Figure 7 and Figure 8):

- Stacked array DMs with a 3.5 to 10 mm pitch, a >10 µm stroke, a <1 ms response time, up to 41x41 actuators, no temperature dependence.
- Bimorph DMs with up to 188 electrodes.

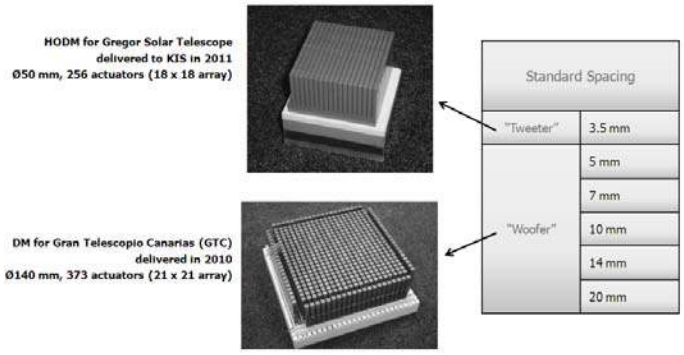

Figure 7. CILAS stacked array DMs. Top: actuator array of the 3 mm pitch, 18x18 actuator DM of the KIS Gregor Solar telescope; the stroke is more than 5 µm. Bottom: actuator array of the 7 mm pitch, 21x21 actuator DM of the Gran Telescopio Canarias; the stroke is more than 10 µm (courtesy CILAS).

To be prepared to compete for 40m class telescope DMs, CILAS designed and manufactured prototypes of a large secondary DM, and of a small and compact 1 mm pitch DM (XAO, MOAO). Prototyping activities are actually on-going to also cover the needs of 40m class telescope SCAO or MCAO systems [17].

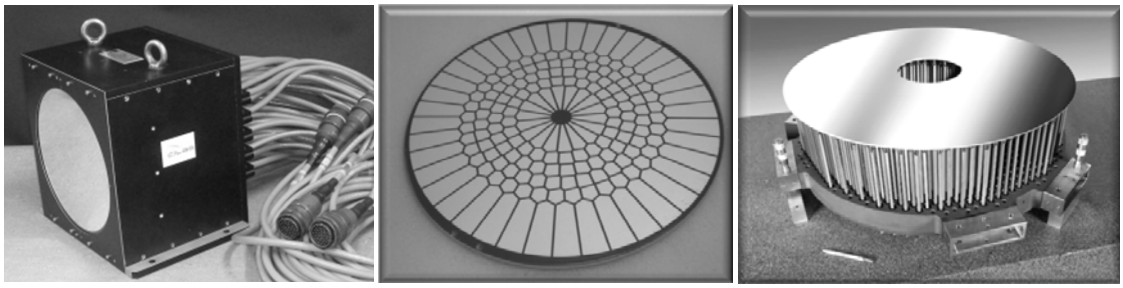

Figure 8. CILAS DMs portfolio. Left: the SPHERE 41x41 actuator stacked array DM, with a 4.5 mm pitch and more than 10 μm stroke. Middle: the 188 electrode bimorph DM delivered to SUBARU; the picture shows the electrode pattern with the central ring and the outermost one being outside the clear aperture. Right: the one meter diameter prototype of the E-ELT M4 DM, with 850 actuators, a 24 mm pitch and a 65 μm stroke (courtesy CILAS).

4.2 Xinetics

Founded by M. Ealey in 1993 as a spin-off from Itek, Xinetics, has been bought by Northrop Grumman in 2007. In 2010, Adaptive Optics Associates and Xinetics, two Business Units of NG merged into a single business venture now called AOA-Xinetics (www.as.northropgrumman.com/businessventures/aoa-xin). The resulting organization has more than 50 years of experience in the field of system integration and is offering today complete turn-key electro-optical systems to their customer, including not only full AO systems but also components as DMs. Xinetics is located in Devens, Massachusetts.

