

ACTIVE DAYLIGHTING USING MICRO MIRROR ARRAYS

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1. Introduction

Using daylight is a gratuitous and maybe the most beneficial and highly valuable way of indoor lighting: it provides highest spectral quality and high comfort at lowest level of energy consumption at the same time, since it derives from pure renewable energy. Nevertheless, direct collecting of solar energy through windows is still applied inadequately and keeps huge idle potentials.

The photomontage (Fig. 1) shows the vision: living and working rooms can be equipped with intelligent systems based on tens of millions of micro mirrors, implemented between the panes of conventional window glazing. Groups of mirrors can be switched from an open to a closed state, so that segments of the window can either guide daylight into the room or keep it outside.



Fig 1: A room equipped with an active window system (photomontage)

The person inside the room has a shaded working place, while the windows on the left, where no person is present, guide the light into the room. However, a segment on the right is opened to illuminate the plant.

Any window can be divided into segments of arbitrary size. For this application a typical segment could have a size of some square decimeters. For special applications also smaller segments are possible to implement a simple black and white display or segments in form of a logo etc. for example. These features are only possible with some kind of micro technology. The (nearly) undisturbed outlook is only possible with very small blinding elements. The height of the elements is also low, so the window distance of standard insulation glazing is sufficient.

2. Principals of Miniaturization

MEMS (Micro Electro Mechanical System) technology is a special kind of micro system technology. In this section we want to motivate the use of this optical MEMS technology for daylighting systems both from a fundamental and from an application point of view:

An obvious reason for the classical implementation of micro system technology is the need for really small solutions, like small grabbers or small pumps. However, it makes sense to miniaturize not only when it is useful or necessary for size reasons, but also when beneficial properties of miniaturized systems can be exploited. These can be their considerably enhanced mechanical stability, increased resonance frequencies, increased lifetime and increased efficiency of actuating forces in direct comparison to those forces causing material fatigue.

Normally a macroscopic movable mirror needs a complex drive mechanism, like an electric motor to be moved. Such a system is subject to material fatigue. Its movement speed is limited to small frequencies. Micro mirrors, however, can be resonantly driven in the kilohertz range with very high mechanical stability, because the inertia force, which is mainly responsible for material fatigue, scales in the order of a power of four when miniaturizing a system. In contrast, the electrostatic force scales much weaker with size. In case of an ideal plate capacitor with fixed voltage the electrostatic force is independent of its size. As a result, electrostatic forces can be used very efficiently for actuating microstructures. For these reasons we decided to use electrostatically actuable micromirror arrays for light steering applications. The diagram in Fig. 2 shows the change of significance and scaling behavior of fundamental forces when going from macroscopic to microscopic domains. Especially inertial forces lose their impact in microscopic dimensions.

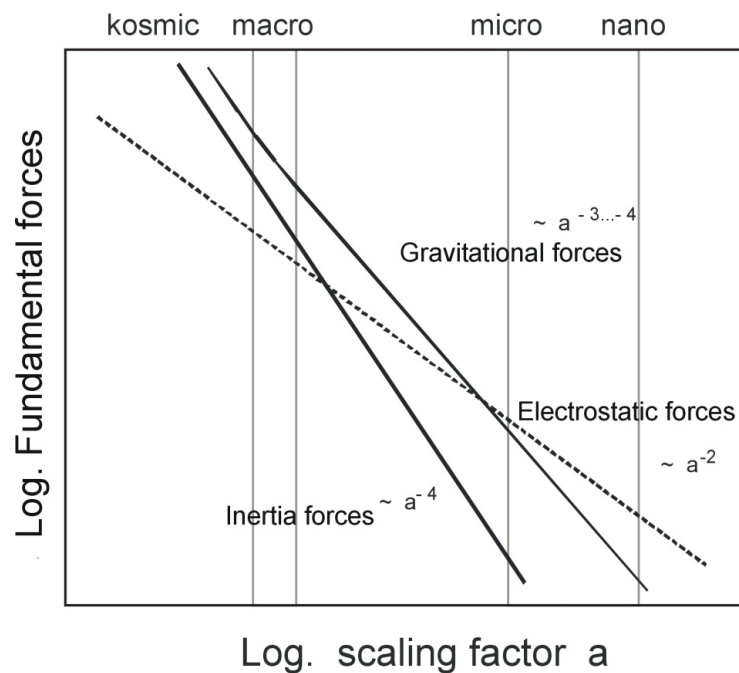


Fig. 2: relative significance of some fundamental forces in the macro- and in the microworld.

