Time Multiplexed Optical Shutter (TMOS) Displays

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Technical Abstract

Time Multiplexed Optical Shutter ("TMOS") describes the operational principal of the patented Frustrated Total Internal Reflection (FTIR) display systems developed by Uni-Pixel Displays, Inc. (Selbrede, U.S. Patent No. 5,319,491). The fundamental principle[1] of FTIR displays is that light, edge-injected into one edge of a thin planar transparent waveguide, reflectively mirrored at the non-insertion edges, remains bound within the waveguide in the same way light is trapped inside fiber optic cables. The violation ("frustration") of total internal reflection (TIR) causes the light to emerge from the waveguide in the area where the violation occurs.[2] TMOS achieves Frustration of TIR (FTIR) by moving a high refractive index material or membrane into contact (or near contact) with the waveguide. The light inside the waveguide then "couples" out into the membrane and further into proprietary surface features on the membrane that direct the light toward the observer. The transient response rates of TMOS pixel actuation enables the use of field sequential color generation (FSC) with pulse width modulated gray scale generation at video-capable frame rates. The typical motional or color break-up artifacts associated with FSC systems[3] are resolved at their source[4]: the unbinding of consecutive primary color image planes.[5,6] A common misapprehension is that such displays would be non-uniform without a full understanding of the factors operative in a TMOS display. These factors include detuned pixels, tuned slab geometries, and mirrored edges yielding uniformity variation under 0.2 dB across the display. In addition, FSC artifact suppression has been resolved in work for an SBIR[7] project.

Technical Summary and Application Space

TMOS is an innovative flat panel display technology based on principles of operation quite distinct from those used in other technologies such as LCD, OLED, plasma displays, and CRTs. Localized frustration of TIR using light valves with large apertures and high speed response permits TMOS to implement field sequential color generation. This approach also significantly simplifies the TMOS display architecture[8] relative to other systems. The fabrication of this novel quasi-MEMS display system involves the precision integration of an elastomeric thin film aerially extended (the *Opcuity*™ *Active Layer*) across a transparent planar waveguide in which primary color light is sequentially edge-injected. This integration of disparate elements involves a patterned bonding mechanism that keeps the central apertures of the pixels free to articulate via ponderomotive deformation, while the thin film at the pixel

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[1] F. de Fornel. **Evanescent Waves: From Newtonian Optics to Atomic Optics**, first edition, Springer-Verlag, New York, 2001, pp. 18-28.

[2] S. Zhu, A. W. Yu, D. Hawley, and R. Roy, *Frustrated total internal reflection: A demonstration and review*, **Am. J. Phys. 54** (7), July 1986, pp. 601-607.

[3] A. Yohso and K. Ukai, *How color break-up occurs in the human-visual system: The mechanism of the color break-up phenomenon*, **Journal of the SID 14/12**, 2006, pp. 1127-1133.

[4] E. Castet, S. Jeanjean, and G. S. Masson, *Motion perception of saccade-induced retinal translation*, **PNAS, Vol. 2**, No. 23, Nov. 12, 2002, pp. 15159-15163.

[5] D. Rodabaugh, et al., *Phase I Final Report: Contract No. F42650-03-P-2751 (SBIR AF03-280) 17NOV03*, Unipixel Displays, Inc., pp. 3f.

[6] M. Selbrede, *Debunking an Urban Legend: Uniformity in Edge-Lit Frustrated TIR Displays*, **Technical Proceedings NSTI Nanotech 2006**, **Vol. 3**, Chap. 1, pp. 82-85. ISBN: 0-9767985-9-X.

[7] Small Business Innovative Research (SBIR) USAF Contract No. FA8201-04-C-0090.

[8] M. Selbrede, *Unicellular Pixel Architectures and the Large Area Display Challenge* (a white paper formally submitted to DARPA), Ticom Technologies, Inc., Chatsworth, California, 1994, pp. 1-5.

peripheries is firmly tethered (analogous to a drum head) to secure reliable low-voltage mechanical actuation.

The unique architecture[9] and associated performance metrics[10] that can be achieved by TMOS align the technology to deployment in application spaces known to be problematic. TMOS is particularly well suited for use in avionics,[11] where some of its attributes (e.g., its inherent transparency, enabling z-axis redundancy[12] in airframe cockpits) permit the extension of display capabilities beyond the limits of currently deployed technologies.[13] TMOS is a transmissive technology that, without advanced optimization, can achieve approximately 61% efficiency (output in lumens divided by raw lumens injected into the waveguide), and can achieve over 80% efficiency if optimized for program content.[14] The absence of color filters and polarizers, when combined with TMOS' multi-pass light depletion approach arising out of its use of a TIR-based stochastic waveguide, fuel this efficiency advantage over active matrix liquid crystal displays. The current weighted tristimulus average power efficiency cited by leading suppliers of light emitting diode (LED) illumination sources (50 lumens per watt for Lumileds, Inc.) will allow TMOS to achieve 30.5 lm/W output. As LEDs improve in power efficiency, TMOS (being a transmissive display system) system efficiency will proportionally improve as well.

TMOS: The Big Picture

UniPixel's TIR-based architecture simplifies the manufacturing and assembly of display panel devices by replacing the many complex structures and materials currently found in LCD panel devices with a single thin film layer (UniPixel's "Opcuity"™ Active Layer).

TMOS can advance the state of the art in display performance in terms of brightness, power efficiency, and image quality. Additionally, the TMOS architecture can support advancements in display design, performance, and unique new features. For example, a TMOS display can eventually be built to be flexible, shaped (conformal), and transparent (offering a heads up type of reality overlay display device, or revolutionizing display redundancy doctrine by exploiting the z-axis). UniPixel's TMOS technology will not require the use of backlights, brightness enhancing films, polarizers, color filters, liquid crystals, noble gases, vacuums, phosphors, nor absorptive layers such as are commonly used to improve display contrast in other display technologies. The absence of polarizers, color filters, masks, and other light-impeding apertures native to LCD technologies can push the relative power efficiency of TMOS up more than an order of magnitude beyond LCD performance.

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[9] B. Cox and M. Selbrede, *Inside FPD: UniPixel's TMOS Display Technology*, **Nikkei Microdevices June 2007**, pp. 43-47.
[10] M. Selbrede, *Design improvements for flat panel displays*, **SPIE Newsroom** July 2006, DOI: 10.1117/2.1200607.0312 (http://spie.org/x8662.xml)
[11] B. Yost and M. Selbrede, *Time Multiplied Optical Shutter (TMOS) display technology for avionics platforms*, **Proc. SPIE, Vol. 6225**, 2006.
[12] Selbrede, US Patent Application 10/678,789.
[13] Sarma, K. R., Schmidt, J., Roush, J., Maner, R, "Current Assessment of AM OLED Technology for Avionics Applications," in *Cockpit and Future Displays for Defense and Security*, **Proc. of SPIE** Vol. 5801 185-193 (2005).
[14] Selbrede, US Patent 7,057,790 and Selbrede, US Patent 7,218,437.

