OLED microdisplays in near-to-eye applications: challenges and solutions

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ABSTRACT

Wearable augmented-reality (AR) has already started to be used productively mainly in manufacturing industry and logistics. Next step will be to move wearable AR from "professionals to citizens" by enabling networked, everywhere augmented-reality (in-/outdoor localisation, scene recognition, cloud access,…) which is non-intrusive, exhibits intuitive user-interaction, anytime safe and secure use, and considers personal privacy protection (user's and others). Various hardware improvements (e.g., low-power, seamless interactivity, small form factor, ergonomics,…), as well as connectivity and network integration will become vital for consumer adoption.

Smart-Glasses (i.e., near-to-eye (NTE) displays) have evolved as major devices for wearable AR, that hold potential to become adopted by consumers soon. Tiny microdisplays are a key component of smart-glasses, e.g., creating images from organic light emitting diodes (OLED), that have become popular in mobile phone displays. All microdisplay technologies on the market comprise an image-creating pixel modulation, but only the emissive ones (for example, OLED and LED) feature the image and light source in a single device, and therefore do not require an external light source. This minimizes system size and power consumption, while providing exceptional contrast and color space.

These advantages make OLED microdisplays a perfect fit for near-eye applications. Low-power active-matrix circuitry CMOS backplane architecture, embedded sensors, emission spectra outside the visible and high-resolution sub-pixel micro-patterning address some of the application challenges (e.g., long battery life, sun-light readability, user interaction modes) and enable advanced features for OLED microdisplays in near-to-eye displays, e.g., upcoming connected augmented-reality smart glasses.

This report is to analyze the challenges in addressing those features and discuss solutions.

Keywords: microdisplay, OLED, near-to-eye, backplane, integrated circuitry, wearable, micro-patterning, electron-beam

1. INTRODUCTION

The prominent emissive microdisplay technology on the market is OLED-on-silicon. A single-crystalline silicon CMOS chip provides the active-matrix circuitry to address and drive the millions of individual pixels (pixel cell circuitry also known as the backplane). Since the silicon substrate itself is intransparent in the visible spectrum, a top-emission OLED setup is required (emitting away from substrate). OLED microdisplays cover by far the major portion of emissive microdisplays on the market today as they are well-suited for extremely small form-factor and low-power consuming optical engines. Due to the size, power, contrast and color-space advantages, NTE applications represent the largest opportunity for OLED microdisplays. This relates to both personal viewers (PV) and electronic viewfinders (EVF). PV are either see-through data glasses used for mixed- and augmented reality (AR) applications, or non-see-through/immersive video glasses used for entertainment or virtual reality (VR) applications in gaming, training or entertainment. Due to their emissive nature OLED microdisplays are specifically suited for see-through/AR smart glasses, since they prevent a virtual grey-shaded monitor-like perception inside the user's field of view, which is caused by the insufficient backlight suppression of non-emissive microdisplays.

OLED-on-Silicon microdisplay technology might be best suited to bi-directional microdisplay techniques too, which combine both image display and image acquisition in a single chip. That is mainly due to the fact that there is no intrinsic saturation of photodetectors embedded inside the microdisplay backplane caused by the external illumination of "modulating" displays (in contrast to the top-emission here), though, optical cross-talk inside the emissive microdisplay device should be factored in. Image sensor elements, for example, pn-junction CMOS photodiodes, are arranged in a fixed matrix/pixel pattern correlated to the image display pixel matrix/pattern. In a common case, both arrays have become intersected to each other; one photodetector pixel per one display pixel. Other design arrangements are feasible and should be adapted to the application. Moreover, optical crosstalk effects can be limited or avoided by design, driving scheme and technological means. For smart glasses application that feature can add eye-tracking capability for enabling hands-free user-interaction with the virtual display content, e.g., via gaze-controlled virtual buttons.

Luminance and lifetime are two critical performance parameters for OLED microdisplays, specifically under high-temperature conditions. For cost reasons, achieving low-pixel pitch is important, since it directly translates into die size and chip cost. For immersive environments (for example, non-see-through or EVF and NTE applications), usually luminance up to 500 cd/m² and lifetime >10,000 hours are sufficient, whereas current see-through optics and consideration of sunlight conditions easily demand >5,000 cd/m² of luminance and beyond, regularly combined with elevated temperature operation. The challenge at high luminance is to supply and modulate the forward voltage at dynamic range levels of 2V up to 7 V (or even more, depending on OLED stack architecture) toward each OLED pixel; this requires integrated driving transistors able to withstand voltage swing of 5 V or more. That's a high-voltage for advanced mixed-signal CMOS processes at minimum feature sizes (usually referenced by minimum transistor channel length), for example, in the range of 0.25 to 0.11 µm at core voltages of about 1.2 to 2.5 V. Such high-voltage transistors require more die area, whereas smaller feature size CMOS processes typically provide even fewer options for HV devices, i.e., shrinking pixel cell size remains limited.

There are plenty of NTE applications which demand long battery life above frame rate and resolution. For such applications it becomes sufficient to display simple graphics (e.g., symbols) and text. Even more, the alteration frequency of screen content is often rather low (<5Hz). Therefore image data can be stored in a static random access memory SRAM-like pixel cell architecture, and the direct pixel-wise addressing scheme enables much lower bandwidth for the display interface as well. That approach allows to drastically reduce display power consumption by minimizing the backplane consumption. Consequently, OLED power (and its efficiency) now determines the overall power consumption. At moderate display resolution and frame rate there is even a power advantage for video display.