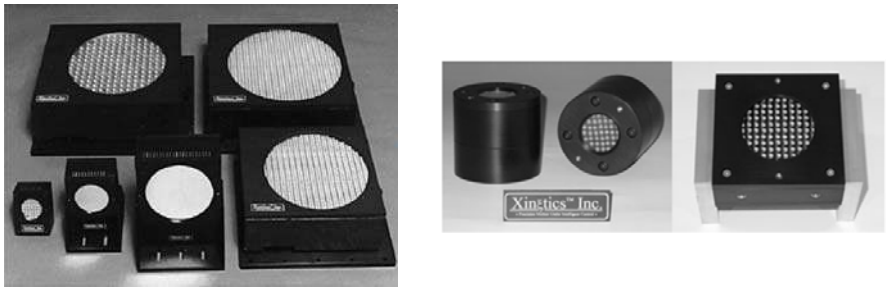

Figure 9. Xinetics DMs portfolio. Left: standard 7 mm pitch DMs, with 37, 97, 177, 241, 349, 577 or 941 actuators. Right: standard 5 mm pitch DMs, with 37, 97, 349 or 577 actuators.

Figure 10. Xinetics 1 mm pitch DMs. Top left: 64x64 actuators. Top right: 48x48 actuators. Bottom: 32x32 actuators.

The commercial DMs proposed by AOA-Xinetics are all stacked array mirrors based on the so-called cofired PMN actuators, with a pitch of either 5 mm or 7 mm, up to 1000 actuators and up to 8 μm stroke (see Figure 9). They can

cover the needs for 8m class telescope post focal AO DMs and have already equipped some of the world largest telescopes (Keck and GEMINI). They have the capability to deliver high order DMs fulfilling the requirements of 40m class telescopes. It has to be noted that they delivered to JPL two 1 mm pitch DMs with 64x64 and 48x48 actuators for the High Contrast Imaging Testbed (see Figure 10) [18].

4.3 Microgate and ADS

Microgate (www.microgate.it) and ADS International (www.ads-int.com) are two independent small size Italian companies, located in Bolzano (Microgate) and near Lecco (ADS). Starting from an idea by Piero Salinari (1993) and thanks to fruitful collaborations with Italian research institutes (INAF-Osservatorio Astrofisico di Arcetri and Aerospace Department of Politecnico di Milano), Microgate and ADS are proposing since 1995 technical solutions based on contactless voice coil actuators to build large secondary DMs. In 2002 a first unit, the so-called MMT336, was delivered to the Steward Observatory to equip the new Multi-Mirror Telescope (MMT). Since then, they delivered two secondary DMs to the Large Binocular Telescope (LBT) and one to the Magellan Baade Telescope (see Figure 11).

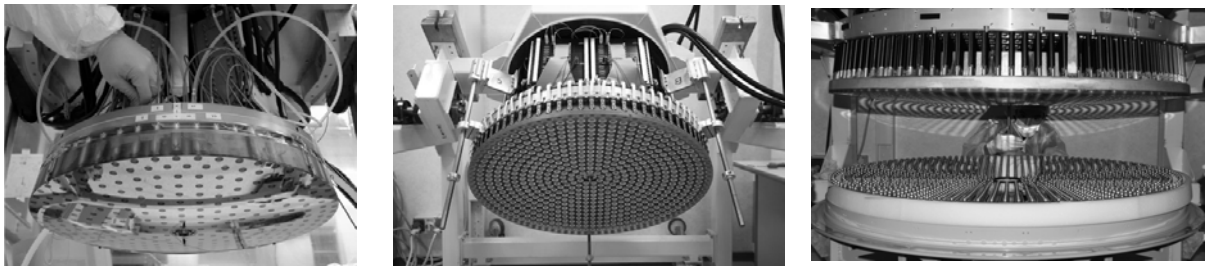

Figure 11. Secondary DMs during integration. Left: the MMT 336 actuator secondary DM with the uncoated thin shell assembled; the array of permanent magnets glued on the back side of the shell is visible. Middle: the LBT 672 secondary DM before the assembly of the thin shell; the array of metallic coated rings defining the armature of the capacitive sensors is visible on the front side of the reference body. Right: the VLT 1170 actuator DSM, with the thin shell sitting below the reference body; permanent magnets are visible on the rear face of the thin shell (courtesy Microgate and ADS)

The VLT deformable Secondary Mirror will be delivered by the end of 2012 [19].

The secondary DMs they built so far have diameter ranging from 0.65 m to 1.2 m, with 336 to 1170 actuators and a stroke large enough to allow compensating for atmospheric tip-tilt in even poor seeing conditions.

