SmartKem TFT Innovation Greatly Increases the Battery Lifetime Between Charges of Portable Display Devices

Executive Summary

The short battery lifetime between charges of portable display devices such as smartwatches, smartphones or notebooks is one of the major issues in user dissatisfaction today.

This white paper demonstrates that the choice of the thin film transistor (TFT) material has a significant impact on battery lifetime. Here it is shown that organic TFTs offer a unique capability to reduce display power consumption by as much as 90% and so significantly extend the battery lifetime on many CE display based devices. It will be shown that this is due to the leading low leakage currents offered by the organic TFT in combination with the ability to use simplified TFT pixel drive circuits due to their superior electrical stability.

This cannot be achieved with any other TFT technology platform and as such, places oTFTs at the forefront for implementation as the TFT platform of choice to realise battery life extension in many portable LCD and OLED display based products.

Introduction

Battery lifetime is one of the major drawbacks with portable display-based consumer electronics. Enabling battery life extension, and so eliminating the need to continually recharge devices, is one of the key drivers in the advance of the next generation of display based materials and processes.

Enabling this next advance in displays is a new type of thin film transistor platform based on organic semiconductors.

No semiconductor platform can be considered a viable alternative to incumbent semiconductor materials such as a-Si unless it surpasses key criteria. Display power consumption is one such criterion and is becoming critical in defining the battery life of portable displays. Any TFT channel material that can offer the potential to reduce display power consumption offers a tangible value-add to the user experience in end product form and a key differentiator to product manufacturers.

The market adoption of organic thin-film transistors (oTFTs) today offers display manufacturers a route to the production of AMLCD and AMOLED displays on glass or plastic substrates with a new, differentiated organic semiconductor platform.

Not fully appreciated until recently is the potential for oTFTs to offer a path to the manufacture of the lowest power consumption LCD and OLED displays.

This white paper examines the mechanisms and implications of the power saving potential of oTFTs for improved battery lifetime - a key technology differentiator that has seen oTFTs break through into pre-production with major display OEMs in Asia.

The power challenge

One of the major challenges facing the display industry today is how to extend the time between charge cycles for display-based products. The need to constantly re-charge display-based devices (and to find a power point on the move) is a major disadvantage of modern display technology. This is especially apparent with the advent of the smartwatch. Developments in battery technology are all focused on how to improve battery lifetime to address this pressing issue.

However, an alternate and more effective means to battery life extension, is to reduce the amount of power consumed by displays which can account for up to 70% of total power consumed in a portable device. A novel organic semiconductor platform, truFLEX® is making significant in-roads in offering manufacturers a simplified route to increased multiples in battery life extension.

Active Matrix and Pixel Refresh Rate

To understand how this power saving is achievable one needs to consider a typical LCD or OLED pixel backplane TFT drive circuit. With an active matrix LCD drive architecture a progressive scan method is used to address each pixel in the display in a line-by-line manner. Figure 1 (LHS) shows this progressive scan principle, where gate 1 (line 1), 2, 3,. N is addressed on a frame basis, usually 60 frames a second (60Hz).

It also shows in more detail (RHS) a pixel and its sub-pixels, of red, green and blue filters, and LCD sub-pixels, which are controlled by the TFT circuits.

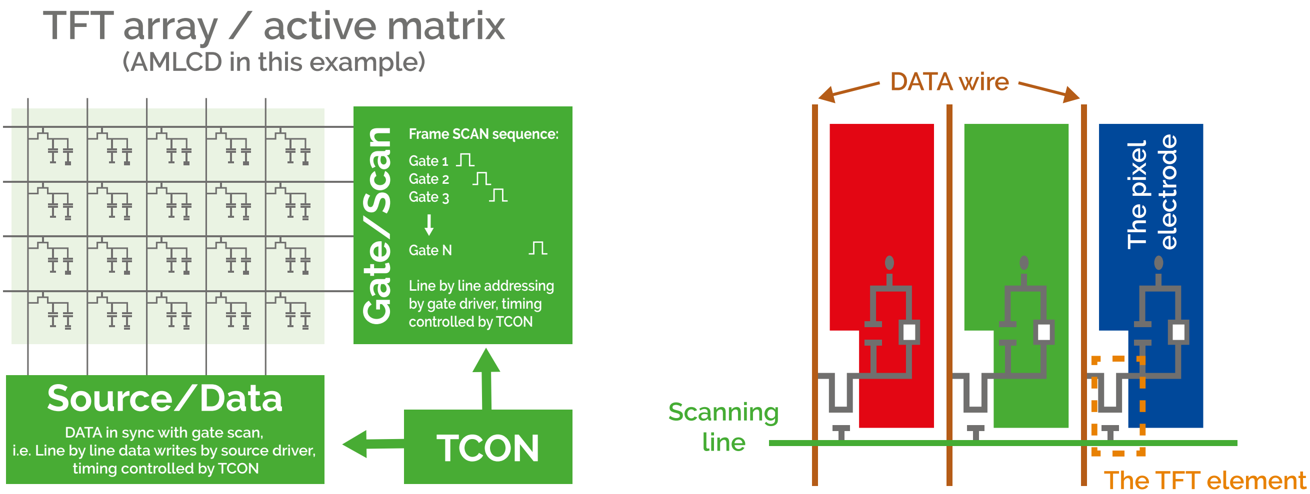

Figure 1.
Active matrix driving for AMLCD (LHS) and Pixel (RHS) with red, green and blue of sub-pixels of AMLCD.