2. BACKPLANE ARCHITECTURE, TOWARDS ULTRA-LOW POWER OLED MICRODISPLAYS

The key enabler of an OLED microdisplay is the monolithically integration of OLEDs on top of silicon wafers (referred as OLED-on-Silicon technology). Hereby the last metal layer of the silicon CMOS process defines the shape of the sub-pixels. The organic layers themselves are typically unstructured inside the active area. In this way it is possible to realize single color displays with high resolution. The minimum pixel size is typically defined by the pixel circuit underneath the OLED electrode.

The organic layers are pretty sensitive and require an excellent encapsulation against humidity and oxygen. Because of this sensitivity the organic layers cannot be structured by processes that are well known and established in the microelectronics. The typical method for structuring the organic layers is the usage of shadow masks during the thermal evaporation of the materials. The lower feature size limit of this technology is in the range of 50 µm. So far there is no established technology for direct patterning of organic layers < 10 µm which would be required for microdisplays. The common solution for full color microdisplays uses a white emitting OLED with lithographically structured color filters on top of the thin film encapsulation. Figure 1 shows a simplified cross-section of that approach. The obvious drawback is the limited efficiency.

The OLED consist of several stacked organic layers with thicknesses down to a few nanometers. That's why the interface between the silicon backplane and the organic stack plays an important role to achieve a good OLED performance with high efficiency. The main issues for the CMOS top metal are hereby low roughness, high reflectivity and a smooth transition from the pixel surface to the pixel gap.

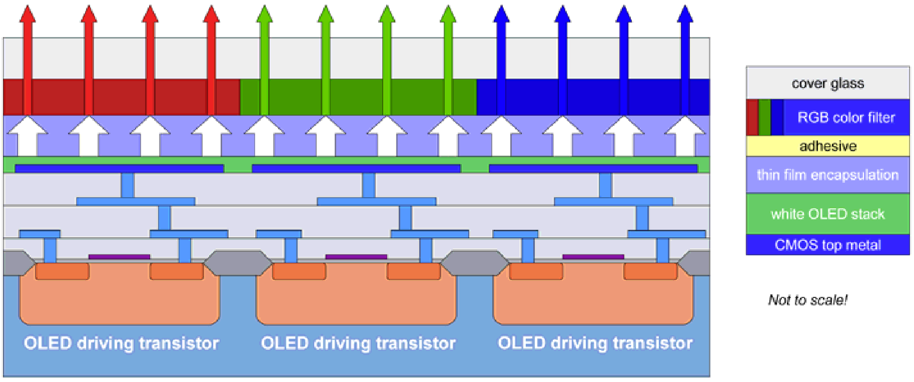

Figure 1. Simplified cross-section of a typical full color OLED microdisplay based on a white OLED with lithographically structured color filters on top of the thin film encapsulation.

The microdisplay backplane is formed by the active display area surrounded by the control and driving circuitry. Inside the active area the pixels have to store the data until the next refresh or update and to supply the corresponding current to drive the OLED. There exist various concepts for the realization of such active matrix OLED displays. The main difference of these concepts is the point of the digital to analog conversion respectively the conversion from the digital video data to the perceived analog image.

The first concept uses a fully analog signal path inside the microdisplay and the digital image data is converted chip external to an analog value. Inside the microdisplay the data is processed completely in the analog domain and finally fed to the pixel circuit that converts that analog value to an OLED current. The advantage of such analog pixel is the low number of required transistors inside the pixel that allows a small pixel size. The drawback is the analog signal processing from the video interface up to the pixel. In the analog domain it is really tricky to handle effects like high pixel-to-pixel contrast, blurring, smearing etc. at high resolutions and high framerates. From the system view this approach requires a lot of efforts in the external driving electronics and additional components.

The second concept is based on a fully digital signal path where the data is stored inside the pixel in the digital domain. That requires a lot of transistor per stored bit and the pixel sizes scale linearly with the number of implemented grayscales. Compared to the analog pixel this results in large pixels that are not suitable for high resolution video displays and high frame rates.

A possible alternative is the usage of only 1 bit storage per pixel and the fast refresh of the so called bit planes from the external driving electronics. That concept realizes the grayscales by pulse width modulation and requires high data transfer rates and an additional frame buffer. The clear advantage of the fully digital concept is the digital signal path which is insensitive against noise, cross-talk and other analog effects.

The most suitable solution for high resolution microdisplays combines the advantages of the before described concepts and uses an analog pixel for high resolution and a mixed signal data path with digital-to-analog conversion directly on the data line of the pixels. This mixed concept eliminates the sensitivity of the analog signal path and allows an excellent display performance with high pixel-to-pixel contrast, high frame rates and perfect color realization. The block diagram of such display is presented in Figure 2.

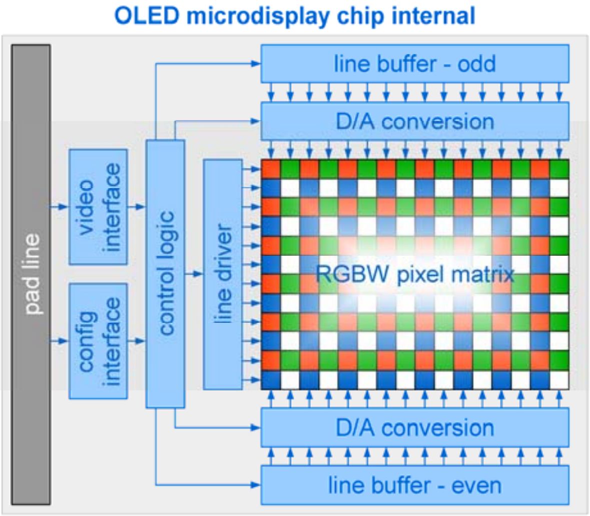

Figure 2. Block diagram of a typical OLED microdisplay with analog pixels and a mixed signal data path.