From an application point of view these fundamentals mean that such daylighting systems based on MEMS technology have much smaller material fatigue and an enhanced mechanical stability compared to macroscopic solutions (Hillmer et al., 2003). Due to their size, the mirrors are maintenance free for their whole lifetime. They can be opened and closed within milliseconds,

compared to some ten seconds in the case of conventional blinds. The mirrors can be moved by applying a voltage from an opened to a closed state. Their power consumption is extremely low: in an ideal case, the mirrors just need some power when they are actuated and no power in their static position. In reality, there are small leakage currents.

3. Working principle

The technological implementation uses common methods of microsystem technologies. In principal, there are three basic fabrication steps (see Fig. 3) : a) thin film deposition of the layer system, b) micro structuring of the layers, forming the mirror shapes and the grip by means of photolithography, c) a release of the mirrors using a self assembling step, making the mirrors upstanding without a voltage applied. This is possible by a special kind of thin film stress engineering in combination with a so called sacrificial layer technology.

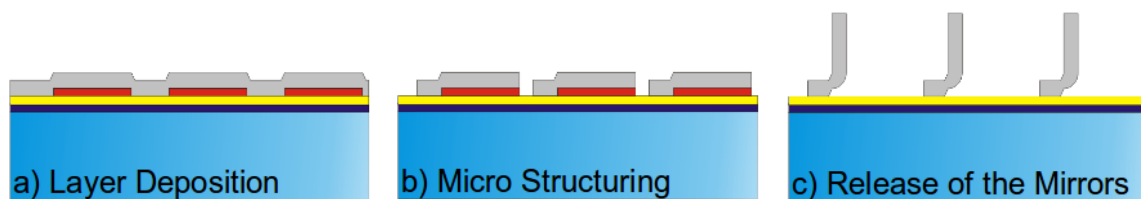


Fig 3: Basic fabrication steps of the micro mirror arrays

All fabrication steps have been chosen very carefully with special respect to i) being low cost and ii) to enable scaling onto large areas. Thus, especially thin single metal layers and dielectrics have been chosen instead of expensive semiconductor materials. Using just a simple grid instead of implementing thin film transistor technologies and separating the control unit from the array enables later upscaling at reasonable cost.

Fig. 4 shows two micro mirror elements on a substrate with their vital components. The basic substrate material is a standard float glass pane. It is covered in total both with a transparent electrode layer and an insulating layer. Each single mirror element consists of an anchor area. With this anchors the mirrors are fixed to the substrate material. The mirrors themselves are flat and free standing. A hinge area between the mirrors and the anchors makes every mirror movable. The position shown in Fig. 4 is the open position without any electric voltage applied. By applying a voltage between the transparent electrode layer and the metal layer, forming the mirrors and the grid, the mirrors can all be moved simultaneously (or optionally in groups of mirrors) to an aligned in-plane position (q.v. Fig. 5, right image).

