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REVIEW

Review of microshutters for switchable glass

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Abstract

Background: Switchable glasses allow the control of light transmission—an attractive property for applications such as car sunroofs, aircraft windows, building windows, augmented reality, imaging, and displays. Commercialized switchable glasses have severe limitations, such as speed, cost, and operating conditions, among others. Microshutters, a type of switchable glass with very distinctive properties, are reviewed, as they are a technology that could significantly improve some or all of the shortcomings mentioned above.

Aim: We will summarize the various types of microshutters and tentatively identify various critical designs, fabrication schemes, and performance criteria by the many research groups implementing them and investigating their properties.

Approach: We will describe the various approaches used to control light transmission through microelectromechanical systems. It will compare their performances and comment on fabrication and implementation challenges.

Conclusions: Microshutters have performance levels that could make them good candidates for switchable glasses. Many research groups have investigated various approaches to fabricate microshutters and have shown that they can be implemented reliably on a small scale, with fast actuation, low power, and high contrast and are relatively easy to manufacture. Work is needed to demonstrate that they can be scaled-up and still be economical to produce.

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Keywords: Micro-opto-electro-mechanical systems; shutters; smart structures; spatial light modulators.

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1 Introduction

Most species on Earth require access to sunlight for their physical and mental health. In ancient Greece and China, dwellings were oriented to take advantage of the sun.[1] Even after much technological advancements, houses are still not constructed to save energy using the sun, even in view of climate changes. Aeschylus, a playwright of ancient Greece, would surely consider us to be barbarians based on our houses' orientations.[1] New buildings incorporate more and more windows but too often with curtains or unaesthetic blinds. "Switchable glass," also referred to as smart glass or smart windows, utilizes light-blocking elements directly embedded into or onto the glass. This technology could transform the way we interact with exterior and daylighting. Windows could be more energy-efficient than regular walls, by adjusting the solar heat gain when needed. Moreover advanced facades could provide better access to daylighting, a significant well-being improvement for workplaces and homes. Moreover, public health could benefit from these advancements; for example, the positive effect of daylighting through glass on microbial control inside of buildings was recently demonstrated.[2]

Smart windows and switchable glass technologies (dynamic glazing) allow control of light transmission. Switchable glass gives access not only to a better human interaction with exterior life but also to an optimized use of sun energy according to the seasons, leading to significant building as well as vehicle energy savings.[3–10]

Switchable glass technologies can be classified as either passive or active. Microshutters are considered active since their state (open or closed) can be remotely controlled based on users' requests. Currently, the most popular types of active switchable glasses are based on electrochromism (EC), suspended particle devices, or liquid crystal devices (LCDs).[10–16] Electrochromic switchable glass was considered very promising from 2000 to 2010, but after several decades of research-development (R-D), thousands of patents, dozens of startups, and one decade of commercial availability, one has to acknowledge that there are important issues (such as speed, memory, tint, cost, blockage, and stability) that still prevent wide customer acceptance. Each switchable technology has the potential to find a niche application depending on its performance; moreover, it may be time to turn our efforts toward other switchable technologies, for example, a technology quite different from the rest, namely microshutters. Microshutters can take different shapes, but this review will concentrate on microshutters made of curling electrodes actuated by electrostatic forces. They could almost be considered in the same family as cantilevers. "Microblinds" are microshutters developed by the National Research Council (NRC) Canada. They have been described in a limited number of publications [in Ref. 17 (republished three times under requests) and slideshare[18]]. Microblinds were also compared with other switchable glass technologies in review papers[14,15] and market reports.[19–21] Several groups

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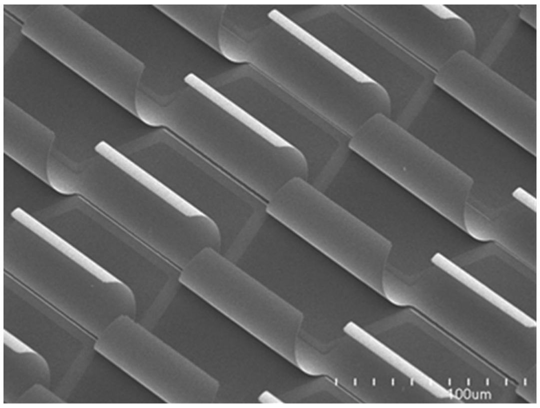


Fig. 1 Scanning electron microscopic (SEM) image of an array of trapezoidal microblinds (microshutters) fabricated at the NRC.

have worked on various versions of microshutters, namely NRC,[17] New Visual Media Group (NVMG),[22,23] University of Kassel,[24,25] Institut National d'Optique (INO),[26] University of Tokyo,[27] Samsung,[28] U.S. Air Force (USAF),[29] Korea Advanced Institute of Science and Technology (KAIST),[30,31] Microelectronic Center of North Carolina (MCNC),[32] Fiat,[33,34] and University of Stuttgart.[35] These groups used various versions of curling electrodes actuated by electrostatic forces for switchable glass applications (window, display, imaging, eyewear, etc.). Other groups have studied the use of curling electrodes for microfluidics,[36] interconnects,[37] and energy storage.[38,39]

This review will describe the various approaches used in controlling the light transmission using microshutters based on curling electrodes and microelectromechanical system (MEMS) principles. It will compare performances and comment on challenges. Figure 1 presents an example of trapezoidal microblinds developed and fabricated at NRC.

1.1 *Microelectromechanical System Microshutters*

MEMS devices are now everywhere, including in pressure sensors, accelerometers, inkjet printers, microphones, telecommunications switches, projectors, etc. They are also often identified as "micromachines" or "micro systems technology." MEMSs usually have a mobile part that is actuated by either external forces (pressure, movement, etc.) or internal forces, such as electrostatic–magnetic forces. Their small sizes make them very sensitive to external or internal forces, as well as very robust mechanically. Their fabrication processes are derived from microelectronic manufacturing. Most MEMS devices are made or built on silicon (Si) substrates with some exception on glass substrates. Electrostatic MEMSs are particularly attractive because of their efficiency (high-energy density and large forces), design simplicity, fast response, and low power consumption.[40]

This review focuses on microshutters fabricated on glass substrates to control the light transmission. Other groups such as the one at NASA[41] have worked on microshutter arrays based on Si substrates The devices described in this review are similar to cantilevers (basic MEMS structure). Nevertheless, microshutters have the top mobile electrode curling up based on stress gradient. The last layer(s) deposited get freestanding or mobile after etching away the sacrificial or release layer. When applying a voltage (electric field) between the bottom and the top electrodes, the top electrodes roll down onto the surface, thus blocking the light transmission.