Typically microdisplays are used in data glasses to show moving video images. The problem: regardless of the image content large data volumes are transferred and processed by the system electronics and the microdisplay. This leads to a short battery runtime and a noticeable heat generation. Moreover all necessary electronics are limiting the miniaturization of the entire system design. In contrast to this a lot of applications focus much more on a long battery runtime and a slim and lightweight design rather than playing high resolution videos. According to these requirements a special implementation of a fully digital microdisplay can achieve an extremely low power consumption and a small and simplified driving electronics.

The basic idea for the reduction of the power consumption is the minimization of the necessary data transfer and - at the same time - the elimination of the normally needed refreshing cycles within the display. Therefore the display pixels are equipped with static memory and arranged in a freely addressable matrix. In this way only the changing parts of the display needs to be updated. If nothing is changing the complete data transfer electronics in and outside of the display can go to idle mode and safe power.

The backplane was designed with focus on minimal pin count, minimal required external components and an easy connection to the data source. The largest reduction in pin count could be achieved by changing the data interface from typical 24 bit parallel RGB data plus additional synchronization signals to a simple 4-wire SPI interface for data and configuration. In this way the realization of a minimalistic system with a simple microcontroller and without additional video sources or –processors is possible.

The backplane is based on a 180 nm CMOS technology and runs on a typical core voltage of 1.8 V. For the simple and flexible connection to various controllers the display interface was designed to be tolerant to IO-voltages from 1.8 V to 5 V. The pixel matrix is supplied from the common core voltage (VDD) with an additional negative supply voltage only for the common OLED cathode (VCAT). Through the introduction of a protection circuitry inside each pixel with an additional protection voltage (VPROT) the pixel matrix is capable to drive OLEDs with increased On-voltages, e.g. stacked OLEDs. Figure 3 presents the realized ultra-low power display and the corresponding block diagram.

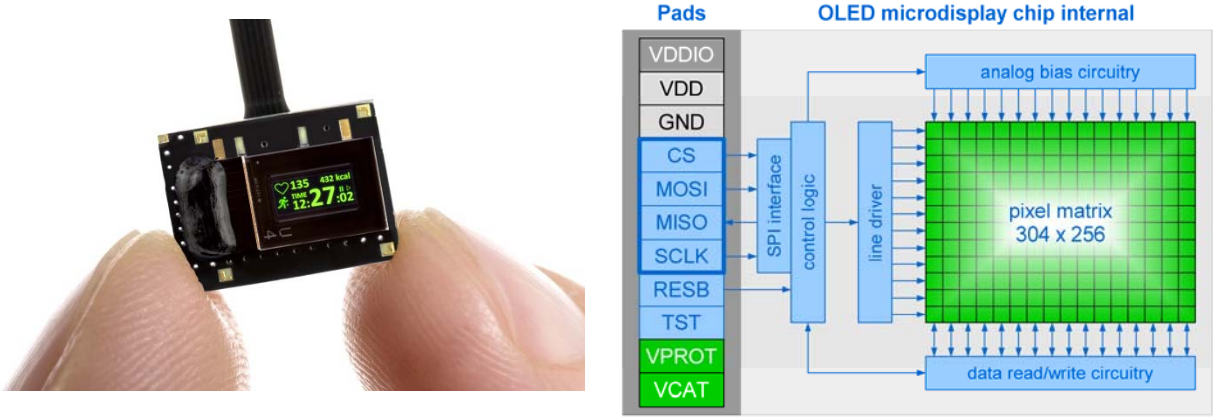

Figure 3. Ultra-low power display with static memory inside the pixels.

Based on the described concept two display backplanes UUGL1120 and UUGL1220 were realized with different resolutions. The key parameters can be found in Table 1. In the current design the maximum SPI clock frequency is limited to 8 MHz. This results in a maximum frame rate of 25 fps (UUGL1120) respectively 50 fps (UUGL1220) for a full image refresh. In addition to this the displays support smart refresh of smaller areas at higher frame rates.

Table 1. Summary of key parameters of the realized ultra-low power displays.

Parameter	UUGL1120	UUGL1220
Resolution	304 x 256	304 x 128
Active area	3.6 x 3.1 mm², 0.19" diagonal	3.6 x 1.5 mm², 0.16" diagonal
Pixel setup	monochrome green, 4 bit grayscale, 12 x 12 µm² pixel pitch	
Interface	SPI with max. 8 MHz	
Max. frame rate for full refresh	25 fps	50 fps
Brightness	typ. 500 cd/m², wide dimming range 20 ... 5000 cd/m²	
Supply voltages	Core voltage 1.8 V, I/O voltage 1.6 ... 5.5 V, OLED cathode voltage -5 V	
Supply current OLED	typ. 500 µA @ 500 cd/m²	typ. 250 µA @ 500 cd/m²
Supply current backplane	typ. 15 µA @ 0 fps, typ. 800 µA @ 25 fps	

The typical application circuit is shown in Figure 4. Hereby the display module is connected to a simple low power microcontroller via a flex cable. This controller is the main device in the local driving electronics and manages the data transfer to the display, the readout of sensors and the communication with the embedded Bluetooth low energy (BLE) module. This BLE module allows the direct communication to various mobile devices e.g. mobile phones, fitness tracker or other wearables. Depending on the application the BLE bandwidth could become a limiting factor. Therefore a full set of drawing functions (line, bar, circle, fonts...) were integrated into the firmware of the microcontroller to decrease the data to be transferred.