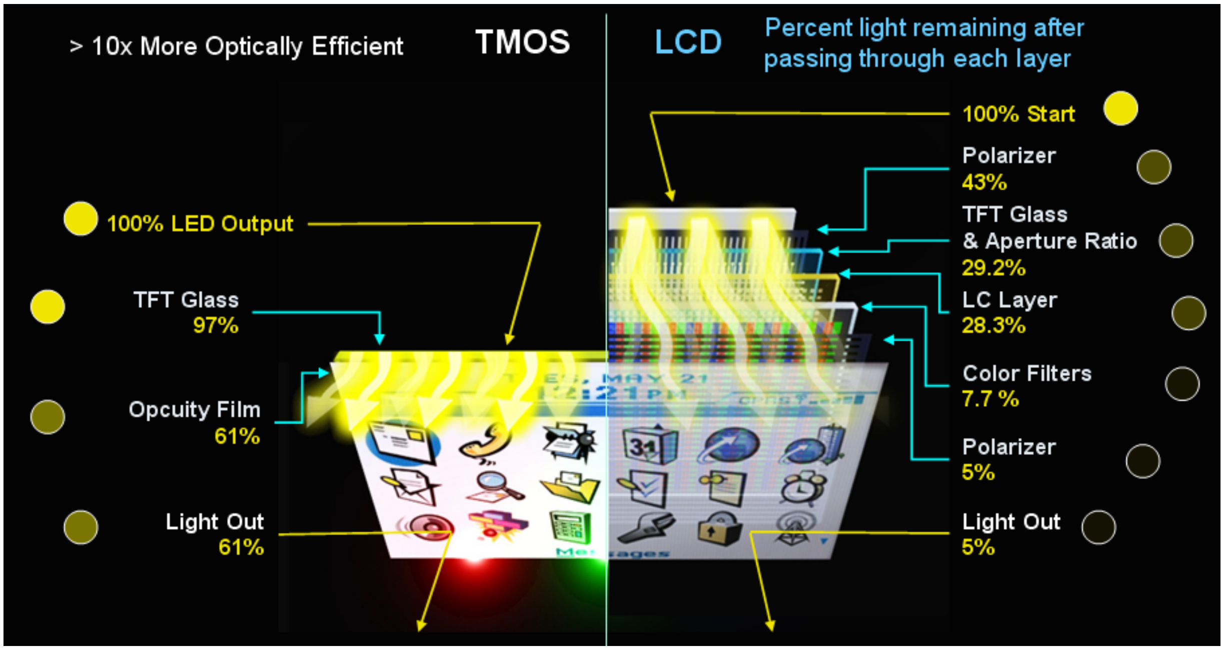

Figure 1. LCD displays (right side) use multiple subtractive layers to modulate light in a one-pass system. TMOS (left side), is a "multi-pass" system that does not incorporate the same number or type of attenuating mechanisms.

TMOS: Sub-Systems Overview

The TMOS display system architecture is a unique combination of discrete sub-systems. Each sub-system can be independently advanced in its development, bringing increased performance and capabilities to the composite system over time by meeting specific milestones for integration into the system. UniPixel has mapped out an extensive parallel development process for each sub-system.

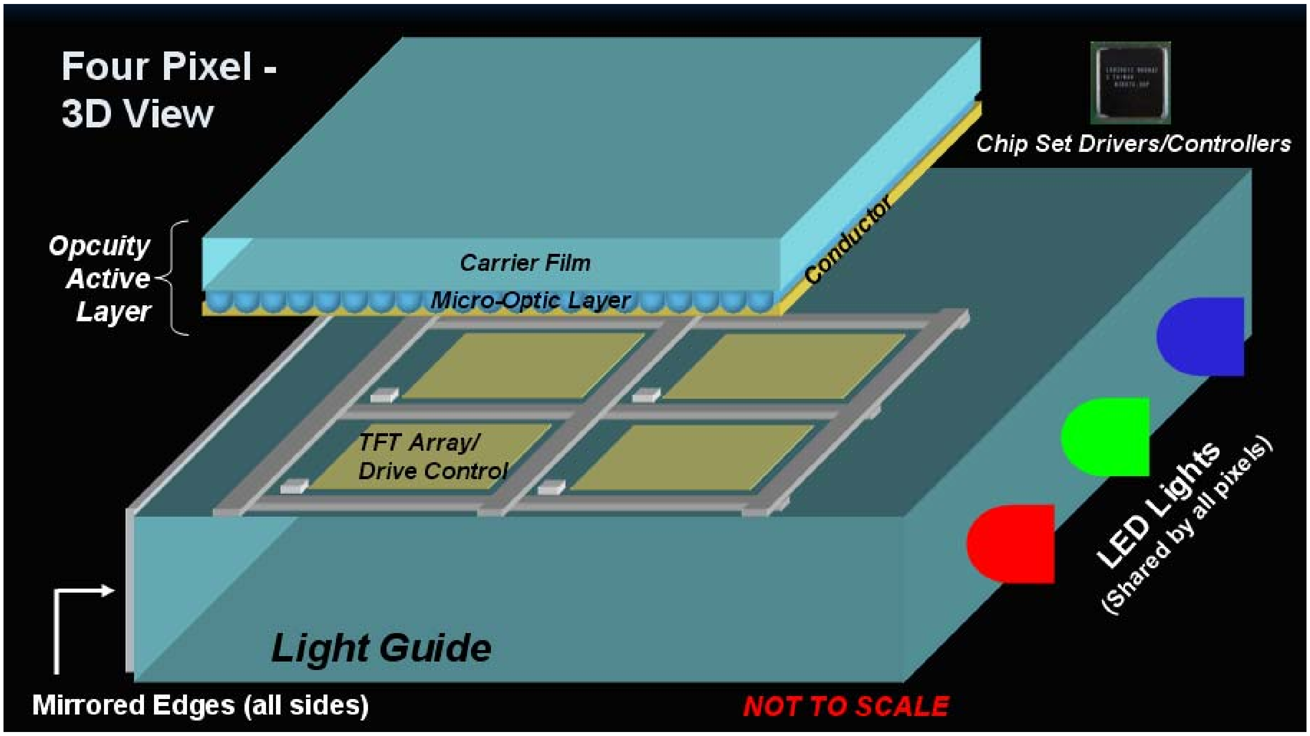

Figure 2: Conceptual exploded view (not to scale in any axis) of four TMOS pixels showing the sub-systems including the Opcuity Active Layer in exploded (unassembled) position above the light guide to which it is to be attached.

Given this architectural approach, UniPixel has directed much of its efforts toward defining the interfaces between sub-systems and the boundary conditions that must be met to insure overall system functionality. Additionally, UniPixel is developing the Opcuity Active Layer and intends to be the supplier of this sub-system for display panel assembly.

The sub-systems are as follows:

Light Guide (LG) – The LG serves as the core light transmission medium in the system. Non-collimated light is injected into the LG from the "illumination system" and is maintained in stochastic multimode TIR propagation in the LG until emitted at an active pixel, depleted by absorption, or exhausted through the natural sink in the system. Initially, the LG is being developed using high quality optical glass characterized by ultra-low volume scattering (to reduce intrinsic system noise). The initial development plan will advance the LG to Thin Film Transistor (TFT) mother glass, then onto flat polycarbonate or monomerized polyolefin[15] sheets, and then onto flexible polymer sheets.

Illumination System – UniPixel's TMOS architecture, based on the conventional tristimulus model of color generation, incorporates red, blue, and green (RGB) LEDs for its light sources. The LEDs are set in a light bar assembly that mounts the individual LEDs and encases them in a manner optimizing the angles of light injected into the insertion edge of the system's LG. The illumination system also incorporates the appropriate attachment means for mating the illumination system to the LG to prevent

[15] Although fluoropolymers have received recent attention as waveguide materials, monomerized polyolefin exhibits the lowest absorptive and scattering losses of the various polymer candidates.

light leakage and to redirect stray light back into the system. The illumination system is tuned to optimize the overall system relative to the required range of transit angles through the LG. Global luminance control can be achieved either through pulse width modulation of the main LEDs or via conventional current control. The former method yields a dimming ratio at least as high as 100,000:1 without affecting chromaticity of the primary colors, which is useful for avionics deployment.