Microgate and ADS have been awarded recently a preliminary design contract for the E-ELT M4 deformable mirror (2.5 m diameter and more than 6300 actuators); they have completed in 2010 the phase A study for the segmented secondary DM of the Giant Magellan Telescope (7 identical 1.05 m diameter 672 actuator DMs – see Figure 12) for which they have recently been contracted the preliminary design phase.

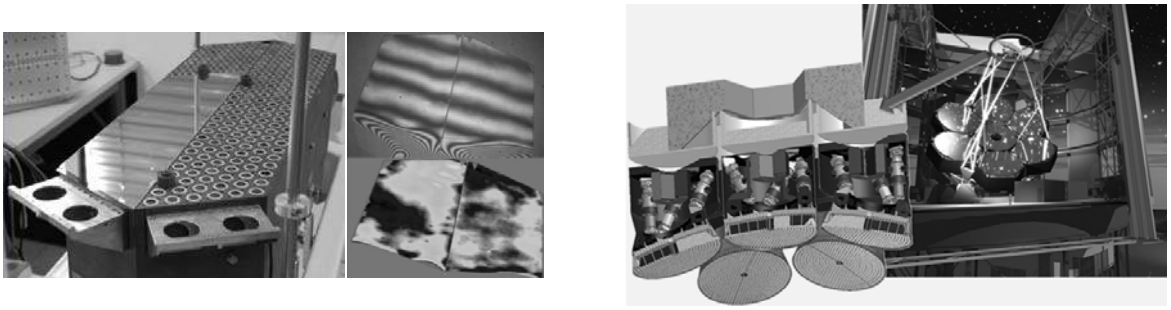

Figure 12. Secondary DMs for ELTs. Left: the 1 m segmented prototype of the E-ELT M4 DM; this prototype was built to validate new technological solutions for the M4 actuators and to demonstrate the capability of the voice coil technology to co-phase segments of a mirror; the attached interferogram clearly assess this capability. Right: the conceptual design of the multi DM secondary mirror of the GMT.

4.4 Boston Micromachines

Boston Micromachines (www.bostonmicromachines.com) is a small size company located in Cambridge, Massachusetts. Founded in 1999, their core business is the development and manufacturing of MEMs DMs based on electrostatics with applications in astronomy, retinal imaging, microscopy, laser beam shaping and defense applications. They are proposing continuous face sheet or segmented DMs (see Figure 13), with strokes up to 5.5 µm, actuator spacing from 300 µm to 450 µm and actuator number up to 4092 (64x64 array). Their DMs are very compact, hysteresis free and have a very short response time. Boston Micromachines equip today the ViLLaGEs 1m telescope, the Subaru Coronographic Imager and the Gemini Planet Imager [20].

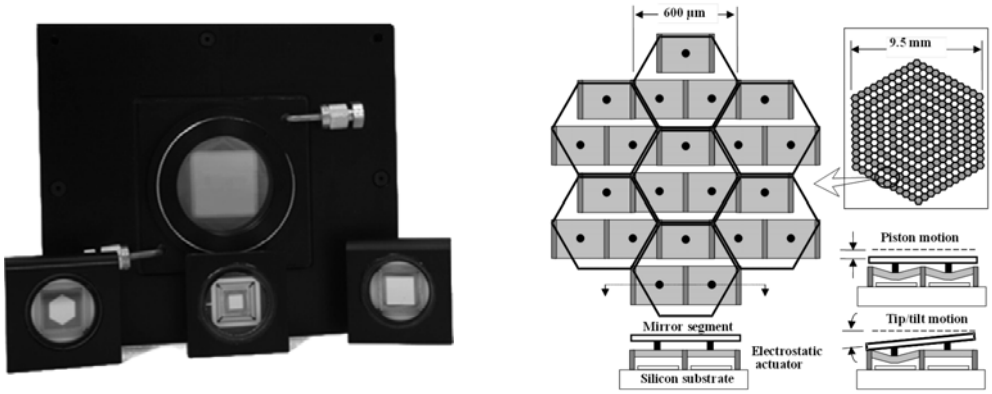

Figure 13. Boston Micromachines DM portfolio. Left: commercially available products; 140, 1020 and 4092 actuator square arrays and 331 segments Hex Tip-Tilt-Piston array; pitch from 300 to 450 µm; stroke from 1.5 to 5.5 µm, depending on the pitch. Right: schematics of the hexagonal segmented MEMS DM; 331 segment DM has 2 µm stroke and 6 mrad tip-tilt; 1021 segments in development (courtesy Boston Micromachines Corporation)

4.5 ALPAO

ALPAO (www.alpao.fr) is a small size spin-off company of a French University (Université Joseph Fourier – Grenoble). They are developing MEMS DMs based on electromagnetic field, with applications in astronomy, ophthalmology, microscopy and free space optical communication [21]. They are proposing DMs with 1.5 and 2.5 mm pitch, up to 277 actuators, a stroke of 15 µm and a <1 ms response time (see Figure 14). Their DMs are very compact, hysteresis free and require low control voltages (±1 V).