The complete system consumes about 40 mW at continuous BLE connection. Typical applications like fitness tracker allow the introduction of idle phases for the data communication, e.g. 1 s refresh for the heart rate. In such setup the power consumption can be reduced below 10 mW. Such low values cannot be reached by typical microdisplays systems because of the need of video sources or converters with constant data transfer and high power consumption of up to 1 W.

The described driving electronics including battery was realized in small package with 42 x 32 x 4 mm^3 dimensions and integrated into an HMD prototype with magnifying optics for the display as shown in Figure 4.

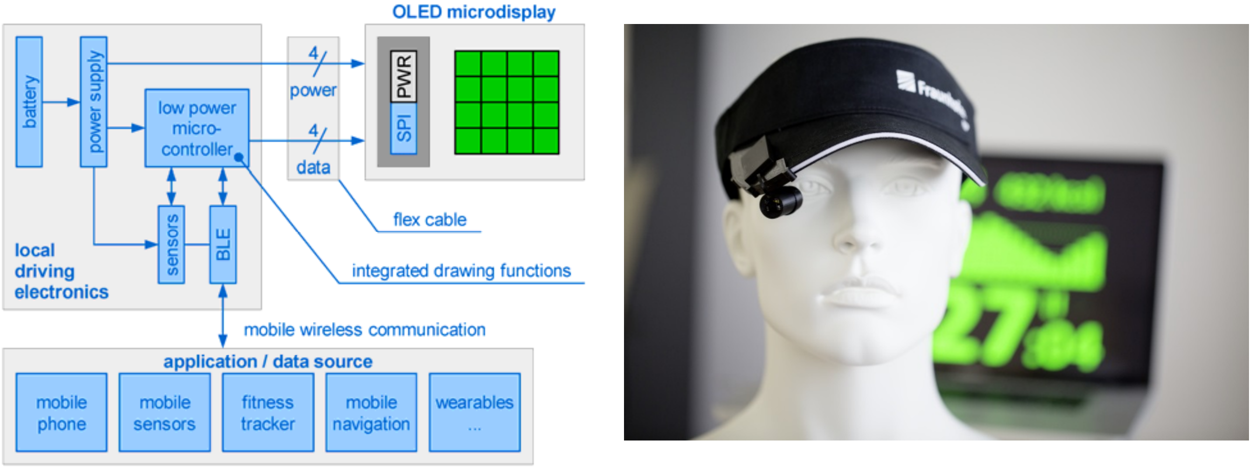

Figure 4. Typical application circuit and HMD prototype.

3. OLED TECHNOLOGY

3.1 Challenges for OLED-on-microdisplay technology

For microdisplays in general, there is a need of high brightness which typically (with respect to current feasibility standards) means front-luminance more than 1.000 cd/m^2 for full-color and more than 10.000 cd/m^2 for monochrome displays. Next to brightness, the displays need to meet further requirements. For full-color displays, prominent challenges are the coverage of color space (typically rated with respect to the NTSC standard), various types of contrast and operation lifetime. Due to a lack of established high-resolution patterning techniques for OLED, the conventional OLED-on-microdisplay technology still realizes RGB colors with the help of a white OLED covered by color filters. This means that only parts of the light generated in the OLED pass through the color filters, and that full-color OLED microdisplays a priori are of considerably lower brightness in comparison to monochrome ones. For many high-brightness demanding microdisplay applications, this is one reason why monochrome microdisplays currently are more attractive than the full-color versions. Further advantages of monochrome displays can be seen in the ease of fabrication and the lower fabrication cost. Moreover, the monochrome OLED spectra can be tuned according to special needs, e.g., intense and narrow spectra are required in combination with AR optics, to compensate the loss of brightness e.g., during in-coupling.

The applications for Augmented-Reality are not limited to indoor activities, but outside in full sunlight the brightness of the embedded microdisplay is key to enable a sufficient brightness even under these conditions. In an AR device beside the driver electronics and an OLED microdisplay some optics is needed to project the screen content towards the human eye. Several techniques have been developed and used for see-through devices [1]. The technologies suffer from poor field of views, color non-uniformities and/or optical losses. To compensate the optical losses of 70 % and more OLED intensity requires a display brightness higher than 20.000 cd/m^2 to achieve ~5.000 cd/m^2 after an optics. Obviously the OLED lifetime at this brightness level has to be sufficient for the device life cycle.

3.2 Green OLED featuring high brightness and narrow spectra

The design of monochrome OLEDs for specific optical requirements can apply different types of OLED architectures and emitters. The emitters are typically classified according to mechanisms of molecular excitation and relaxation. Among the most common and best efficient emitters, there are three types named phosphorescent, fluorescent and TADF emitters. Due to impressively high efficiencies reported in the recent years [2-4], phosphorescent and TADF emitters may appear to be best suited for high-brightness microdisplay applications. However, the choice is not simple because high efficiencies are typically accompanied by broad spectra, tremendous efficiency roll-off at higher brightness and low lifetimes. Moreover, effects such as pixel shrinkage have been reported and linked to the application of certain emitters on display backplanes [5]. In terms of OLED architecture, for microdisplays, the choice is simpler. Due to opaque CMOS backplanes with feasible voltage sweeps of about 5V, only top-emitting single and double units can be integrated.