Over time, the illumination system will be able to incorporate a broader mix of LED colors to achieve photo quality imagery (extended gamuts not limited to the tristimulus color space) and also will be able to house Infrared (IR) light sources in addition to visible light sources. Operating with such super-gamuts (switchable and/or superimposed) presupposes image content that is suitably encoded to take advantage of this TMOS feature. It is expected that a mix of visible and non-visible light will make the system night vision compatible; the global luminance can be tuned to meet the needs of any ambient light environment, from night vision compatibility to readability in direct sunlight.

Drive Control mechanism at the individual Pixel – The TMOS "optical shutter" light valve mechanism is controlled using a variable capacitor architecture at each individual pixel. The capacitor is constituted by two conductive planes held parallel to one another and separated by a sub-micron gap. When a voltage differential is created in the capacitor, Coulomb attraction pulls the two conductive planes together. In the TMOS architecture, one of the capacitor planes resides on the light guide (LG) and the other resides on or within the active layer (AL) film. For the LG capacitor conductive plane, it is expected that a pad of Indium Tin Oxide (ITO) or other transparent conductor will be used. For the AL capacitor conductive plane a thin continuous layer of conductive material extending across the entire surface of the film will provide a suitable ground plane. Controlling the charge and the discharge of the LG plate provides the control of the attractive force that activates the individual pixel through controlled local deformation of the AL membrane.

Initially, prototype devices were built that utilized individual conductive traces extending from the edge of the LG to each individual pixel conductive pad on the LG. This "direct drive" approach allows the control of the pixels to be managed by transistors that are located off of the LG. In addition, current development prototypes have TFTs located at each pixel which provide the pixel drive control capacitor management. Leveraging a unique approach invented by UniPixel called "Simple Matrix,"[16] UniPixel expects to be able to eliminate the TFTs from the system over time and provide individual pixel control by patterning the conductors on the LG and AL as stripes. The crossover intersection point of the row stripes on the LG and the column stripes on the AL will provide the capacitance point of the pixel for hysteretically controlling the optical shutter. Once the Simple Matrix approach is implemented, large TFT foundries will no longer be required for TMOS display panel production. Apart from the increased ease of manufacturing, Simple Matrix has significant advantages in regard to immunity to electromagnetic pulse and other factors relevant to modern electronic countermeasures.[17]

Opcuity Active Layer – The core elements that allow the TMOS system to perform as required are built into the Opcuity Active Layer (AL). The AL will evolve over time to interface optimally with the drive control system implemented in the individual device. The AL for every implementation has the same basic core elements. These include a base carrier film, micro-optic structures added to one surface, and a conductor added either in a contiguous ground plane layer or as a patterned set of stripes. The size,

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[16] K. Derichs, US Patent Application 10/529,114.
[17] See footnote 12.

geometry, and optical properties of the micro-optic structures govern the light output performance of the display system (extraction efficiency, dispersion pattern/viewing angle, backscatter, ambient light handling as it relates to contrast ratio, etc.).

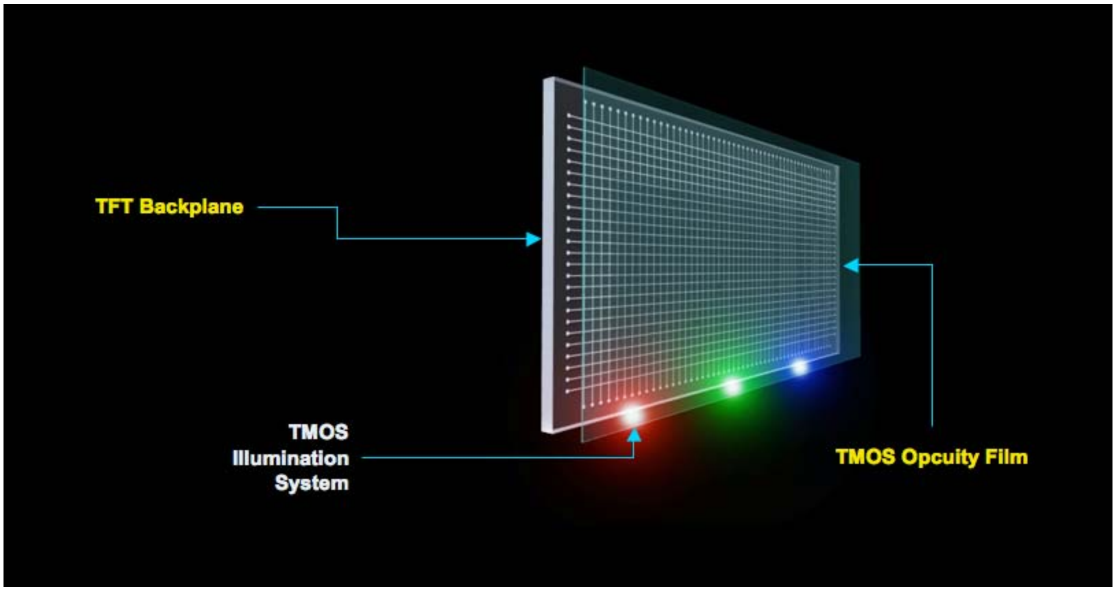

Figure 3: Relationship of the primary elements of a TMOS display. The TFT Backplane is on the Light Guide, which is edge-illuminated (number of LEDs determined by formula), onto which the TMOS Opcuity Film is assembled using close tolerances.

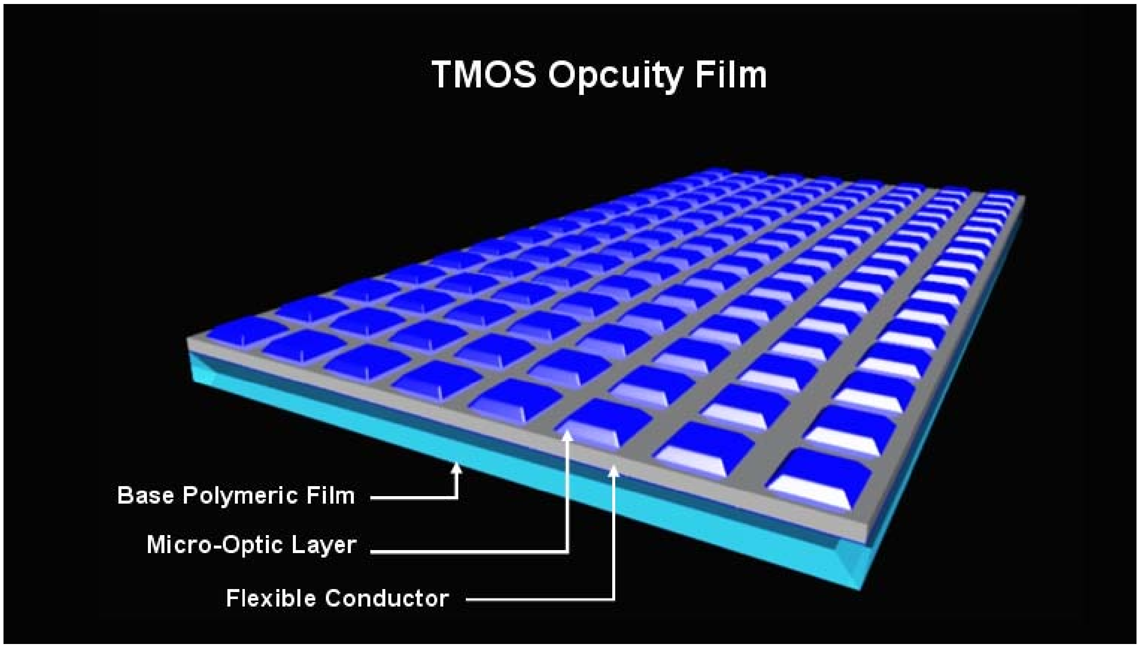

Figure 4: Notional construction of TMOS Opcuity Film comprising the Active Layer in TMOS (the deformable element suspended over each pixel region). The shape of the micro-optics is notional; actual geometries are different.