1.2 *Materials*

The choice of materials being deposited for the various layers is critical for the reliability of MEMS devices.[42] It also determines their operating conditions as well as their manufacturing cost over large areas. The bottom electrode is usually a transparent conductive oxide (TCO), such as indium tin oxide (ITO), tin oxide (SnO_2), zinc oxide (ZnO), or even silver (Ag)-based conductive layers. These layers will reduce the light transmission by a certain amount; some of them may also significantly reduce the transmission of near-infrared light critical for maximum solar heat gain in cold climates. The insulating or dielectric layer(s) are critical as well since a high electric field will exist between both electrodes. Most research groups have used SiO_2 as an insulating layer (a common dielectric for microelectronics), whereas some others have used SiN_x, Al_2O_3, and polymers. The reliability of the microshutters depends strongly on the performances (for example, breakdown voltage and leakage current) of the dielectric layer(s).[43–46] A sacrificial (or release) layer is then deposited on the dielectric. The top electrode is usually made of metal (Cr, Al, Au, sometimes combined with a dielectric layer). Once the sacrificial layer is etched away, the top electrode becomes freestanding and mobile.

The choice of materials is also critical for the general reliability of the device, for example, their stabilities in chemical environment (humidity, oxygen), temperature cycling, or UV exposure are keys for long-term reliability. In this context, hard, high melting point, inorganic materials are often preferred over less stable materials. Some switchable glass technologies that are sensitive to UV have added UV-blocking layers or stabilizers at the expense of reducing the UV (long wavelengths) benefits of daylight.

1.3 *Fabrication Steps*

Most microshutters are based on standard microelectronic fabrication processes, such as e-beam evaporation, magnetron sputtering, optical lithography, and plasma etch and deposition. Figure 2 presents the main fabrication steps for the microshutters presented in this work.

The lithography (layer patterning) steps are particularly critical for defining the various planar geometries. More lithography steps result in an increased cost of manufacturing. These steps could be performed using conventional optical lithography (contact or projection) or printing techniques or could be laser-based.

The gradient of stress in the top electrode determines the curling behavior. The control of the stresses is crucial in order to get reproducible and uniform results (radius of curvature, actuation voltage, etc.) Many groups[17,26,31] have used magnetron sputtering to deposit the top electrode to tune the intrinsic stresses. University of Tokyo[27] has used evaporation techniques, relying on material dependent stresses. Other groups[22,27,32] have taken advantages of the different coefficients of thermal expansion (CTEs) of bilayers. Universities of Kassel[24] and Stuttgart[35] have used plasma-enhanced vapor deposition (PECVD) layers with stress

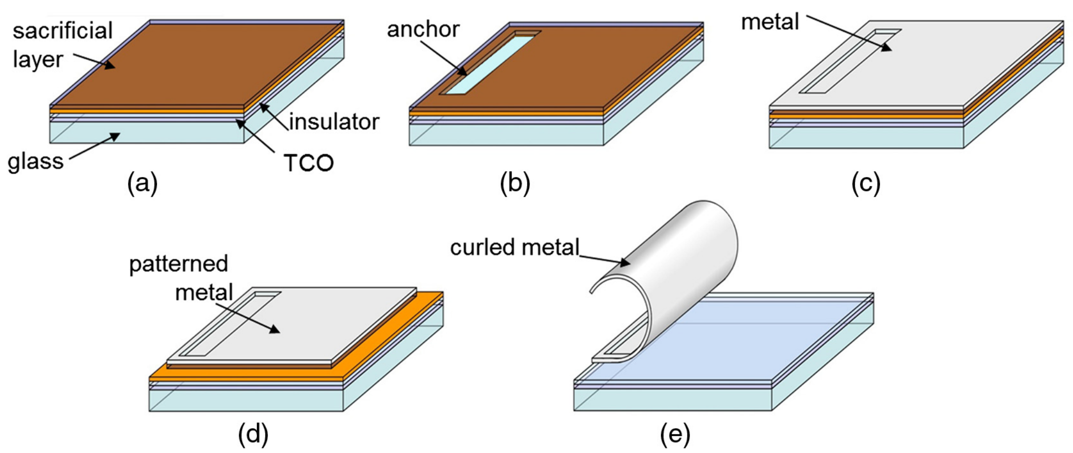


Fig. 2 Typical fabrication scheme for microshutters. (a) Glass substrate coated with TCO, insulator, and sacrificial layer; (b) patterning and etching of the sacrificial layer to define the anchor; (c) deposition of the top electrode; (d) patterning the geometry of the microshutters by etching the top electrode; and (e) releasing the microshutters by removing the sacrificial layer.

gradient. Controlling and characterizing the stress are the keys to reproducible and reliable devices.

The release of the mobile top electrode is performed by removing (etching) the sacrificial layer. This could be done by dry etching or wet etching, depending on the nature of the layers. The choice of the sacrificial layer is often made in such a way that it can be selectively removed without attacking the remaining layers in the device such as the dielectric layer and the top electrode. For example, NRC's microshutters (microblinds) use a very thin sputtered amorphous Si layer as a sacrificial layer, which is etched away using fluorine-based plasmas or wet chemistries. This release step is delicate and can lead to fabrication issues such as improper curling up.[29] Some groups[28–31] have included special and extra patterning steps (such as corrugation) to promote the proper release or curling behavior.

1.4 *Design*

Depending on the required performances, individual microshutter area may vary from a few square microns to a more macroscopic order (cm^2). They can be individually connected together or grouped by areas. The patterning steps required for manufacturing the microshutters may be viewed as a weakness, compared to other switchable glasses technologies, but it can also be considered a strength for applications that demand selectively actuated areas or even individually addressed microshutters using passive or active matrix thin film transistor (TFT) technologies. For this purpose, and for facilitating the dimming or improving the reliability of the devices, various groups have chosen to also pattern the bottom electrode.