Consequently, our development of a green OLED with intense and narrow spectrum started with a single top-emitting unit. We tried to optimize the OLED performance by localizing and well defining the recombination zone and dipole oscillations in the center of the emission layer, within the optical cavity between the highly reflective anode and the semitransparent cathode. The focus of optimization was set on common OLED stack parameters such as layer thicknesses, doping concentrations, choice of materials and others. In the following plots of OLED characteristics, we demonstrate that we achieved very good OLED performance in a series of experiments on 8inch wafers. The goal was to tune the emission spectrum to a narrow peak with a maximum at 525 nm wavelength, which equivalently meant to maximize the OLED spectrum color coordinates in y direction.

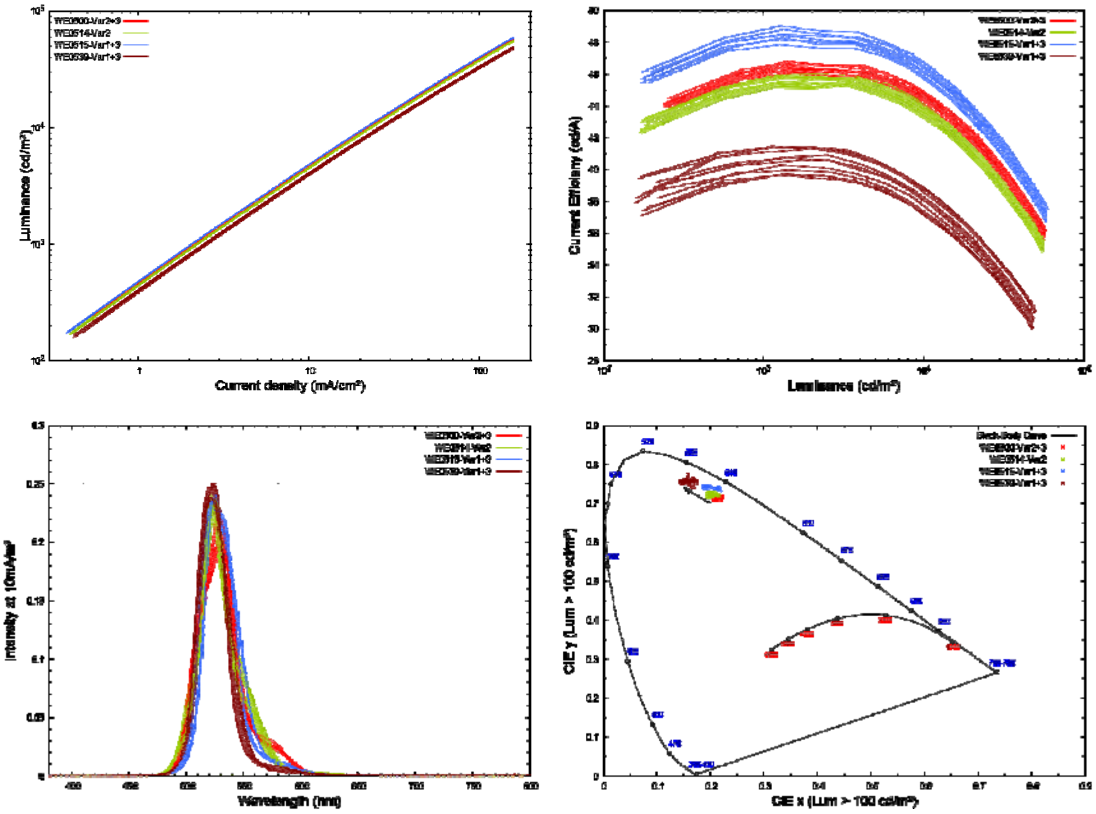

Figure 5. Top-Left: luminance vs. current density, Top-Right: current efficiency vs. luminance, Bottom-Left: spectra, and Bottom-Right: CIE xy coordinates of all measurements with luminance greater than 100 cd/m², respectively for the best performing chips in the series of experiments.

The spectra illustrated in Figure 5 are tuned narrowly to the range of wavelength between 500 and 550 nm, and reach color y coordinates up to 0.77. This is achieved simultaneously with respectable efficiencies of about 40 cd/A up to a brightness of 50.000 cd/m². For the measurement of OLED lifetime, we did accelerated tests with high initial luminance up to 100.000 cd/m². The drop of luminance was measured for 48 h and extrapolated with a typical decay function for OLED lifetime, given in the following equation.

$$L(t) = L(0) \times \exp[- (t / \tau)^{\beta}]$$

The extrapolation predicts that 80% of the initial luminance is maintained for 10.000 h if the initial brightness of the OLED is equal or below about 25.000 cd/m² for the OLED stacks WE0550, WE0514 and WE0539, and equal or below about 35.000 cd/m² for the OLED stack WE0515. The results of lifetime measurements and extrapolations are illustrated in Figure 6. Potential for further optimization is given by means of special light-outcoupling layers that can be added to the OLED stack, alteration of electrode materials and utilization of double unit structures.