Figure 14. ALPAO DM features. Left: stroke vs correction mode, expressed in wavefront amplitude (DM277-15). Center: picture of an ALPAO DM. Right: response time characterization

4.6 OKO

OKO Technologies (www.okotech.com) is a small size company located in Rijswijk (The Netherlands). They are historically the first company to have ever proposed DMs at very low cost (few k€) and good overall quality. Their DMs are based on Piezoelectric DMs and Micromachined Membrane DMs. OKO is only proposing low order correction DMs with less than 110 actuators which can find application in astronomy for telescopes up to 8m diameter. Their most

popular product, the so-called “OKO Mirror” is a 17 mm diameter 37 electrodes electrostatically driven membrane DM; hundreds of this DM have been sold for applications as laser beam control, real time atmospheric correction, ophthalmology, intracavity laser control, etc… [22]

Figure 15. OKO DMs portfolio. Left: Piezoelectric DM, with 30 or 50 mm diameter, 6 µm stroke and up to 109 actuators. Right: Micromachined membrane DM 15 mm diameter, 17 actuators integrated on a tip-tilt stage.

4.7 TNO

TNO (www.tno.nl) is a large size independent research organization in The Netherlands aiming at contributing to the competitiveness of Dutch companies and organizations. Few years ago, they proposed a very interesting modular MEMS DM concept based on the electromagnetic actuation of a membrane. They first developed a prototype 61 actuator module and then assembled together 7 of these modules to make a 427 actuator, 150 mm diameter DM (see Figure 16); the pitch is of the order of 6 mm and the stroke per actuator is ±10 µm, with a maximum interactuator stroke of 0.5 µm. Control voltages are only few Volt. This project is still at a prototype stage.

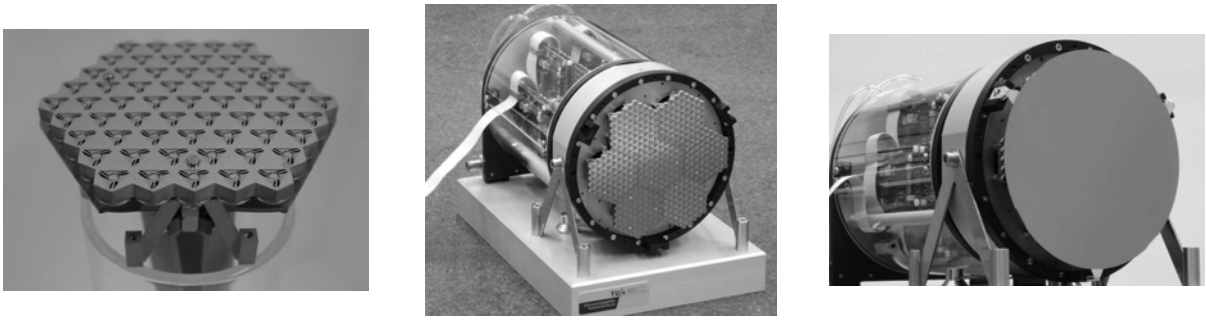

Figure 16. TNO 427 actuator DM prototype. Left: single 50 mm diameter 61 actuator module, without any membrane mirror; the 120° flexure structure is clearly visible. Middle: the assembled 150 mm diameter 427 actuator prototype, without any membrane mirror; the control electronic is inside the cylinder on the rear of the DM. Right: the complete prototype, equipped with its reflective surface.

4.8 Iris AO

Iris AO (www.irisao.com) is a small size company founded in 2002 on the Berkeley campus. Iris AO is manufacturing small size MEMS based segmented DMs. Their design is making use of 3 diamond shaped electrodes allowing 3 degrees of freedom electrostatic actuation (see Figure 5); bimorph flexures are used to raise the DM segments above the actuators to increase the global available stroke.