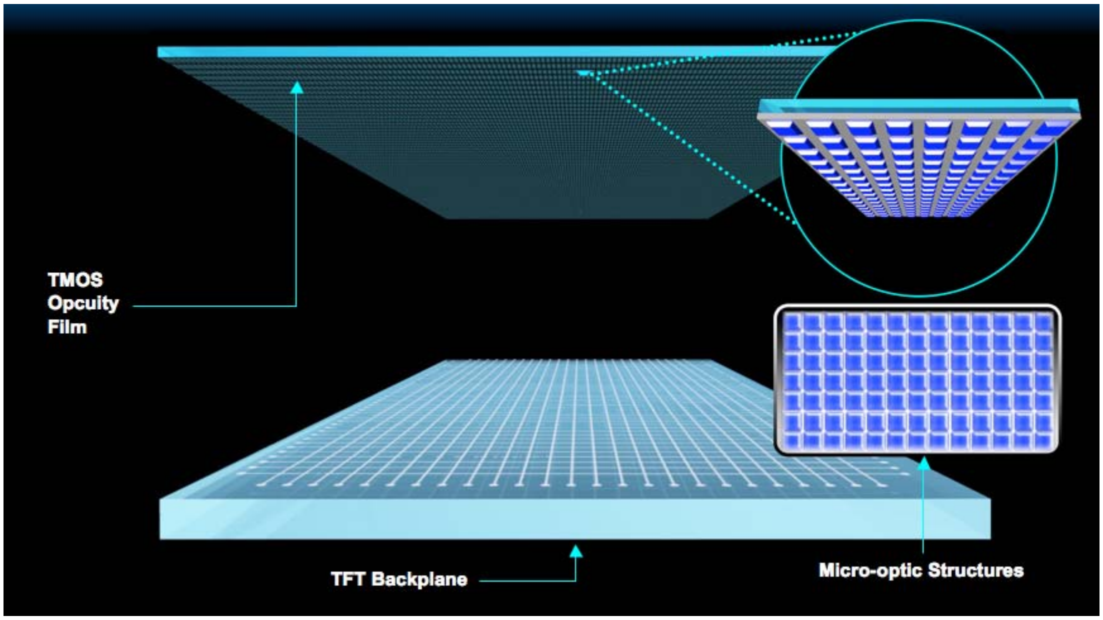

Figure 5: Pre-Assembly view of the TMOS components to be assembled. Note that the micro-optical structures in the TMOS Opcuity Film are intended to face the Light Guide, upon which the TFT Backplane is situated. The final spacing after assembly is between 300 and 500 nanometers

Drive Control Circuitry System Level – As in every display panel technology, TMOS has its own unique drive control timing and voltage requirements. It is expected that one or more semiconductor manufacturing partners will provide the semiconductor drive control solution required for TMOS. During initial prototyping, all of the drive control logic was programmed into an FPGA processor. The next step will be the ability to flash the specific programming to a target FPGA platform as a means to reproduce the FPGA in low volume for panel prototype volumes and sampling.

A TMOS display is a series of optical shutters as pixels, with each pixel opening and closing to emit time slices of light over a specific time period. One pixel handles all colors: there are no sub-pixels for red, green, or blue (hence the term "unicellular" pixel). Pixel operation is an "all digital" function, meaning that either the pixel is open ("on") or closed ("off"). As opposed to other technologies that require analog settings to control light modulation, TMOS uses only on/off timing. This approach leverages Field Sequential Color (FSC) generation techniques for which UniPixel has developed a series of unique patents[18] to handle known issues associated with FSC systems and extend their functionality and utility. Gray scales for each primary are generated by way of pulse width modulation using UniPixel-specific encoding algorithms.[19]

UniPixel has developed a road map of drive control timing advances that will be implemented in TMOS systems over time. These advances will support the overall extension of the technology as it incorporates a broader mix of input light color sources, non-visible light sources, color breakup mitigation techniques, and other planned enhancements to the system architecture.

[18] US Patent Applications 10/513,631, 11/671,087, etc.
[19] C. King, US Patent Application 11/201,220.

TMOS: Pixel Operation

Panels start with a transparent rectangular planar substrate composed of either glass (or plastic) termed the Light Guide (LG). Light Emitting Diodes (LEDs) are attached to one or more edges. Mirrors are placed on all remaining edges[20] to keep the light in the Light Guide. Red, green or blue light enters the light guide from the LEDs on the edge of the display. Each color cycles for an equal amount of time[21] in very rapid succession. The light reflections off the mirrored LG edges (and continual TIR reflections on the large LG surfaces) producing a highly uniform geometric distribution of light energy within the Light Guide. This dispersed photon cloud is tapped by the individual pixel light valves as required. Note that only one color of light fills the LG at any instant in time.

A simple variable capacitor structure is imposed on top of the Light Guide to function as an "optical shutter" at each pixel. This capacitor is comprised of two parallel conductive planes separated by a microscopic (sub-micron) gap.[22] The respective conductive planes that make up the capacitor architecture are a pad of transparent conductor on the Light Guide, and a conductor on the elastomeric deformable "Active Layer" that is affixed to the Light Guide by microscopic standoffs tethering the Active Layer to the perimeter of each pixel. The center of the untethered region, like a drum head stretched over a frame, is free to move under the influence of electrostatic force (Coulomb attraction); the potential energy stored in the now-deformed Active Layer provides the necessary restoring force to turn the pixel off and return it to its quiescent state suspended over the Light Guide.[23]

Indium Tin Oxide (ITO) will likely comprise the pad layer on the Light Guide due to its chromatically neutral filtering behavior, contra TPG (transparent gold). As stated before, patterned stand-off elements are used to affix the Active Layer to the Light Guide and create the air gap between the Active Layer contact surface and the Light Guide. This prevents the part of the pixel that actually moves (by induced deformation) from touching the Light Guide until needed. Materials used for bonding the Active Layer have been developed to keep light from escaping from the Light Guide, such that TIR is fully preserved when no pixels on the display are active.

The Active Layer, made using a base carrier film such as a P.E.T.-type film, is the only moving part in the TMOS display architecture. On the surface of the Active Layer facing the Light Guide, tiny micro-optic structures are distributed that serve as the coupling interface for light transmission and direction. These micro-optic structures create small convex projections ("mountains") on the Active Layer surface with corresponding concavities ("valleys") between features. These valleys are filled by an opaque

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[20] In practice, mirroring is also applied between the LED light sources as well. The amount of such "insertion surface" mirroring is a function of individual light valve efficiency, which is itself a function of coupling efficiency at the contact plane and aperture (ratio of contact area to total pixel area).

[21] M. Selbrede, US Patents 7,057,790 and 7,218,437, teaches the relaxation of this requirement based on program content, on the principle that the drive LEDs shouldn't operate if there is no image data for the temporal subframe remaining to transduce. Elimination of such energy waste entails truncating the duration of the source LEDs. This real-time modulation is program content-specific at the individual temporal subframe level.