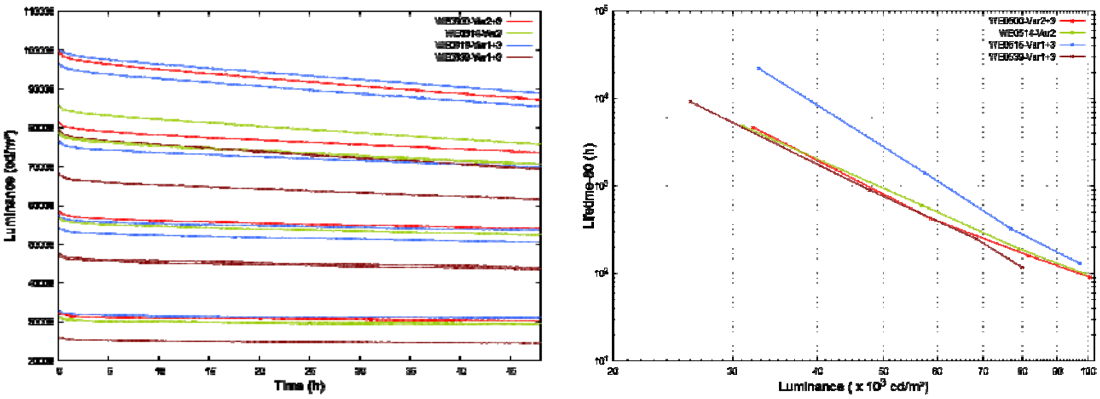

Figure 6. Left: measured luminance vs. time, Right: extrapolated lifetimes for the decay to 80% of the initial brightness, respectively for the best performing chips in the series of experiments.

4. OLED MICRO-PATTERNING

One of the major challenges in OLED manufacturing is the patterning method of the organic semiconductor materials. Especially for microdisplays high-resolution is a key aspect that have to be fulfilled. Conventional OLED-on-CMOS microdisplays realize RGB colors by a color filter technology, which means that a white OLED is covered with a corresponding color filter for each subpixel. This method allows high resolution due to the fact that the pixel size is mainly determined by the feature size of the CMOS electrode, which can be structured by photolithographic processes. Nevertheless only a part of the generated light passes through the color filter, which results in lower display brightness and a low efficiency. Thus, there is a strong need to use direct patterned emitting organic layers also for microdisplays.

State-of-the-art full color displays are produced by sequential vacuum deposition of red, green and blue emitting materials through a pre-patterned shadow mask, typically made of a thin metal sheet. Although this method is simple, it has several inherent limitations such as inefficiency of the process, mask deformation, difficulties in overlay alignment and the ability to make masks with micrometer accuracy. For those reasons, this method finds its limits at features sizes of 20 µm [7].

A new promising approach uses electron beam technology for OLED patterning. Electron beam micropatterning provides the opportunity either for a direct write with high resolution or a local thermal ablation of organic material at higher energies.

With low electron doses the OLED emission area can be modified to various shapes and to adjustable intensity profiles (e.g. any grey-level). The treatment of either a single organic layer or a complete OLED layer stack including the encapsulation with a focused electron beam leads to a permanent and local diminishing of the charge transfer. As a result the luminance output and the current density decrease accordingly [8]. The process is determined by the acceleration voltage of the electrons on the one hand, which defines the penetration depth in the OLED stack. On the other hand the electron dose adjusts the degree of diminishing. With increasing electron dose, the electron beam processed areas appear visually darker. The effect of emission modification by electrons is achievable for area processing, but also for high-resolution structures in µm-scale. Fig.7 shows a high-resolution picture written into an OLED, whereby the electron dose was varied during the patterning process for each point of the picture depending on the desired grey-value.

Processes with higher electron doses lead to thermal impact of the electron beam which allows a local evaporation of the organic material. The concept of generating RGB colors with this local removal is based on the microcavity effect in OLEDs. The desired color is achieved by using a white OLED and adjusting the resonator length, which is defined by the layer thickness of the HTL. To realize an HTL staircase an electron beam ablation process is used. The initial HTL is removed by evaporation locally followed by an additional areal deposition. Repeating this sequence results in three different HTL thicknesses which lead to the RGB colors after finalization of the white OLED (Fig. 8). In a first proof of concept green and blue colored diodes could be successfully demonstrated by using this electron beam ablation process [9].

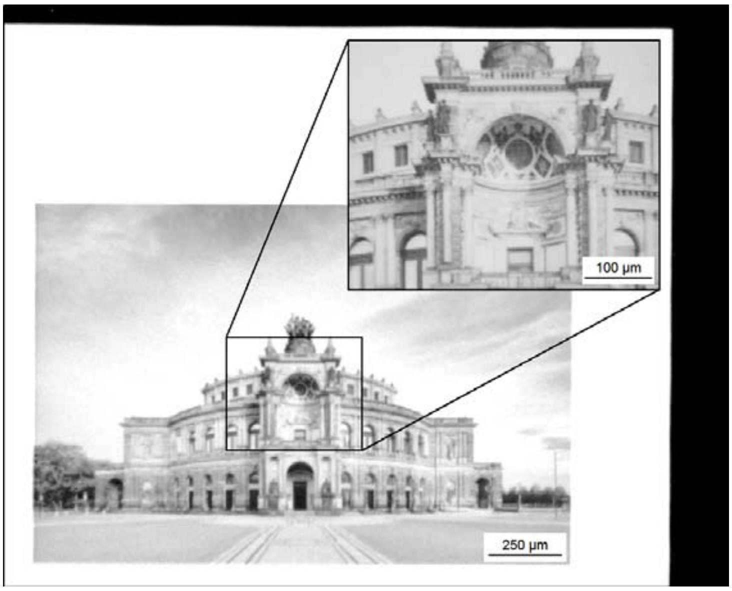

Figure 7 Light microscope picture showing OLED emission area with electron beam written high-resolution picture of Opera house Dresden with varying electron doses for each point.