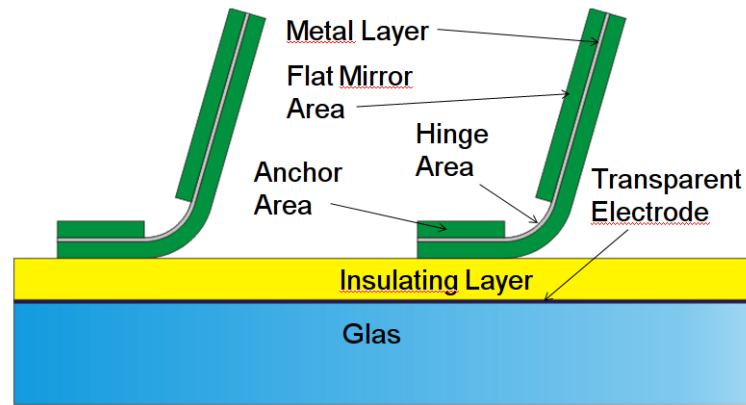


Fig 4: Cross Section of a micro mirror element with its vital components

Theoretical model calculations result in a usable angular range from nearly 90° out of plane up to about 45° . In this range the mirrors can be set to any angle by varying the applied voltage. Below this angle of 45° there is no stable equilibrium state between the electrostatic actuation force and the mirrors restoring force. Fig. 5 shows the visualization of an FEM simulation. The mirror on the left picture is at the critical angle (left). The mirror on the right, actuated with a slightly higher voltage, is lying down on the substrate. However, it is obvious that for the daylight guiding functionalities the angular range between 90° and 45° is sufficient. For the blinding functionality the 0° position is necessary. The angular range between 0° and 45° is not important from an application point of view.

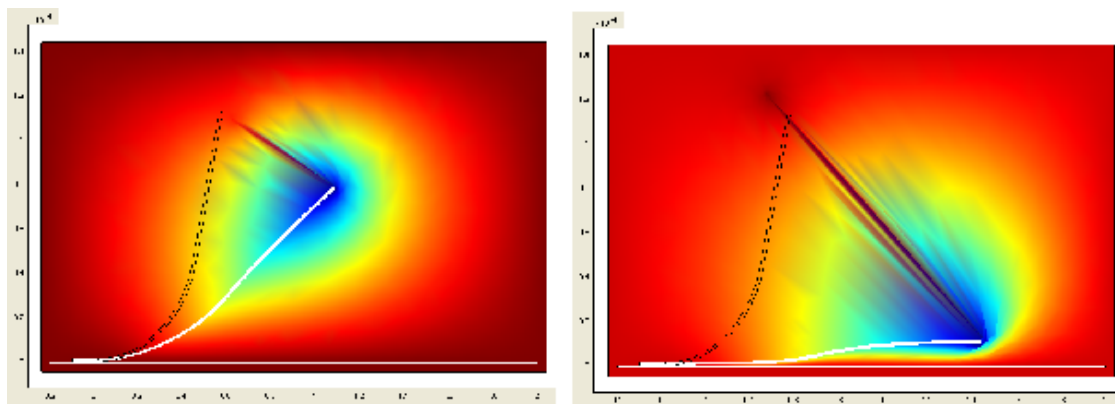


Fig 5: Theoretical model calculations by FEM showing the pull-in-effect: before pulling in (left) and after pulling in (right)

4. Laboratory scale demonstration

Currently the active windows exist as a laboratory demonstrator with a size of 10 cm x 10 cm. However, that means about 100,000 micro mirrors upon this area. In the following section such arrays are illustrated. Fig. 6 shows a module with the opened micro mirrors, offering a view through the array onto a landscape in opened and closed state. It can be seen that the vision through the module is nearly undisturbed, even though more than a third of the module is not transparent in the open state. In the closed state the module becomes totally reflecting (the reflection of the photographers hand can be seen in the right image of Fig. 6).