[22] During actuation, it is undesirable for the conductors to make contact, causing a short, so one or both of them is usually encapsulated, or dielectrically coated, or recessed relative to other micron-level topological features, to bar dielectric breakdown. Consequently, the referenced gap between conductive planes is usually configured as partially air or vacuum (permitting the required motion to freely occur) and an encapsulating dielectric. The airgap portion tends to measure 300 to 500 nanometers, while the dielectric portion of the gap varies between 1 and 3 microns, as determined by voltage limitations.

[23] Recent patent filings by UniPixel teach the option of active, rather than passive, release mechanisms. The energy stored in the elastomeric Active Layer must exceed the surface energy and other stiction-oriented effects operative at the contact plane by a sufficiently large margin to permit use of passive release systems. Where a safe ratio is absent, active release is required.

conductor material that serves to assist in increasing the system's contrast ratio as well as providing the upper plate of the capacitor. This composite structure creates a simple optical shutter mechanism above the light guide that sandwiches the micro-optic structures in the Active Layer between the two conductor plates.

This capacitor structure – two conductive layers separated by a dielectric or insulator – exists at each pixel and forms the optical shutter drive control. When a voltage differential is created between the two conductive layers at any given pixel, the conductive planes attract via Coulomb attraction. The micro-optic structures are pulled down between the standoff features. When they finally touch[24] the light guide, the pixels are activated and light escapes. Pixels are turned on and off by alternately pulling the Active Layer into contact with the Light Guide and then releasing it to return to its quiescent state.

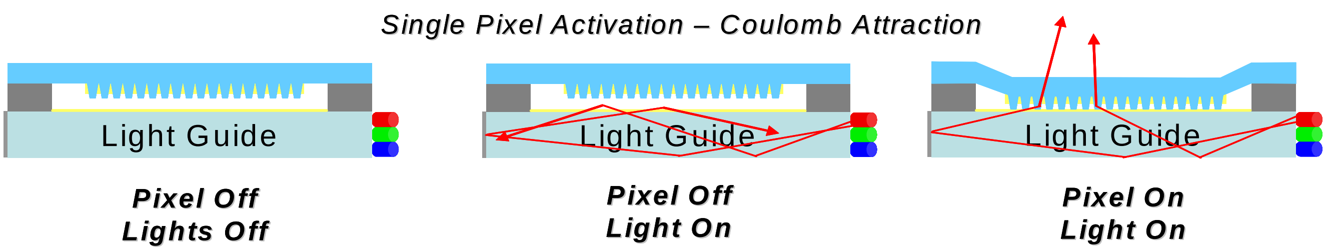

Figure 6: The three allowed states of a TMOS pixel. Micro-optical structures don't couple light out until contact or near-contact occurs. Pixel turns on when adequate charge differential is applied between the conductors across the gap. (Layers and deformations not to scale). The combined layers are less than 15 microns thick.

TMOS: Field Sequential Color Generation

A TMOS display takes sequentially injected red, blue, and green LED light bound inside a planar waveguide and controllably redirects it to the viewer at each pixel locale through a time controlled optical shutter on the surface of the display. Unlike LCD displays, the absence of color filters and polarizers in a TMOS display allows a very high percentage of the input light to reach the viewer. This architecture requires only a single light emission area as opposed to the three light emission areas (red, blue, and green sub-pixels) required for pixels in LCD or other spatially additive color technologies. TMOS uses the same color generation method (field sequential color) in a direct-view device that Texas Instruments has successfully commercialized for projection-view devices in its DLP™ image projectors and televisions.

Color generation is achieved by using the field sequential color technique, whereby the system frame rate is subdivided among primary colors (red, green, and blue). Gray scale for each primary color is achieved via pulse width modulation at the pixel level.

Traditional displays use three closely spaced dots that display different intensities of red, green and blue to create one color – somewhat like the dots that comprise a printed image. Because these dots are so close together, the human eye perceives them as a single color due to the proportionally small subtended angle between them. This technique exploits what is called "spatial additive color."

[24] The actuation process can occur in significantly less than a microsecond, from application of the voltage to maximum surface contact between the Active Layer and Light Guide.

TMOS is based on "temporal additive color." Short bursts of red, green and blue light are emitted through the same dot so quickly that the eye perceives them as a single color. At sufficiently high frequencies, the individual colors are received at the retina faster than the temporal resolving power of the human eye can discriminate. At such frequencies, different durations of red, green and blue create different shades and hues, permitting image generation encompassing the range of colors enabled by accessible permutations of the three chosen primaries.

The duration of the charge across the variable capacitor comprising each pixel controls the opening and closing of the "shutter." At any given pixel, this duration determines the relative intensity of the colored light being emitted at that region.

Examples:

- Black Text on a White Background
    - To produce the white background, each pixel is open for the entire duration of the red, green and blue cycles. To produce the black text, each pixel comprising a letter's shape is closed for the entire duration of each cycle.
- 50 percent gray
    - Each pixel is open for 50 percent of each red, green, and blue cycle.
- Blue background
    - Each pixel is closed during red and green cycles, but open during the blue cycle. The shade of blue is determined by the percentage of the blue cycle that the pixel is open. 10% = deep blue; 100% = bright blue. Aqua is achieved by adding green light, while navy blue is achieved by adding a fractional amount of red.
- Photograph
    - Each pixel is left open for different percentages of the red, green, and blue cycles to produce millions of different colors and shades of gray. Note, again, that *only one color* is being modulated at any given time. At no point do all three colors (red, green and blue) exist simultaneously in the Light Guide.

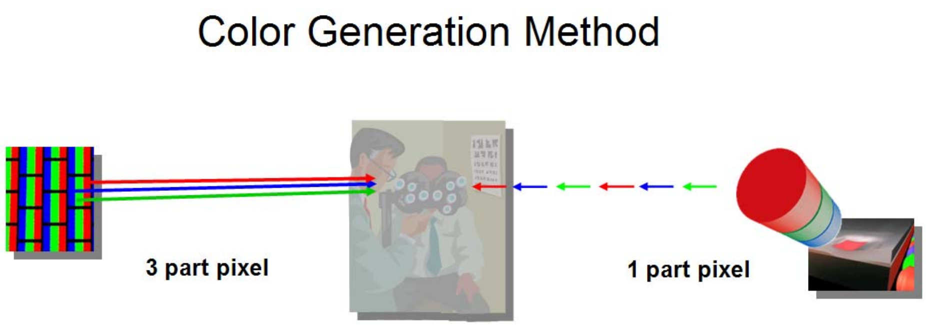

Figure 7: On the left, spatial additive color sends all colors at once to the human eye. At right, temporal additive color sends the colors one at a time, but at a higher frame rate.