Most research groups did not report any analytical or mathematical approaches to design their devices. However the U.S. Air Force[29] used mathematical expressions developed for cantilevers. Other groups performed modeling using simulations software such as Fiat (Ansys), NRC (Comsol), and INO (Intellisuite).

1.5 *Actuation*

Microshutters are based on MEMS devices, more specifically on capacitive MEMSs. There are many publications[43,44] describing how to reliably actuate capacitive MEMS devices. The most popular methodology to actuate electrostatically driven microshutters is by using bipolar square waves at frequency around 100 to 1000 Hz. It is also possible to actuate them using DC voltages. The operation voltage varies from 10 V to a few hundred volts depending on the dielectric used, its size, the release layer thickness, and the top electrode (stress and thickness). There is a lot of know-how behind the actuation especially when millions of microshutters are simultaneously actuated on the same device.

2 Various Versions of Microshutters

As mentioned in Sec. 1, many versions of microshutters have been reported in the literature and on the web. This section will briefly describe each of the many versions reported in the published literature and compare them.

2.1 *New Visual Media Group, United States*

NVMG has developed electropolymeric shutters based on shrinkable polymer-laminated using rolls.[22] They may be considered milli- or mini-shutters instead of microshutters because of their size of the order of millimeters and larger. They follow the work done by Charles G. Kalt some 30 years ago (resulting in more than 20 patents, for example, Ref. 47). These devices are included in this review since their working principle (electrostatic forces unrolling a mobile electrode) is the same as the usual microshutters. Moreover, they are the only ones commercially available on large area. The stressed curling top electrode is based on shrinkable polymer (1- to 5-μm thick). Once rolled up into multiple turn coils, their diameter is around 1 to 5 mm or greater. The dielectric is based on polymer (4- to 10-μm thick). Their fabrication involves roll laminator and adhesives. The operation voltage usually ranges between 100 and 500 V DC.

Most of the details are available from their patents, but they also have a website[23] where videos demonstrating the technology are available.

2.2 *National Research Council Canada*

NRC's microshutters have been called microblinds.[17]

Details about microblinds are available through few conference proceeding paper,[17] patent, and web presence.[18,48] Their video has been quite popular, and they have been cited in few reviews on switchable glass[14,15] and market reports.[19–21] They successfully tried various TCOs. The desired stress gradient in the top electrode is obtained using magnetron sputtering (varying deposition conditions) [Fig. 3(a)]. They optimized the dielectric to improve the reliability. The thin sacrificial layer (a:Si, 40-nm thick) and the thin top electrode allow the microblinds to be operated at relatively low voltages (around 20 V). Their fabrication scheme is relatively simple. Nevertheless, it leads to an impressive blockage in closed state (around 99.9%). The microblinds can be fabricated by regular microelectronic or flat panel display (FPD) technologies but also possibly using laser patterning for yielding a much lower fabrication cost.

2.3 *University of Kassel, Germany*

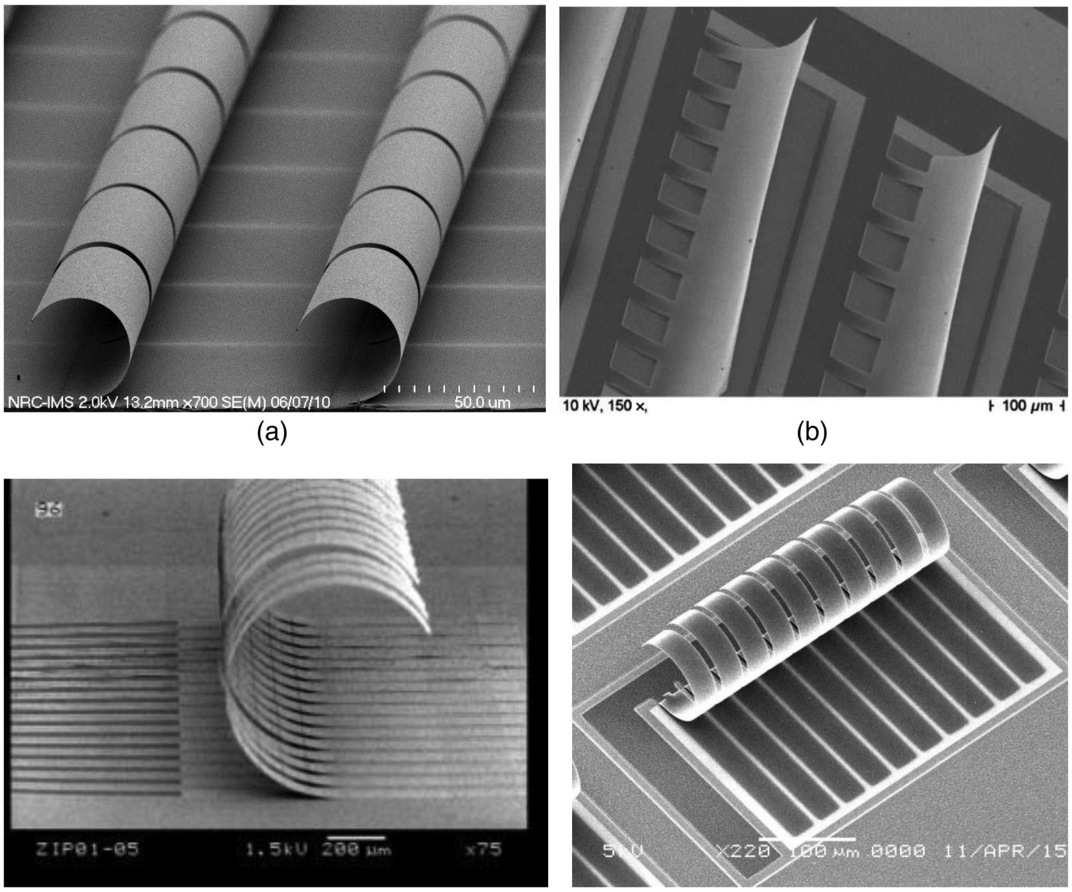
University of Kassel has been developing optical MEMS micromirrors for daylight steering.[24,25] They are a kind of microshutters with curling hinges and a flat micromirror [Fig. 3(b)]. Their micromirrors are also actuated by electrostatic voltages (40 to 100 V). Their sacrificial layer is usually based on photoresist, and their usual stress gradient is obtained using PECVD. Many papers and dissertation theses in which they described the various fabrication schemes are available.