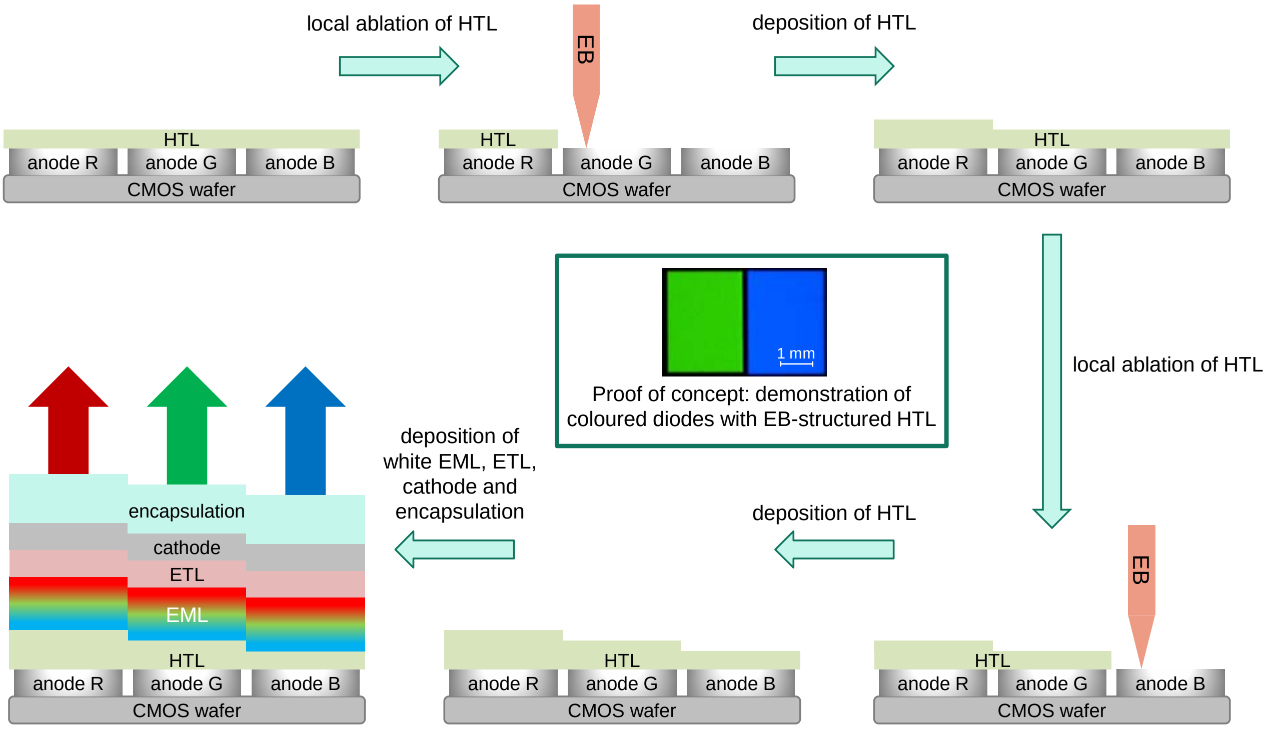

Figure 8. Concept of RGB-OLED patterning by electron beam ablation. Inset: Green and blue emissive diodes fabricated with electron beam structured HTL

5. EMBEDDED SENSORS

The silicon backplane technology of OLED microdisplays allows the integration of all the necessary electronic blocks for controlling and driving the display as well as the realization of additional sensor functions. These functions can be simple temperature sensors, light sensor for ambient light detection up to highly integrated and nested image sensors inside the active display area. The latter forms a bidirectional microdisplay that can display and capture images in the same plane [10].

In a typical bidirectional microdisplay each pixel comprises 5 sub-pixels: 4 sub-pixel for the display (RGBW) and 1 image sensor pixel. The latter uses the photodiode inside the silicon substrate as sensing element. The circuitry for the sensor pixel can be placed underneath the OLED electrodes and does not further reduce the fill factor of the photoactive area. Without sub-structuring of the OLED at pixel level the organic layers cover the complete active area including the photodiodes. The organic layers are almost transparent in the visible range but the semi-transparent counter electrode of the OLED reduces the sensitivity to a certain extend. Figure 9 shows the cross-section and an SVGA sample of such bidirectional OLED microdisplay.

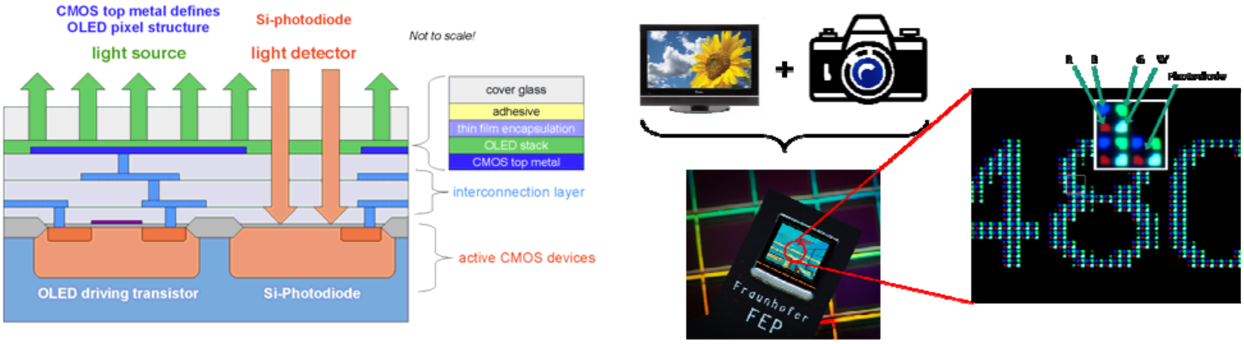

Figure 9. Cross-section and SVGA sample of a bidirectional OLED microdisplay.