Their main features are a pitch of 0.7 or 1.4 mm, up to 163 segments, 5 to 8 µm stroke and a very short response time (see Figure 17). They are now aiming at developing a 925 segment prototype with a pitch of 1.4 mm and more than 8 µm stroke. Application areas are astronomy (MOAO), retinal imaging, space applications and free space optical communication [23].

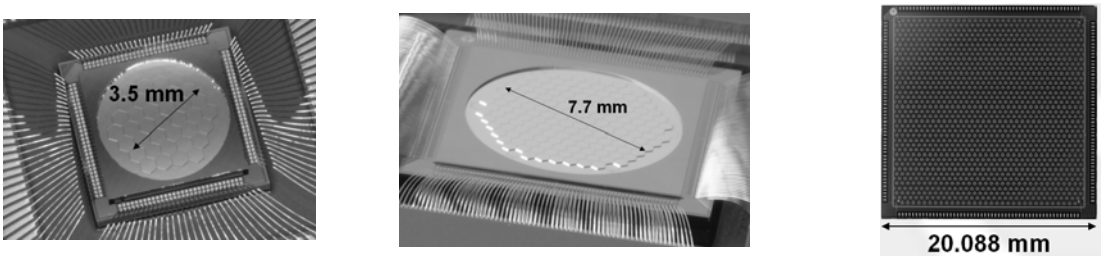

Figure 17. Iris AO MEMS DMs. Left: 37 segment DM, with a pitch of 0.7 mm. Middle: 163 segment DM, with a pitch of 0.7 mm. Right: prototype of a 925 segment DM, with a pitch of 0.6 mm.

5. CONCLUSION

In the first part of this paper, the main drivers for the design of DMs have been recalled and their main specifications have been derived depending on their field of application. Then the different technologies available today for the manufacturing of DMs have been detailed and pro and cons analyzed. As a conclusion, Table 2 is summarizing for different AO system applications the DM requirements and the applicability of the different available technologies.

Table 2. DMs specifications and associated technologies as a function of their field of application. ✓ means that the related DM technology is already in use for the application or could be used; ☺ means that the technology is ready to be used; 😐 means that the technology is almost there but needs to be prototyped; ☹ means that the technology concept is well suited but is still in development; ☠ means that the technology is not applicable at all.

	8m class telescope			40m class telescope		
	SCAO	MCAO	XAO	SCAO	MCAO	XAO
number of actuators	200	100	1200	5000 - 6000	2000	30000
pitch (mm)	30[i)] / -[ii)]	-[ii)]	- [ii)]	30[i)] / 4 to 5	6 to 8	1
mechanical stroke (µm)	10	6 to 10	10	70 to 80	10	2 to 3
control bandwidth[iii)] (Hz)	30	30	110	80	40 to 80	110
Stacked array DM	✓	✓	✓	😐	☺	☹
Bimorph DM	✓	✓		☠	☠	☠
Voice coil actuator DM	✓	iv)	iv)	😐	iv)	iv)
MEMS	✓	✓	✓	☠ v)	☠ v)	☹

i) 30 mm pitch is given for a 1m class secondary deformable mirror
ii) there is no particular requirement for this parameter: it depends on the system design and constraints
iii) within this bandwidth, the phase lag of the DM transfer function has to be smaller than 5 degrees
iv) For MCAO and for XAO, a secondary deformable mirror can be associated to post focal DMs
v) The pitch of MEMS DMs is too small to fit with the requirements

For 8m class telescopes, the DM needs are well covered by the actual technologies and procurement can be done through a real competition between different providers.

For 40m class telescopes, the actual available technologies can cover most of the AO needs but XAO and still need some time for development and prototyping. This intermediate phase will certainly require 2 to 3 years before it is possible to really start the final manufacturing. For XAO, an important effort has to be done to push the technology and to have it leaving the lab; it will certainly not be possible to get a final product with the expected level of reliability and robustness before 10 years.

Besides the DM technology itself, one should not forget the associated drive electronics. Going for high actuator count is a real challenge for the drives. Control voltages in the range of 200 to 400 V are required for most of the DM technologies that will be used for the 40 m class telescope AO systems and a real effort should be made to improve the efficiency and the robustness of these devices. Last but not least, cabling will also become a major issue. This is where new DM technologies as optically addressed MEMS have a lot of potentiality for the future.

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