2.4 *Institut National d'Optique, Canada*

INO developed microshutters for spectrometry applications.[26] They are not aimed for large areas but mainly to cover slits in front of spectrometers. Each individual microshutter has a length of 1 mm and a width of 60 μm [Fig. 3(c)]. Contrary to most microshutters, they do not use TCO as a bottom electrode, but rather side electrodes made of Al layer. The dielectric is SiN_x, the sacrificial layer is based on photoresist, and the top electrode is based on MoCr. The stress gradient is obtained by varying deposition conditions during the magnetron sputter deposition.

2.5 *University of Tokyo, Japan*

The University of Tokyo developed microshutters using stress gradient based on evaporated metal on SiO_2 at 180°C.[27] The different CTEs create the stress gradient at room temperature but may make them sensitive to the operating temperature. Each individual shutter is 200-μm long, 30-μm wide, and 0.3-μm thick [Fig. 3(d)]. The sacrificial layer is photoresist. The closing speed is around 3 ms and the operating voltage is 55 V.



(a) (b) (c) (d)

Fig. 3 SEM images of microshutters developed at (a) NRC, (b) University of Kassel (reproduced from Ref. 25 with permission of Springer), (c) INO (reproduced from Ref. 26 with permission of SPIE), and (d) University of Tokyo (reproduced from Ref. 27 with permission of IEEE).

2.6 *Samsung, Korea*

Samsung developed a 2-mm diameter iris shutter for camera using MEMS microshutters.[28,49] The iris is formed out of 36 individual 1.4-mm-long triangular shutters [Fig. 4(a)]. On their first reported attempt, they used SiN_x/Al bilayer top electrode. Their second report pointed out a detrimental temperature sensitivity when using SiN_x/Al; they switched to Mo/Mo for better results. Mo/Mo describes two layers of Mo with different intrinsic stresses and ideal insensitivity to temperature. Their operating voltage is 30 V. They used corrugation to improve the curling and dimples to reduce stiction.

2.7 *United States Air Force*

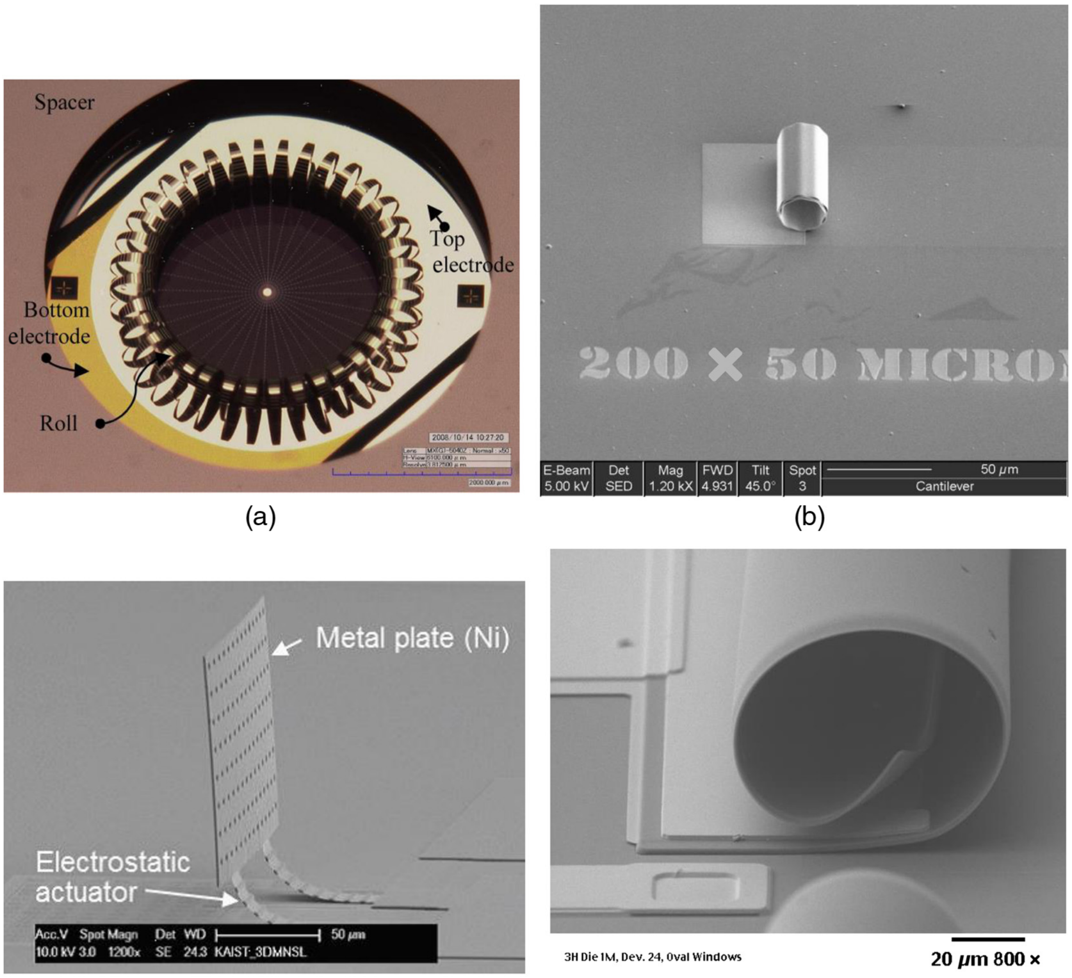
USAF Research Laboratory developed microshutters for adaptive coded aperture imaging and nonimaging applications.[29] They used AlZnO as the TCO on fused silica, and the dielectric is SiN_x. The sacrificial layer is 0.5-μm photoresist and the top electrode is made of Ti and Au [Fig. 4(b)]. Their research compared models of the DC actuation to their fabricated devices. These shutters used corrugations to improve the curling up but also revealed the difficulty of releasing depending on the geometry of the microshutters.