Spatial Additive Color	**Temporal Additive Color (Field Sequential Color)**
The human vision system adds closely spaced colored dots together into a single color.	The human vision system adds bursts of closely sequenced colored light together into a single color.
CRT, LCD, OLED, Plasma	TMOS, DLP, LCOS

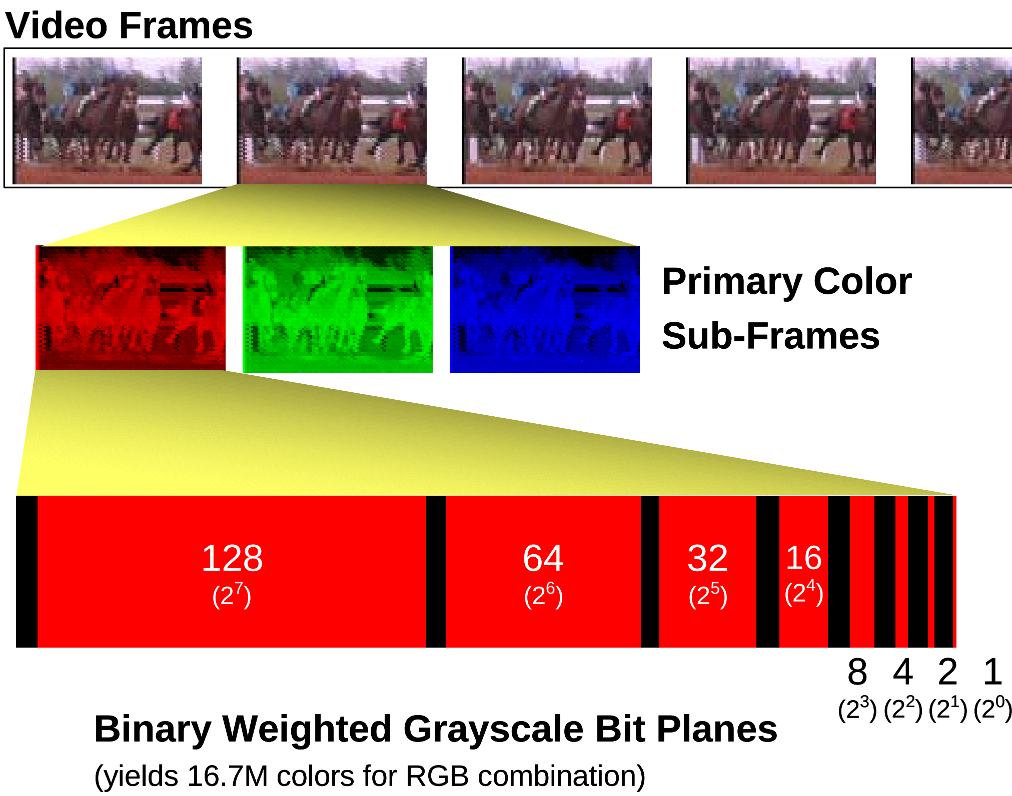

Figure 8: Decomposition of video information being modulated by the TMOS pixels.

UniPixel currently holds, or has applied for, a number of patents on the shutter, materials,[25] micro-optics,[26] construction techniques,[27] and software drivers that enable temporal color systems to surpass the limitations of spatial color.

TMOS: Performance Analysis

Brightness

Unlike liquid crystal-based light valves that leak light in the opaque state, the FTIR-based light valves in TMOS maintain signal-to-noise better as screen brightness increases. TMOS can achieve 1,400 nits in a 12.1" diagonal display (1024x768 XGA) with 176º viewing angle (requiring 385 lumens) at 13.2 watts. Further, TMOS can achieve the more aggressive luminance value of 3,430 nits (same spec as above, 944

[25] US Patent Application 11/215,515.
[26] US Patent Application 11/338,251.
[27] M. Selbrede, US Patent 7,092,142.

lumens) at 30 watts. Being a transmissive light valve, the output luminance is a purely a function of input energy. The display's efficiency being so high (61%+) gears it toward applications where either (1) high brightness is required (sunlight readable deployment), or (2) energy efficiency is paramount (where battery life issues predominate).

Contrast Ratio

Fresnel reflection off the top BBAR[28] surface of TMOS is 0.1% with subsequent layers eight times lower due to the aperture effect of the micro-optic structures. Contrast ratio in high ambient (sunlight) environments ranges from 32:1 to beyond 160:1; the core signal-to-noise ratio exceeds 3200:1 for 12.1 inch displays. The noise floor is determined by the optical purity of the waveguide and its geometry.

Night Vision Compatibility

TMOS uses discrete monochromatic LEDs in a field sequential color regime with highly peaked chromaticity. Since the red LED is under independent control, there is no necessity to add the traditional – and expensive – infrared cut-off filter to a TMOS display to achieve night vision compatibility. TMOS can achieve a compatible signature without use of such IR filter elements.

Night vision compatibility also requires ultra-high dimming ratios without loss of gray scale. The global brightness of a TMOS display to achieve such high dimming ratios is controlled by *three cumulative methods*:

- Pulse Width Modulation applied to the source LEDs (rated to 10,000:1 dimming ratio)
- Number of LEDs operational (6:1 dimming for 12.1" diagonal)
- Current applied to the LEDs in operation (approx. 5:1 dimming)

Total dimming ratio from all three methods reaches 54 dB, which permits coexistence of sunlight readability and night vision compatibility in same system.

Resolution

TMOS can readily achieve quarter-millimeter dot pitch, in part due to its unicellular pixel structure. Densities as high as 300 dpi are projected. Near-eye applications are not considered a primary development target for TMOS at this time, since they require implementation of an alternate TMOS architecture[29] to gain the required high-density images.

[28] BBAR stands for Broad Band Anti-Reflective coating. Such excellent BBAR performance in ultra-thin (sub-micron) layers is achievable with so-called Halpern Equivalents, which commonly invoke graded refractive indices.

[29] The gap between the Active Layer and Light Guide is a fixed engineering parameter, so when the pixel diameter is reduced, the ratio of the pixel's surface area to its required z-axis excursion becomes smaller, necessitating increased mechanical strains upon the Active Layer to achieve pixel actuation. Apart from the rise in activation voltage such scaling would necessitate, the Active Layer may approach or even exceed its elastic limit as ever smaller pixels are attempted. This can be dealt with either by selecting elastomers with greater elastic limits, or moving toward alternate TMOS embodiments that are either (1) solid state approaches or (2) utilize surface acoustic wave phenomena to impose a dynamic diffraction grating on the surface of the waveguide. Neither of these embodiments is under current development at Unipixel, in the interests of focusing on the preferred embodiment, which is applicable to 99% of all direct view applications, excepting such near-eye high-resolution systems.

Viewing Angle and Light Emission

The Opcuity Active Layer film can be fabricated with customized micro-optical structures to secure a customizable range of solid angles. These more restricted emission patterns can be achieved without adding extra optical layers to the TMOS display. Modeling has shown that angles as narrow as 25º x 12º (12.5º left, 12.5º right, 6º up, 6º down) can be achieved *in situ*, without additional steering optics, by appropriate choice of Opcuity Active Layer microgeometry. The output values cited previously are based on the widest dispersion pattern available with TMOS (176º) and are thus quite conservative.

Gray Levels

Patent pending encoding methods for TMOS permit operation beyond 24-bit color within a highly optimized field sequential color generating domain. TMOS is a purely digital system which converts analog video to digital equivalents. Matching the drivers to TMOS' inherent digital transduction system permits operation up to 36-bit color. Moreover, TMOS can be configured to instantly switch from visible to infrared operation and back again: the gray levels for monochromatic infrared (IR) operation are three times the primary color gray scale for visible operation (e.g., for 256 levels per primary, IR would have 768 gray levels).

Dimming Range

As articulated above, maximum dimming ratio is controlled by *three cumulative methods* (see **Night Vision Compatibility**). For applications where such dimming ratios are called for, a nominal value of 34 dB (3000:1) is specified.[30] TMOS exceeds this nominal value by two orders of magnitude.

Video Capability

TMOS is targeted toward COTS (Commercial Off-The-Shelf) applications in the highly competitive display market sectors where excellent video performance is required. Accordingly, TMOS specifications (such as the power dissipations provided earlier for sunlight-readable operation) are premised on 60 frames per second video operation while displaying 24-bit color (eight bits per primary color). Due to its reliance on field sequential color within a quasi-MEMS-based architecture, the notion of screen refresh is not entirely applicable to TMOS.