The core of the bidirectional microdisplay is built from the common active matrix that is controlled by the surrounding driving and read-out electronics. The electronics of display and image sensor work synchronized and can be configured independently to support different modes.

The time sequential mode addresses the original motivation of bidirectional microdisplays - the usage in smart data glasses. In this application the display provides image content that is projected by an optics into the user's eye. At the same time the embedded image sensor captures the eye-scene of the user which is illuminated by an external IR light source. The resulting eye image is used for the realization of eye-tracking and the interaction between the user and the data glass by eye movements. In this application the bidirectional display works in time sequential mode to prevent local optical cross-talk from the OLED to the neighboring photodiodes. Following this the frame time is split into two parts: one for the display and one for the exposure of the image sensor. Figure 10 illustrates the application of bidirectional microdisplays in data glasses.

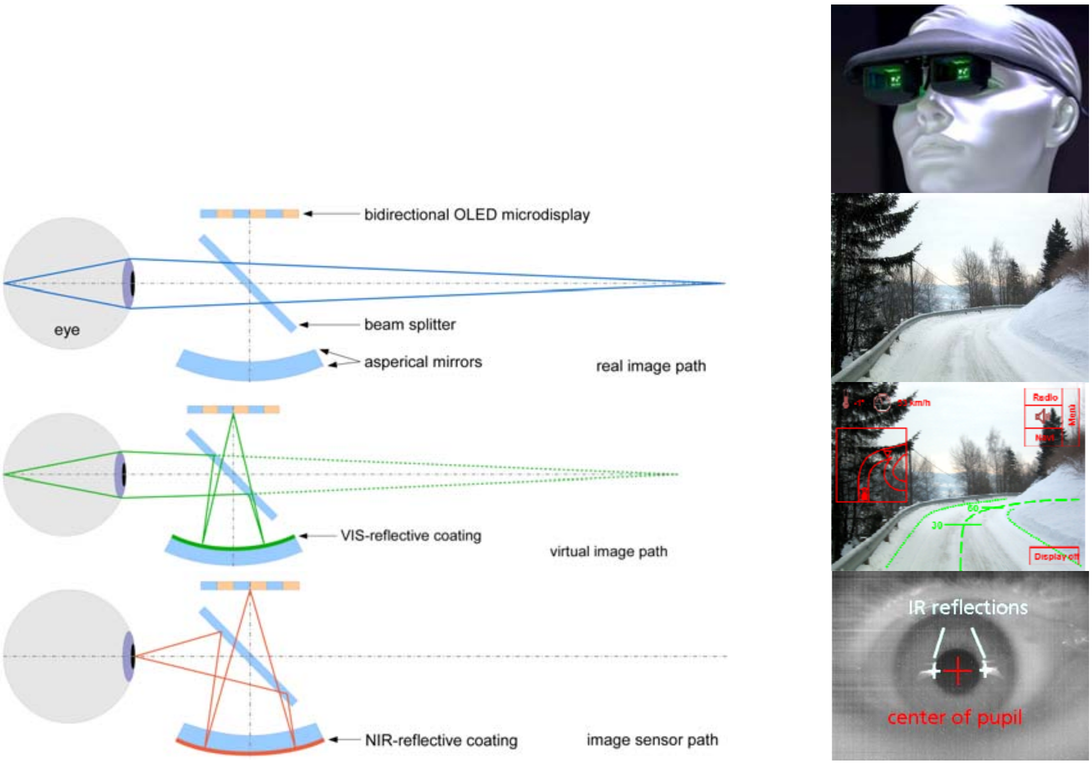

Figure 10. Application of bidirectional microdisplays in data glasses

Beyond the application in AR/VR data glasses the bidirectional microdisplay can be used in further applications as image sensor with embedded smart illumination. A prominent example here fore is an optical fingerprint sensor which is illustrated in Figure 11. In this application the display and the embedded image sensor are operating in parallel which means that the display emits light and the image sensor captures an image at the same time. This results in a local optical cross-talk from the display towards the photodiodes which is limited to the adjacent pixels. This effect can be solved with a special illumination pattern that switches-off the direct neighboring display pixels of the photodiodes.

Figure 11. Bidirectional microdisplay in fingerprint application, captured fingerprint sample.

6. CONCLUSIONS

Advancing near-to-eye applications of microdisplays demand improved parameters and extended features, such as full-color high-brightness, low-power and embedded sensors for user interaction. OLED micro-patterning for achieving R, G, B sub-pixels appears to be an inevitable approach, though remaining unsolved for commercialization yet. That will require further technology progress - electron-beam patterning might potentially contribute to that. Moreover, low-power backplane architectures will enable significantly longer battery operation in those NTE applications, that do not require high-resolution full-frame video capability.

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