2.8 *Korea Advanced Institute of Science and Technology*

KAIST developed cascaded microshutters for variable transmission in next-generation displays.[30,31] Their microshutters are composed of ITO/SiO_2/photoresist (sacrificial)/Ti-Au and require four patterning steps, including one to make corrugations [Fig. 4(c)]. The gradient of stress in the top electrode is based on different intrinsic stresses of sputtered Ti and Au layers. They measured a pull-in voltage of 20 V and a closing speed of 20 μs. Reliability testing of the first-level microshutters revealed some dielectric charging; nevertheless, they estimated their lifetime to 500 billion cycles.

2.9 *Microelectronic Center of North Carolina, United States*

MCNC and the University of Florida developed microshutters for protecting optical sensors.[32] Their microshutters are based on polyimide as the dielectric and Al as a sacrificial



(a) (b) (c) (d)

Fig. 4 Images of microshutters developed at (a) Samsung (reproduced from Ref. 28 with permission of IEEE), (b) USAF (reproduced from Ref. 29 with permission of SPIE), (c) KAIST (reproduced from Ref. 31 with permission from SID), and (d) MCNC (reproduced from Ref. 32 with permission from SPIE).

layer [Fig. 4(d)]. The top electrode is based on a sandwich of polyimide/Cr/Au/polyimide. The stress gradient is induced during the curing of the polyimide. They also experienced curling issues. Their operating voltage is around 100 to 300 V; the closing speed is measured as 18 μs. They reported that low operating voltages yield longer lifetime, and 450 million cycles were tested.

2.10 *Fiat, Italy*

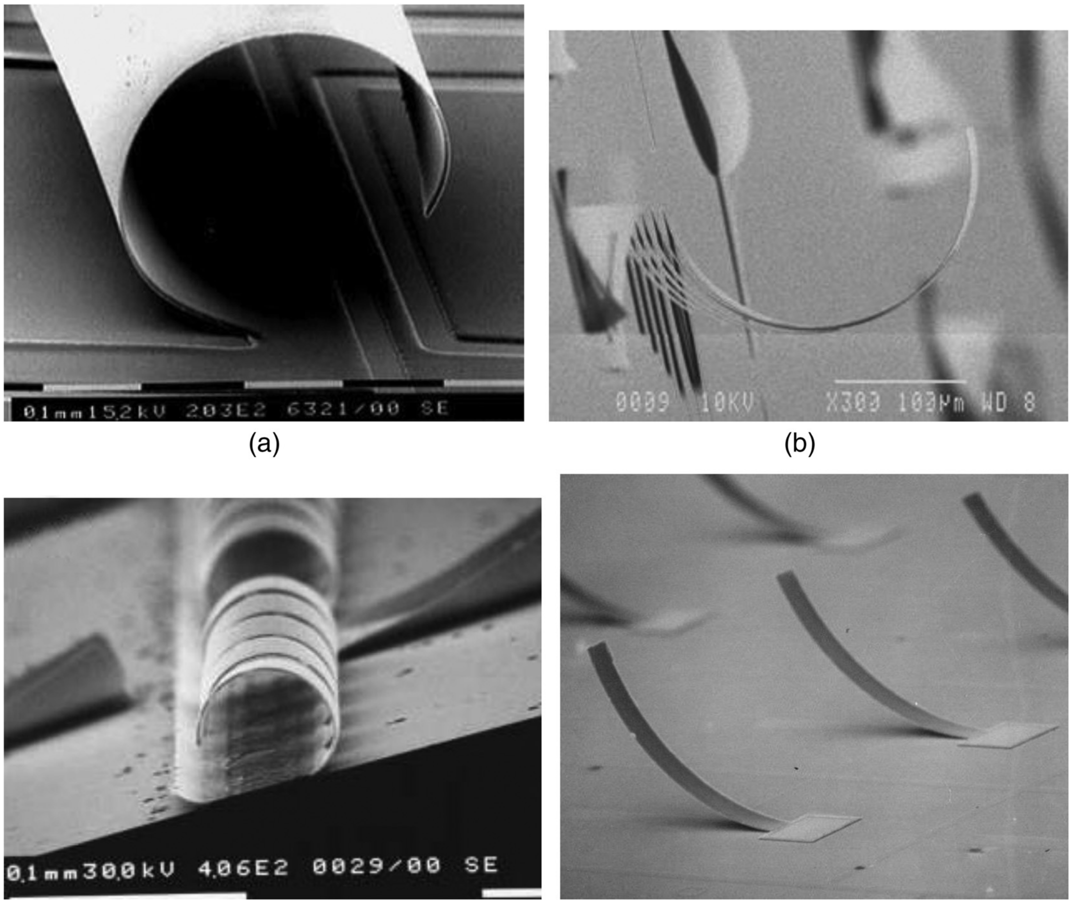
They developed microshutters for display and spectroscopy applications [Fig. 5(a)].[33,34] They did not reveal much about the fabrication; nevertheless, their microshutters are relatively big (0.5 to 2 mm) and required around 80 V actuation voltage. Modeling results were obtained in collaboration with the Université de Bordeaux.

2.11 *University of Stuttgart, Germany*

Following a collaboration with NRC, University of Stuttgart decided to implement microshutters with their TFT expertise.[35] Their microshutters are mainly aimed toward display application with low aperture ratio (15%) [Fig. 5(b)]. They are fabricated on TFT-based active matrices with a wet-etched Si sacrificial layer (150 to 200 nm thick). The top electrode is SiN_x with gradient of stress obtained during PECVD, and a molybdenum-tantalum (MoTa) conductive layer (total thickness around 500 nm). The operating voltage is around 30 V, and they estimated a response time below 50 μs.