As specified earlier, UniPixel has innovated patent-pending solutions to motional and color breakup artifacts (SBIR AF03-280, Contract F42650-03-P-2751 and U.S. Patent Application 60/704,605).

Temperature Range

At the high end, the entire TMOS display can exceed 90ºC in operation, well above the specification for even the harshest application environments. At the low end, the TMOS screen proper can operate well below –40ºC (so far as the light valves are concerned), but the illumination LEDs that feed light into the waveguide are officially limited to operation at or above –40ºC. Alternative sourcing of these LEDs, or extreme temperature binning of LEDs, would be required to exceed this low-temperature specification for the entire system. It is likely that differential CTEs (Coefficients of Thermal Expansion) at this threshold cause issues for the commercially available illumination sources.

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[30] Sarma, K. R., Schmidt, J., Roush, J., Maner, R, "Current Assessment of AM OLED Technology for Avionics Applications," in *Cockpit and Future Displays for Defense and Security*, Proc. of SPIE Vol. 5801 185-193 (2005), 185.

In avionics applications, AMLCD displays are dominant. In that application space, they require retrofitting not only for shock, vibration, night vision compatibility, EMC, etc., but also require bulky heaters to permit operation at lower temperatures. TMOS displays do not require such expensive retrofits to operate at such temperatures. LCD heaters, apart from bulk and weight, represent a significant power drain on an avionics platform. The absence of such retrofitted heaters for TMOS represents a significant advantage for TMOS in this application space.

Shock and Vibration

TMOS exhibits intrinsic robustness to mechanical stresses, particularly during operation, as the applied forces are distributed globally and not locally at the individual pixels. The low mass of the Opcuity Active Layer film, and its submicron lamination to the standoff over a distributed standoff system, combine to mitigate harmful resonances and modes (such as would affect image quality or cause delamination to occur) from arising in the system.

The primary shock/vibration failure mode will be fracture of the planar waveguide in which the TIR light travels. It is expected that TMOS displays will far exceed AMLCD displays in respect to mechanical damage under shock and vibration testing, especially if high-transparency monomerized polyolefin waveguides are deployed.

Mean Time Between Failure

TMOS pixels as quasi-MEMS structures at the mesoscale exhibit some of the same lifetime properties as Texas Instruments Inc.'s DLP (digital light processor) torsional mirrors: extremely long life despite high actuation duty cycles.

The long pixel life is premised on mechanical strains in the Opcuity Active Layer that are well below the elastic limits of its substrate. The mode of actuation being different from a DLP micromirror, the source of long life is also different (for DLP elements, it's predominantly due to the lack of friction within a single-grain metallic structure). The first component expected to fail in a TMOS display is the LED subsystem that feeds the waveguide. These are commercially rated at 100,000 hours MTBF under continuous operation. Since TMOS uses LEDs at 1/3 duty cycle, the maximum expected MTBF in TMOS deployment is expected to approach 300,000 hours MTBF. Rapid cycling under normal operating conditions has not been shown to seriously affect MTBF for Lumileds LEDs.

Rethinking Display Redundancy

TMOS displays are intrinsically transparent. This property permits Z-axis redundancy.[31] The advantages of this approach to display redundancy are many, particularly in avionics applications where cockpit space is at a premium. Advantages include the following factors:

- The displays can be larger. Two conventional displays side-by-side can be replaced by two z-axis-stacked displays on top of one another that are 41% larger in area, without using any extra cockpit space.
- Ergonomically, the flight crew doesn't need to look at a different point within the cockpit to see the backup display: it occupies the same physical space as the original display. This has significance in the realm of human factors engineering.

[31] M. Selbrede, US Patent Application 10/678,789.

- Z-axis-stacking permits data segregation (e.g., cartography on one layer, symbology on another, etc.) during simultaneous operation of both displays.

Because a TMOS display fails in the transparent mode, a backup TMOS display situated directly underneath the primary display can be activated and take over video generation from the failed unit. The adoption of TMOS display technology in such application spaces will permit rethinking the doctrine of redundancy and how best to achieve it.

TMOS: Manufacturability and Display Assembly

UniPixel has conducted evaluation projects with industry experts that have concluded that TMOS displays can be fabricated on a legacy LCD line by *removing* many steps in the manufacturing process that are not required. This macro-scale simplification of an LCD foundry has implications relative to yields and the cost to produce TMOS displays vs. LCD displays. A simpler architecture makes possible a simpler manufacturing process.

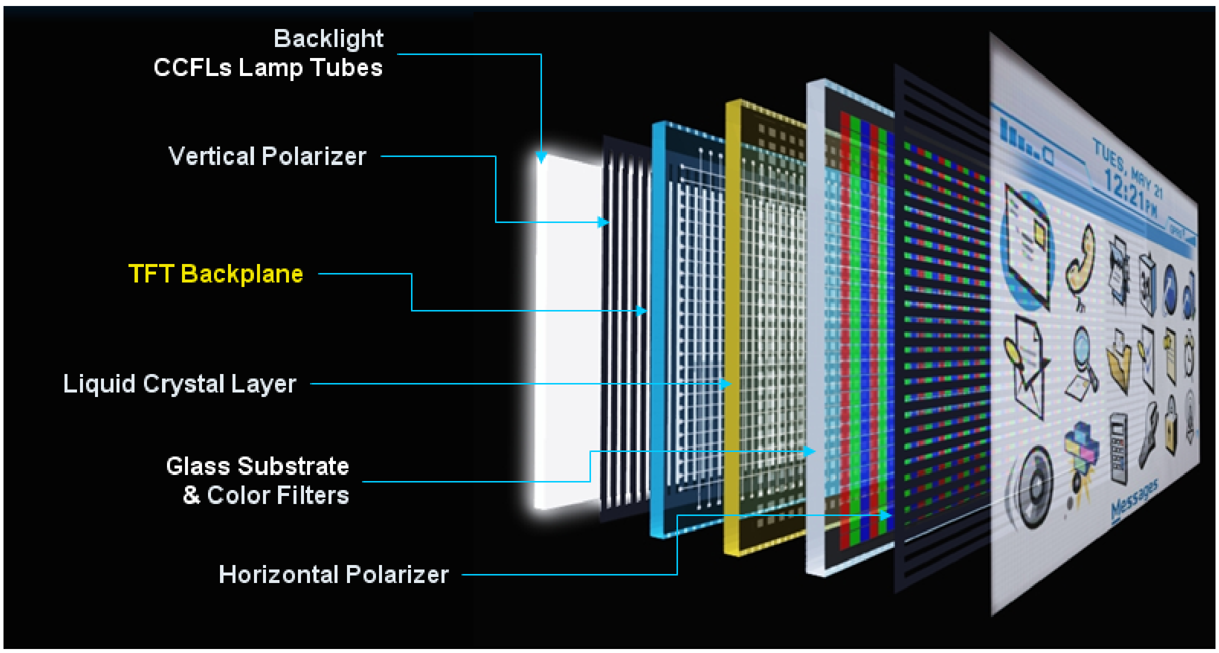

Figure 9: Conceptual illustration of AMLCD fabrication process.