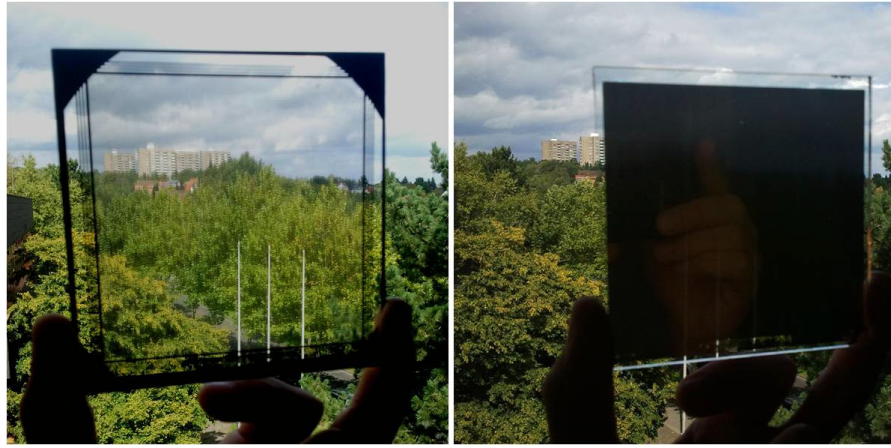


Fig. 6: Outlook through a micro mirror array – module with a size of 10cm x 10cm in opened state (left) and closed state (right)

Both the shading and the light guiding functionality are demonstrated and visualized in Fig. 7 in direct comparison with a simple uncoated glass module. In the opened state it can be seen that a large amount of light directly passes the modul, however a part of the light is redirected and can be used for indirect lighting, e.g. illuminating a white ceiling. This improved the daylight distribution within a room significantly. The right image states that the modules in closed state are nearly non transparent, even with strong light incidence. These functions, in combination with the segmentability visualized in Fig. 1, provide very efficient active daylighting.

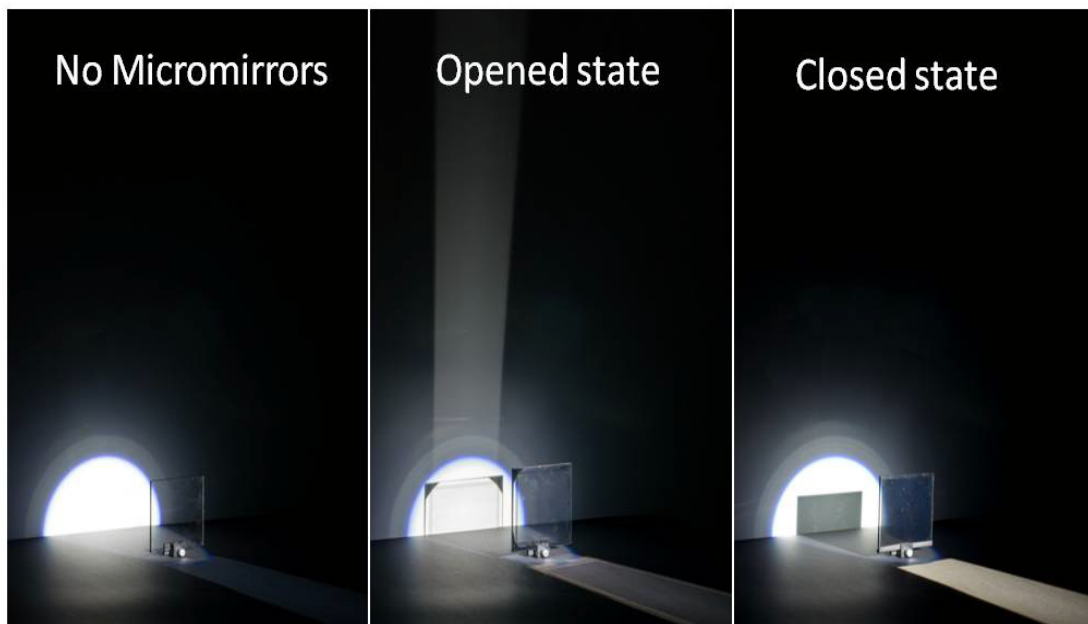


Fig. 7: Shading and light guiding functionality

5. Conclusion

Micro mirror arrays for future active daylighting applications have been developed in laboratory scale, based on MEMS technologies with a size of 10 cm x 10 cm. The developed fabrication process is designed to be scalable upon large areas, even though the upscaling is still the most challenging task to be done.

The modules consist of about 100.000 individual micro mirrors, which can be moved in groups from an open out-of-plane position to a reflective in-plane position by applying a voltage of some ten volts. Fabrication and functionality have been successfully demonstrated.

6. References

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