3 Comparison of the Various Approaches

Table 1 presents the various versions of microshutters developed as a function of year (first publication known to us), material choice (bottom electrode, dielectric, sacrificial, top electrode), sizes, and fabrication processes. The references shown usually correspond to the latest publications. The first dates correspond to the date of first publication (paper or patent), although we recognize that work started before publications were made. Many of the research groups developed microshutters several years ago and stopped the R-D project for unknown reasons. Most of the groups used ITO for the bottom electrode. There is a diversity of materials (polymer, Si, and Al) used for the sacrificial layer. This choice is critical for the fabrication (ability to etch quickly, manufacturing cost) as well as for the operating voltage. The ability to coat a very thin sacrificial layer without pinholes reduces the actuation voltage and thus increases the microshutter lifetime. Most of the microshutters have sizes around 200 μm;



(a) (b) (c) (d)

Fig. 5 SEM images of microshutters developed at (a) FIAT (reproduced from Ref. 34 with permission of Springer), (b) University of Stuttgart (reproduced from Ref. 35 with permission of SID), (c) Philipps (reproduced from Ref. 36 with permission from The Royal Society of Chemistry), and (d) PARC (reproduced from Ref. 37 with permission of SPIE).

Table 1 Comparison of the various microshutters depending on materials and fabrication.

			Materials				Fabrication	
Research group	Ref.	Time	Bottom electrode	Dielectric	Sacrificial	Top electrode	Size	Processes, comments
NVMG	22	2007 to present	TCO	Polymer (4- to 10-μm thick)		Shrinkable polymer layer (1- to 5-μm thick) with Al, NiCr, SS (100- to 500-A thick)	Centimeter (r: 0.5 to 2 mm or greater)	Temperature-induced stress, electropolymeric, roll laminator
NRC	17	2005 to present	SnO_2, ITO, Ag low-e	SiO_2, SiN_x, Al_2O_3	Si and others, around 40 nm	Cr and others, 1000 A	50 to 300 μm (r: 10 to 100 μm)	Optical or laser patterning, magnetron sputtering
University of Kassel	24	2003 to present	ITO, ZnO or Ag low-e	SiO_2, polymer	Photoresist, 0.5 μm	SiO_2–SiN_x–Al–Cr	150 × 400 μm	PECVD stress and Al thickness, optical litho or imprinting
INO	26	2008 to 2009	Al	SiN_x	Polyimide	MoCr	60 × 1000 μm (r: 370 μm)	Stress controlled during sputter dep
University of Tokyo	27	2015 to 2016	ITO, 200 nm	SiO_2, 200 nm	Photoresist, 0.5 to 2 μm	SiO_2, 200 nm/Al, 100 nm	200 × 100 μm (r: 70 μm)	Al evaporated at 180°C on SiO_2
Samsung	49	2009 to 2011	ITO	PECVD SiO_2 0.5 μm	Perylene	SiN_x–Al (3500/3000 A), Mo/Mo	Iris, 2-mm diameter, 36 1.4-mm-long triangular shutters (r: 230 to 500 μm)	Similar CTE is much better. Corrugations and dimples are patterned.
Air Force	29	2008	AlZnO	SiN_x	Photoresist, 0.5 μm	Ti–Au	200 × 50	Corrugation, difficulty to roll them up depending on geometry
KAIST	31	2010 to 2016	ITO, 0.2 μm	SiO_2, 0.5 μm	Photoresist, 0.2 μm	Ti–Au 100 nm	200 × 160 μm	Four patterning steps, different intrinsic stress of sputtered Ti and Au
MCNC	32	2000 to 2002	ITO	Polyimide, 0.5 μm	Al	Polyimide–Cr–Au–polyimide	Various sizes 50 μm to 1 mm (r: 50 to 100 μm)	PI cured at 400°C
Fiat	33	1999 to 2005	ITO				458 μm to 2.4 mm	
University of Stuttgart	35	2016 to present	MoTa	SiN_x	Si, 150 to 200 nm	MoTa on stressed SiN_x (400 to 600 nm)	200 μm (r: 64 to 300 μm)	Structural SiN_x with stress gradient, release by wet etching the Si

Table 2 Comparison of the various microshutters depending on performances.

Research group	Ref.	Actuation	Speed	Demo size (active area)	Max/min transmission contrast	Applications comments
NVMG	22	100 to 500 V	second	5000 cm^2	High contrast	Macro-curling shutters, commercialized, eight U.S. patents issued, impressive demos
NRC	17	15 to 25 V	Around 40 μs to close	20 cm^2	60/0.1 to 600	High contrast, low voltage
University of Kassel	24	40 to 100 V		100 cm^2	80/5 to 16	Mirror steering sunlight; lifetime >50 years, startup
INO	26	110 V	2 ms to close, 7 ms to open	<1 cm^2	Low contrast	Space instrumentation (slit for spectrometer), substrate: sapphire
University of Tokyo	27	55 V	3 ms	0.25 cm^2	53/36	Implemented on TFT
Samsung	49	30 V	1 to 2 ms	Iris of 0.04 cm^2	High contrast	Shutter for camera
Air Force	29				Low contrast	Adaptive coded aperture imaging
KAIST	31	20 V	20 μs to close	Small	Low contrast	Active transparent display
MCNC	32	100 to 300 V	18 μs	5 cm^2	Low contrast	Eyelid for protection
Fiat	33	80 V	0.1 ms		Low contrast	Display
University of Stuttgart	35	25 to 45 V	<50 μs (model)	2 cm^2	Low contrast	Display, implemented on TFT, low transmission

those dimensions should make them reliable (MEMS) as well as practically invisible to the eye.

There are different strategies used to make the top electrode. This is a very crucial step: the gradient of stress in the top electrode needs to be well controlled and uniform over relatively large areas depending on the applications.

It seems that more reproducible and uniform stress gradients are expected with magnetron sputtered layers (given the fact that targets can be over 4-m long and that it is a low-temperature process) than with evaporated, PECVD, or thermally cured layers for large areas.

Moreover, as Kim and Hong (Samsung)[49] pointed out, with experimental results, that stress gradients in the same material is much more temperature-stable than in bilayers such as Al/SiN_x. The different CTEs may have detrimental effects on switchable glass, unless used on thermally activated switchable glass.

Contrary to most switchable glass, microshutters require patterning steps to define the anchors and the microshutters. These steps are usually based on optical lithography and represent a major manufacturing cost. Most microshutters require two patterning steps, but many research groups reported a required extra one for corrugating the top electrode. This extra step makes it easier to release and curl up successfully the top electrode but increases the manufacturing costs. Two groups have investigated other patterning approaches, such as imprinting (University of Kassel) and laser patterning (NRC). These approaches could lead to much lower manufacturing costs.

