Wearable OLEDs: from Form-factor Engineering to Biomedical Applications

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ABSTRACT

The inherent compatibility of organic light-emitting diodes (OLEDs) with various form factors such as flexible, foldable, rollable, and even stretchable devices makes OLEDs attractive in wearable applications. This work introduces engineering methods of OLEDs for wearable devices and benefits that can be provided by OLEDs for biomedical applications.

1 Introduction

Organic light-emitting diodes (OLEDs) have established themselves as mainstream technologies for displays in modern IT devices from small watches and phones to large TV sets. The excellent scalability comes mainly from thermal evaporation technique used for fabrication of their active layers – organic thin films and metal electrodes. In addition, substrates during thermal evaporation are maintained at low temperature (e.g. room temperature), allowing for realization of use of various non-conventional substrates including plastics. For this reason, electronic devices containing OLEDs can have a greater degree of freedom in form factors. Flexible, rollable, foldable, and stretchable displays may be good examples that illustrate the form-factor versatility of OLED technology. This form-factor advantage can make them shine beyond display technologies. In particular, wearable devices are considered as an area that can receive great benefits from OLED technologies [1]. It is noteworthy that the application of OLEDs in wearable devices is not limited to displays; for example, OLEDs may be employed as light sources for health-monitoring sensors as well as phototherapeutic devices that can be worn without little discomfort [1,2].

In this respect, this work summarizes what kind of engineering can be done to OLEDs from the perspectives of wearable devices and what benefits can be provided by OLEDs for wearable biomedical applications.

2 Engineering OLED Device Architecture for Ultra-flexible and Stretchable Form Factors

2.1 Designing Ultrathin OLEDs with Typical Transparent Conductive Oxides and Multilayer Gas Barrier Encapsulation

Ultrathin OLEDs are essential building blocks for body-attachable applications for their light weight and superior conformable nature. It is also nice to note that ultrathin OLEDs can easily work as foldable light sources. In such applications, the design parameter that is critical is the minimum bending radius of curvature (= R_c^{min}). Near foldable and highly conformable applications would require sub-mm R_c^{min}. When typical flexible substrates such as 100 μm-thick PET, for example, are used, such a small bending radius is highly challenging to achieve because tensile strain (ε) due to bending at such a small radius of curvature could be too high for some of the materials used in OLEDs. For instance, transparent conductive oxides (TCOs) and aluminum oxides used for encapsulation are subject to bending-induced crack formation when the strain applied is merely around 1%. Note that ε for the layer on top of the substrate with the thickness of d_{sub} bent at a radius of curvature R_C is given approximately by the by the following simple relation [3]:

$$\varepsilon = \frac{d_{sub}}{2R_C} \quad (1).$$

Hence, R_C of 2mm for d_{sub} of 100μm leads to ε of 2.5%, which is already too large for most oxide and nitride materials. For this reason, the research field responded mainly in two different ways: (i) to develop materials alternative to TCOs, etc., which have low crack onset strain (COS); or (ii) to use ultrathin substrates such as Mylar substrates with d_{sub} below 10-20μm or solution-coated polyimides, which may later be lift-off from a carrier glass. The latter is useful in that one can use TCO and other inorganic layers already proven effective in rigid or mildly flexible devices. (Fig. 1a) What has to be cautioned in this approach is that Eq. 1 shown above might not be legitimate any longer because its validity rests on the assumption that layers on top of the substrate is much thinner than the substrate, which may no longer hold when substrates get thinner and become comparable to the thickness of the layers on its top. In such a case, Eq. 1 should be revised, and, in many cases, there may not be a closed-form analytic expression and numerical mechanical analysis may need to be done to learn the strain applied to each of the layers upon bending [3]. What is also interesting to note is that the neutral plane can also be no longer at the exact center line of the substrate when layers with different mechanical properties are placed on top of a very thin substrate [3]. Figure 1b shown below indicates that it is in fact fairly close to the top of the substrate; this can be beneficial for design of ultrathin devices as it provides a more headroom for actual strain applied to materials with low COS (e.g. TCO such as indium tin oxides (ITOs) or indium zinc oxides (IZOs), and Al_2O_3, etc.). Figure 1c shows that fully encapsulated OLEDs with conventional TCO can be made on 6 μm-thick Mylar substrates and that they can withstand bending at R_C smaller than 1 mm [3].

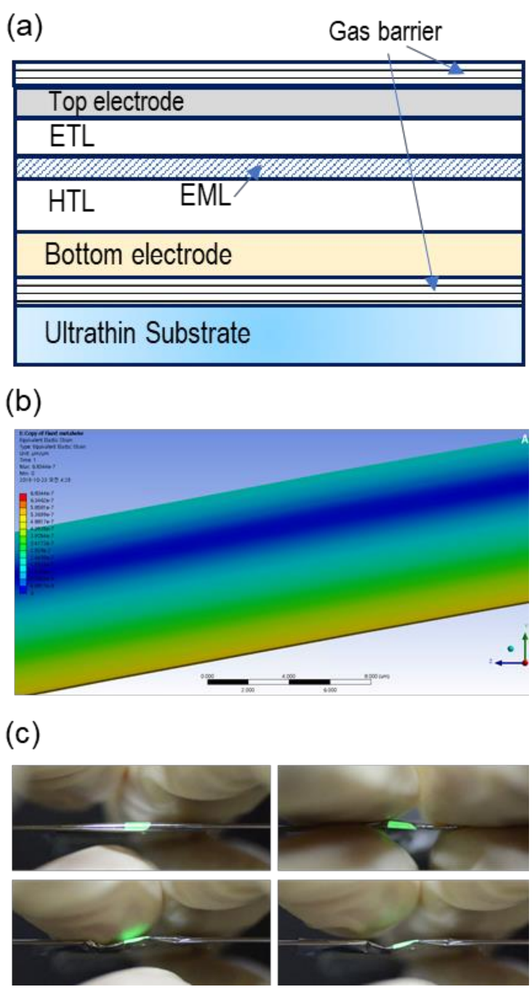

Fig. 1. (a) Structure of encapsulated an ultrathin OLED (b) Strain distribution across the cross-section. Note that the zero-strain plane is near the top side. (c) Flexible OLEDs operating under bending at R_c of ca. 0.3 mm.