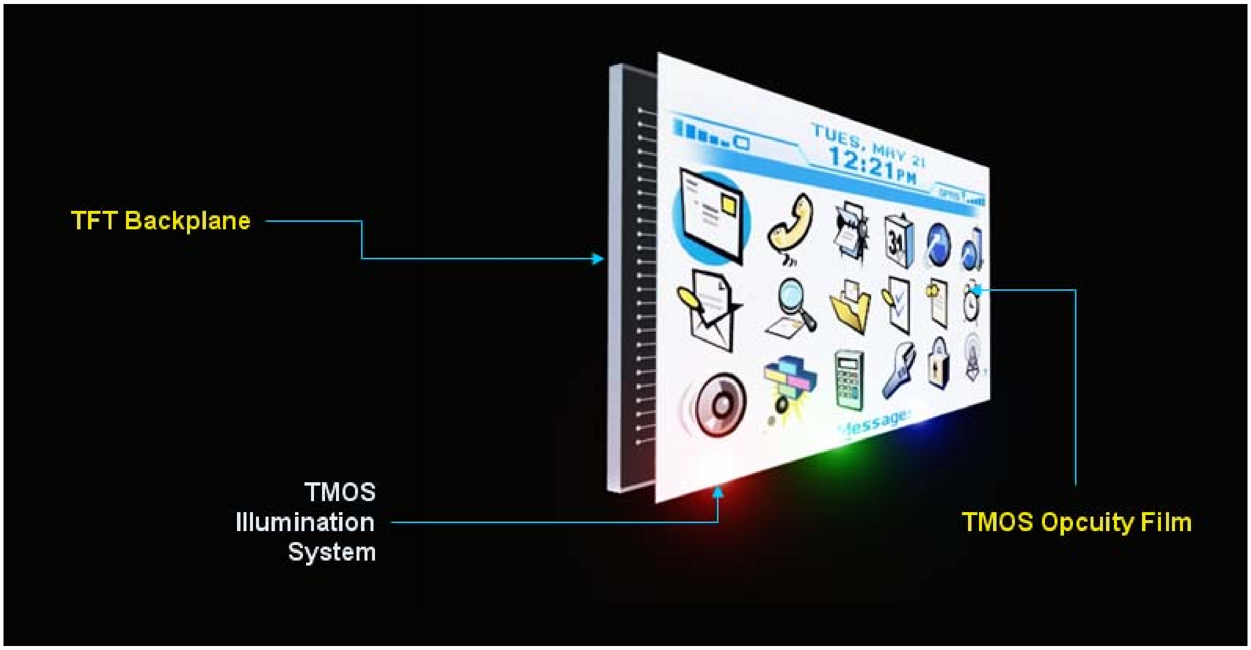

Figure 10: Conceptual illustration of TMOS fabrication process. Note that TMOS has far fewer manufacturing steps than does LCD (and thus fewer failure points).

TMOS architectures not only provide performance advantages, they also reduce the cost of display manufacturing in contrast to mainstream technologies. Significantly greater yields for a unicellular display (as a function of the display diagonal measure) arise from its potential for a registration-free assembly, its reduction of the TFT count by a factor of at least two-thirds, and its comparatively larger feature sizes (which, electronically, are far removed from pushing the technological envelope).

Fabrication of the Opcuity Active Layer, and the assembly of the active layer to the waveguide, continue to be the primary focus of manufacturing research being conducted by UniPixel, insofar as all the other steps in the process are quite well known in the display industry (and therefore do not warrant extended discussion herein). The proprietary structures comprising the micro-optical topology of the active layer lend themselves to roll-to-roll manufacturing. Moreover, for most embodiments of TMOS, the contiguous nature of the conductive plane forming the electrical core of the Opcuity Active Layer, and the circumstance that the micro-optical structures can be randomly oriented with regard to the waveguide and its electrically-controlled ITO pad structures, lead to the conclusion that registration of the active layer with respect to the waveguide is not required. As this particular assembly process can be registration-free, system assembly yield issues can potentially be reduced by an order of magnitude.

The fabrication of Opcuity active layer film, with its proprietary micro-optical structures to optimize light output during pixel actuation, is innovative insofar as no such thin contiguous polymer sheet structures have ever been deployed within a quasi-MEMS architecture to form pixels that exploit frustration of TIR. The controlled attachment of the Opcuity active layer film to the waveguide using noncontiguous adhesion means to insure that each pixel has a tethered periphery and a freely deformable central zone is manifestly novel. If the Opcuity Active Layer film didn't have a highly articulated surface bearing micro-optical structures, the desired TMOS architecture could theoretically be achieved by monolithic means (epitaxy, sacrificial layers, etc.), but the topological complexities involved compel resolution in the direction of *assembly after the fact*. Because no other technology has had the specific requirement mandated by the TMOS architecture, there has been no incentive within industry to execute the suite of parameters and properties being pursued by UniPixel.

Within the TMOS architecture, Opcuity Active Layer film needs to be adhesively attached to the waveguide. The attachment plane *is not contiguous*, but rather forms a highly patterned micro-geometry (i.e., although the active layer is a single continuous elastomeric sheet, the adhesive regions on it form a pattern and not a plane coterminous with the active layer). Opcuity Active Layer film is to be physically attached to the waveguide only at the periphery of each pixel, which entails *noncontiguous adhesion* at the micro level across a very large planar area. One possible arrangement would be a geometric grid in which the regions between the horizontal and vertical adhesion zones are adhesion-free. Reliably fabricating such an ultra-fine mesh is the focus of UniPixel and its manufacturing partners.

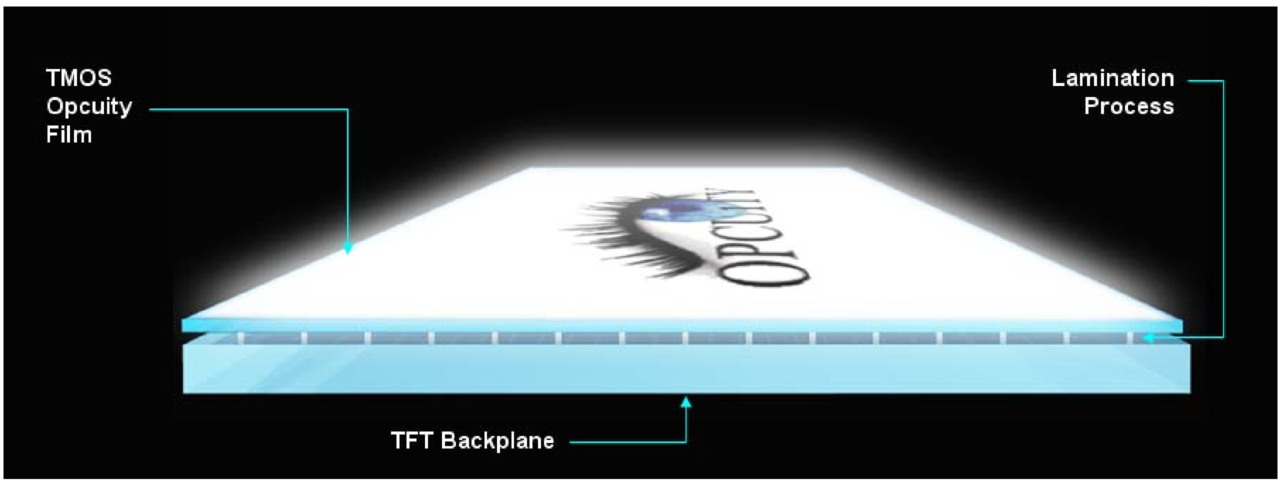

Figure 11: Noncontiguous attachment of Opcuity Active Layer to the TFT Backplane/Light Guide assembly.

The better the standoff adhesive structure and the closer it meets dimensional tolerances, the better a TMOS display performs. Existing operational prototypes are a first-line proof that a properly bonded TMOS display will achieve its performance targets by healthy margins.