As for the reliability, many researchers have proven experimentally that the microshutters (at least on small areas) are very reliable, cycling them millions of time.[24,30,32]

Table 2 presents the various microshutters based on their actuation voltages, speeds, demonstrated sizes, visible transmissions, and applications. The required performances depend on the application; however, there are obvious general advantages in low operating voltage, high contrast, temperature stability (no CTE gradient in top electrode, high-melting-point materials), UV durability (inorganic), and low manufacturing cost (thin layers and simple patterning).

The operating voltage is a critical parameter for many applications and the electric field is critical for the reliability of the devices. They depend on the dielectric, the mechanical properties of the top mobile electrode, the radius of curvature, the thicknesses of dielectric, space, and top electrode. The operating speed is inversely proportional to the size and thickness of the microshutters.

Scaling-up. Most research reports on microshutters are for devices covering only small areas. Although a few groups have made devices on opaque wafers, most work is designed to control light transmission (switchable glass) on small areas, such as spectrometer slits and eyeglasses, or large areas, such as car sunroof, aircraft windows, or even building windows. The electrostatic principle of operation scales to large areas as demonstrated by NVMG.[22,23] FPDs based on LCDs are functionally similar to switchable glass and integrate additional complex electronics. These devices are made on glass panels as large as 3.4 m and require many high resolution patterning steps. Large area microshutter panels are less complex than LCD panels but can be fabricated with similar manufacturing processes lines. Most research groups already used glass as a substrate and fabrication processes already employed in large scale manufacturing.

The operation voltage does not depend on the size of the area covered by the microshutters (voltage driven). Nevertheless, the total current will not only depend on area but also mostly depend on the operation frequency. The NRC modeled the effect of size, electrodes' resistivities, dielectric and operation frequency on actuation. They found that scaling-up is not limited by the voltage distribution if the right materials and geometries are used. Realistically, it makes sense to target small- and mid-sized applications, before addressing the building window market. As pointed out earlier, laser processing could allow the microshutters to become a very competitive switchable glass technology for large areas such as building windows.

4 Weaknesses and Challenges

Microshutters are very different from the current most common switchable glass technologies, such as EC. For example, microshutters are particularly fast switching, without unintentional tint, low power consumption, superior for solar use-control, and area-selective. Moreover, the microshutters with single material top electrode and without organic materials might be temperature-stable and UV-durable. One of the requirements for many applications, such as car sunroof and augmented reality, is the possibility to implement the switchable glass on curved glass substrates. EC did not succeed yet to reach that goal. Some microshutters based on high-melting-temperature materials (e.g., Ref. 17), can be implemented on glass substrates to be bent. Nevertheless, microshutters still have weaknesses, such as visual disturbance, required enclosure/encapsulation, manufacturability on large areas at low cost, reliability, and stress control. For example, the microshutters once curled up become tiny opaque lines that induce Fresnel diffraction, resulting in haze or visual disturbance. This diffraction is inherent to the technology, but it is also possible to reduce the resulting haze to an indiscernible level. There is a real market pull to develop such a switchable glass. The microshutters might not replace completely the competitive technologies. However, for applications where speed, contrast, durability, and temperature stability are critical, they might be the best candidate.

5 Conclusion

Microshutters have very interesting performance levels, making them good candidates for switchable glasses or light modulators. Many research groups have investigated various approaches to fabricate microshutters. They proved that microshutters can be reliable on small scale, fast, low power, high contrast, and relatively easy to manufacture. There is a need to prove that they can also be scaled-up and cost-competitive.

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References

1. K. Butti and J. Perlin, *A Golden Thread: 2500 Years of Solar Architecture*, Cheshire Books, Palo Alto, California (1980).
2. A. K. Fahimipour et al., "Daylight exposure modulates bacterial communities associated with household dust," *Microbiome* **6**(1), 175–187 (2018).
3. D. R. Roberts, "Preliminary assessment of the energy-saving potential of electrochromic windows in residential buildings," Technical report NREL/TP-550-46916, National Renewable Energy Laboratory (2009).
4. A. H. Sadek and R. Mahrous, "Adaptive glazing technologies: balancing the benefits of outdoor views in healthcare environments," *Sol. Energy* **174**, 719–727 (2018).
5. S. Attia et al., "Current trends and future challenges in the performance assessment of adaptive façade systems," *Energy Build.* **179**, 165–182 (2018).
6. A. Piccolo et al., "Energy performance of an electrochromic switchable glazing: experimental and computational assessments," *Energy Build.* **165**, 390–398 (2018).
7. A. Cannavale, U. Ayr, and F. Martellotta, "Innovative electrochromic devices: energy savings and visual comfort effects," *Energy Procedia* **148**, 900–907 (2018).
8. J.-M. Dussault, L. Gosselin, and T. Galstian, "Integration of smart windows into building design for reduction of yearly overall energy consumption and peak loads," *Sol. Energy* **86**(11), 3405–3416 (2012).
9. E. Syrrakou, S. Papaefthimiou, and P. Yianoulis, "Eco-efficiency evaluation of a smart window prototype," *Sci. Total Environ.* **359**(1–3), 267–282 (2006).
10. J. Al Dakheel and K. T. Aoul, "Building applications, opportunities and challenges of active shading systems: a state-of-the-art review," *Energies* **10**(10), 1672–1703 (2017).
11. Y. Wang, E. L. Runnerstrom, and D. J. Milliron, "Switchable materials for smart windows," *Annu. Rev. Chem. Biomol. Eng.* **7**, 283–304 (2016).
12. R. Baetens, B. P. Jelle, and A. Gustavsen, "Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: a state-of-the-art review," *Sol. Energy Mater. Sol. Cells* **94**(2), 87–105 (2010).
13. M. Casini, "Active dynamic windows for buildings: a review," *Renew. Energy* **119**, 923–934 (2018).
14. J. Marchwiński, "Architectural evaluation of switchable glazing technologies as sun protection measure," *Energy Procedia* **57**, 1677–1686 (2014).
15. Y. P. Singh and M. S. Gupta, "Future of intelligent windows," *Int. J. Res. Eng. Technol.* **4**(3), 17–26 (2016).
16. S. D. Rezaei, S. Shannigrahi, and S. Ramakrishna, "A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment," *Sol. Energy Mater. Sol. Cells* **159**, 26–51 (2017).
17. B. Lamontagne et al., "The next generation of switchable glass: the micro-blinds," in *Proc. Conf. Glass Perform. Days*, Tampere, Finland (2009).
18. B. Lamontagne, "Smart automotive headlamp based on arrays of optical shutters," 2012, https://www.slideshare.net/BorisLamontagne/smart-automotive-headlamp-based-on-arrays-of-optical-shutters (17 September 2019).
19. MarketsAndMarkets, "Smart glass market by technology (Suspended particle display, electrochromic, liquid crystal, photochromic, thermochromic), application (architecture, transportation, consumer electronics), and geography—Global Forecast to 2023 2017," Report Se-2552, 2017, https://www.marketsandmarkets.com/Market-Reports/smart-glass-market-907.html (17 September 2019).
20. Research and Markets, "The global market for smart glass and windows to 2030," 2018, ID:4615164, https://www.researchandmarkets.com/research/7p62fr/global_smart?w=5 (17 September 2019).
21. BCC Research, "Global markets and technologies for smart glass," 2018, Report AVM065D, https://www.bccresearch.com/report/download/report/AVM065D (17 September 2019).
22. E. Schlam, J. Finch, and J. Koskulics, "Highly reflective electrostatic shutter display," in *Proc. Int. Disp. Workshops*, Sendai, Japan (2017).
23. New Visual Media Group, https://newvisualmediagroup.com/index.php/technology (17 September 2019).
24. H. Hillmer et al., "Optical MEMS-based micromirror arrays for active light steering in smart windows," *Jpn. J. Appl. Phys.* **57**(8S2), 08PA07 (2018).
25. Q. Li et al., "Design of self-assembling micromirror arrays for light guiding applications," *Microsyst. Technol.* **16**, 895–899 (2010).
26. S. Ilias et al., "Programmable optical microshutter arrays for large aspect ratio microslits," *Proc. SPIE* **7099**, 70992D (2008).
27. K. Mori et al., "A MEMS electrostatic roll-up window shade array for house energy management system," *IEEE Photonics Technol. Lett.* **28**(5), 593–596 (2016).
28. C. Kim, K. Jung, and W. Kim, "A wafer-level micro mechanical global shutter for a micro camera," in *Proc. IEEE 22nd Int. Conf. Micro Electro Mech. Syst.*, pp. 156–159 (2009).