2.2 Stretchable OLEDs: Using Stress-Relieving Layers for High Performance

Stretchable OLEDs could be particularly important for body-attachable applications so that light sources can accommodate the body movement. Stretchable OLEDs are being developed either through development of intrinsically stretchable materials or through introduction of structures such as serpentine-shaped interconnects. While both approaches are valid, the former is pursed from a long-term perspective for OLEDs, which require various layers with different functionalities. On the other hand, the latter may be done with existing material sets, and thus it can be accomplished more in a near-term basis. In this approach, a proper device architecture for stretchability should be developed while maintaining device performance as much as possible.

Figure 2 shows an example of stretchable OLED arrays in which rigid islands are formed on top of a bilayer platform based on an elastomer base substrate and a highly soft stress-relieving layer (SRL) [4]. While the elastomer serves as a main carrier and defines the range of stretch-induced strain that can be sustained, the SRL provides a means to reduce stress applied to device active layers and interconnects to a significant degree. OLEDs that can be stretched by 140% (for interconnects) with performance comparable to rigid counterparts are demonstrated with the proposed method [4].

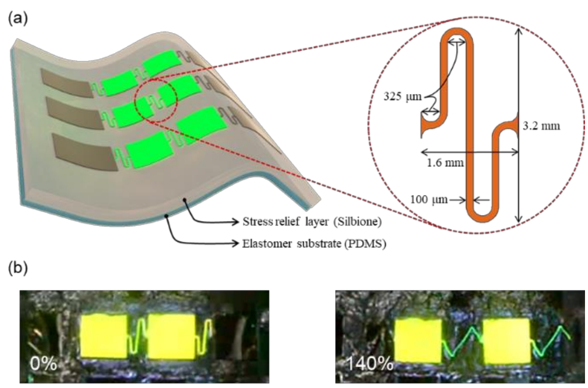

Fig. 2. (a) Schematic device structure for stretchable OLEDs based on a bilayer platform containing an elastomer (PDMS) and a stress-relieving layer (Silbione^{TM}). (b) Photographs of the working stretchable OLEDs: (left) as-is (right) interconnect stretched by 140%.

3 Wearable OLEDs for biomedical applications

Some biomedical applications such as photodynamic therapy (PDT), photothermal treatment, and photobiomodulation (PBM) rely on interaction of human body and light. While common phototherapeutic applications are typically based on the clinical environment where light sources are installed typically in a fixed location, combination of wearable form factors and OLEDs as highly uniform areal light sources can provide an ample opportunity for personalized point-of-care therapeutics that may not be restricted in time and place. Good examples can be found in flexible red-to-NIR OLED patches, developed by K. Choi, K. Park, and their coworkers [5], for promoting healing of damaged skins or for uniform light sources for photodynamic therapy.

In addition, OLEDs can be used for monitoring heart rate and blood oxygen level, which are key bio-signal for human health [6]. Combination of a light source and a photodetector can monitor the change in light absorption associated with the volume change of blood vessels following cardiovascular cycles, providing one with a means to measure heart rate. Because hemoglobin bound with and without oxygens have different absorption spectra, one can measure the level of blood oxygen saturation often called 'SpO_2' simply by adding another light source with a different color. The device measuring both heart rate and SpO_2 values is called 'pulse oximeter.' Using OLEDs and an organic photodiode (OPD) can allow one to realize body-attachable pulse oximeter, which may be combined with other physiological sensors with little limit on locations. In addition to their inherent advantages in form factors, organic technologies were found to play a key role in achieving pulse oximeters with much reduced power consumption, important for wearable devices, which typically have limited power sources.

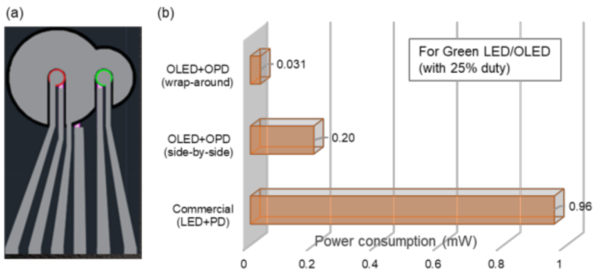

Fig. 3. (a) The schematic layout of the proposed organic pulse oximeter with the 'wrap-around' geometry where an OPD wraps around circular green and red OLEDs. (b) Comparison of power consumption of green light sources with 25% duty vs. the device layout.

Figure 3 shows the OPD wrapping around OLEDs could lead to order-of-magnitude reduction in power consumption compared to conventional side-by-side geometry [7].

4 Summary

The inherent compatibility of organic technology with various form factors such as flexible, foldable, rollable, and even stretchable devices can play a significant role in displays but also in wearable applications, which may include biomedical applications. In this work, we introduced some of the important engineering steps that can be done to enable highly flexible OLEDs and stretchable OLEDs with sufficient device performance. Furthermore, we demonstrated that organic technologies can go far beyond just wearable form factors and can help achieve much-need reduction in power consumption in wearable health-monitoring sensors.

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