29. D. Langley, S. Rogers, and L. Starman, "Fabrication studies for scaling photonic MEMS micro-shutter designs," *Proc. SPIE* **7096**, 709601 (2008).
30. K.-H. Lee, J. Chang, and J.-B. Yoon, "High performance microshutter device with space-division modulation," *J. Micromech. Microeng.* **20**(7), 075030 (2010).
31. K.-S. Lim et al., "Wide bandwidth reflective microshutter blind panel for transparent organic light-emitting diode display," in *SID 2016 Int. Symp.*, San Francisco, Vol. 47, no. 1, pp. 1389–1391 (2016).
32. S. Goodwin-Johansson et al., "Reduced voltage artificial eyelid for protection of optical sensors," *Proc. SPIE* **4695**, 451–458 (2002).
33. P. Roux et al., "Fem modelling of an electro-optical micro-shutter," *Sens. Actuators A: Phys.* **119**(1), 1–7 (2005).
34. M. Pizzi et al., "Electrostatically driven film light modulators for display applications," *Microsyst. Technol.* **10**(1), 17–21 (2003).
35. P. Schalberger, S. A. A. Nusayer, and C. Raichle, "Parallel fabrication for integration of electronic and microelectromechanical systems," in *SID 2016 Int. Symp.*, San Francisco, Vol. 47, no. 1, pp. 731–734 (2016).
36. J. Toonder et al., "Artificial cilia for active micro-fluidic mixing," *Lab Chip* **8**(4), 533–541 (2008).
37. M. A. Rosa et al., "A novel external electrode configuration for the electrostatic actuation of MEMS based devices," *J. Micromech. Microeng.* **14**(4), 446–451 (2004).
38. P. Deb Shuvra and S. McNamara, "The strain capacitor: a novel energy storage device," *AIP Adv.* **4**, 127158 (2014).
39. C. C. B. Bufon et al., "Self-assembled ultra-compact energy storage elements based on hybrid nanomembranes," *Nano Lett.* **10**, 2506–2510 (2010).
40. Y. Zhang and Y.-P. Zhao, "Flexural contact in MEMS stiction," *Int. J. Solids Struct.* **49**(17), 2203–2214 (2012).
41. D. E. Burns et al., "2-D electrostatic actuation of microshutter arrays," *J. Microelectromech. Syst.* **25**(1), 101–107 (2016).
42. V. T. Srikar and S. M. Spearing, "Materials selection for microfabricated electrostatic actuators," *Sens. Actuators A* **102**, 279–285 (2003).
43. W. M. van Spengen, "Capacitive RF MEMS switch dielectric charging and reliability: a critical review with recommendations," *J. Micromech. Microeng.* **22**, 074001 (2012).
44. H. Camon and C. Ganibal, "Advantages of alternative actuating signal for MEMS actuators," *Sens. Actuators A: Phys.* **136**(1), 299–303 (2007).
45. R. Saha et al., "Analysis of pull-in-voltage and figure-of-merit of capacitive MEMS switch," *Trans. Electr. Electron. Mater.* **17**(3), 129–133 (2016).
46. Y. Huang et al., "MEMS reliability review," *IEEE Trans. Device Mater. Reliab.* **12**(2), 482–493 (2012).
47. C. G. Kalt, "Electro-static device with rolling electrode," patent USPTO US 4094590A (1976).
48. B. Lamontagne, "Micro-blinds for smart glass," 2011, https://www.youtube.com/watch?v=RqwL2egaqYY.
49. C.-H. Kim and S. Hong, "Study on the reliability of the mechanical shutter utilizing roll actuators," in *Proc. IEEE 24th Int. Conf. Micro Electro Mech. Syst.*, Cancun, Mexico, pp. 501–504 (2011).

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