For AMLCD, during each 'frame refresh' the pixel capacitance is charged to a new voltage to enable the correct amount of light (greyscale) to pass through the LCD from the backlight beneath and through the colour filters above.

For AMOLED, during each frame refresh the storage capacitor is charged to a new voltage which is converted into a new current that determines the light output (greyscale) from the OLED material.

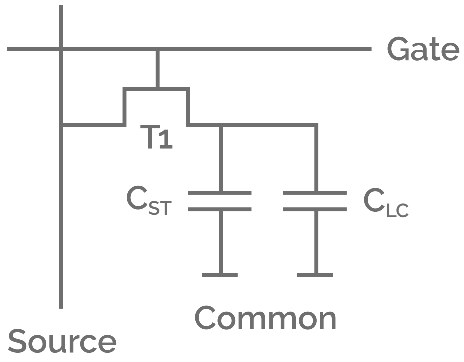

Figure 2
Typical LCD pixel driver circuit (1T1C)

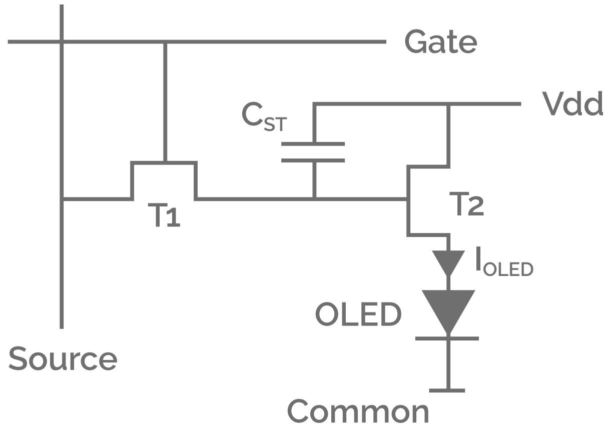

Figure 3
Typical OLED pixel driver circuit (2T1C)

Figure 2 illustrates an LCD TFT driver circuit in more detail. This pixel driver circuit will be updated for every frame refresh where the new voltage on the capacitors controls the LCD and determines the amount of light from the backlight through the colour filters. As such the ability of T1 to prevent charge leaking from the pixel capacitors determines if the capacitors need to be refreshed when the same voltage is needed on the pixel, even for the same light output, for example, when displaying a static image. If current is allowed to leak from these capacitors then they will need to be refreshed for every frame regardless of whether it is a static image or a new image therefore expending power on every frame refresh.

The simplest OLED drive circuit is the so-called 2T1C pixel architecture, which comprises two pixel transistors, T1 and T2, and a storage capacitor Cst as shown in Figure 3. Being the simplest pixel architecture it has no compensation for drift in TFT performance over lifetime and as such can only be used with the **most stable, robust TFT platform.**

A particular pixel is selected for updating by switching on the transistor T1 and writing a controlled voltage onto the storage capacitor, st. This voltage in turn switches on the gate of the drive transistor T2 and controls a programmed drive current to the OLED supplied by T2. This current is maintained when T1 is switched off again to address the next row of the display as **Cst holds the voltage on T2.**

This is the key to the potential power saving – how often does Cst need to be refreshed for the same pixel to be maintained in the ON state for a pixel that does not need to change its light output.

When LCD and OLED displays are driven by most semiconductor TFT drive circuits the pixel needs to be refreshed constantly (regardless of whether there is a change needed in light output of a pixel) with a typical 'frame refresh rate' of 60 times a second (60Hz). This results in a constant drain on the battery and is due to the high leakage currents from typical a-Si circuits and larger more complicated LTPS TFT circuits when they are switched off which results in Cst losing its charge.

LTPS and IGZO pixel driver circuits cannot operate with simple 2T1C circuits. LTPS and IGZO in fact require much larger 5T1C, 7T1C or circuits with an even higher number of transistors to compensate for deficiencies in uniformity and TFT voltage instability. Therefore using a lower frame refresh rate is not possible with LTPS due to excessive TFT leakage and limited with IGZO due to the complexity of the TFT driver circuit.

In addition, the high complexity of LTPS and IGZO driver circuits seriously lowers production yield, due to faulty driver circuits, so increasing the cost of production.

If the TFT has an extremely low leakage current, otherwise called the 'off current' or 'off state', then the storage capacitor will not need to be refreshed as often. This can result in significant savings in power consumption by reducing the number of times each pixel needs to be addressed and refreshed. This is particularly the case when no change in pixel status is required such as with a static image. If this can be achieved with a simple TFT driver circuit, the number of transistors contributing to current leakage is minimised and so the need to refresh each pixel is also minimised.

This is the concept of 'low power frame refresh' where display pixels can be cycled or refreshed at lower frequencies of 1-30 Hz compared to the standard rate of 60 Hz, thus enabling the same display performance but with reduced power consumption for appropriate image content as illustrated in Figure 4.

Power consumption is particularly relevant to wearable and mobile device displays where a static background image and black pixels are a regular and common feature.

This reduction in the refresh rate is only made possible by an oTFT platform that offers both very low intrinsic "off currents" (low leakage currents) in combination with a much simplified 2T1C TFT pixel driver circuit.

The reduced number of transistors using oTFT (due to its high electrical stability and lack of need for compensation circuitry) allows a significant increase in the charge retention time of the pixel driver circuit capacitor.

Pixel Driving Mode

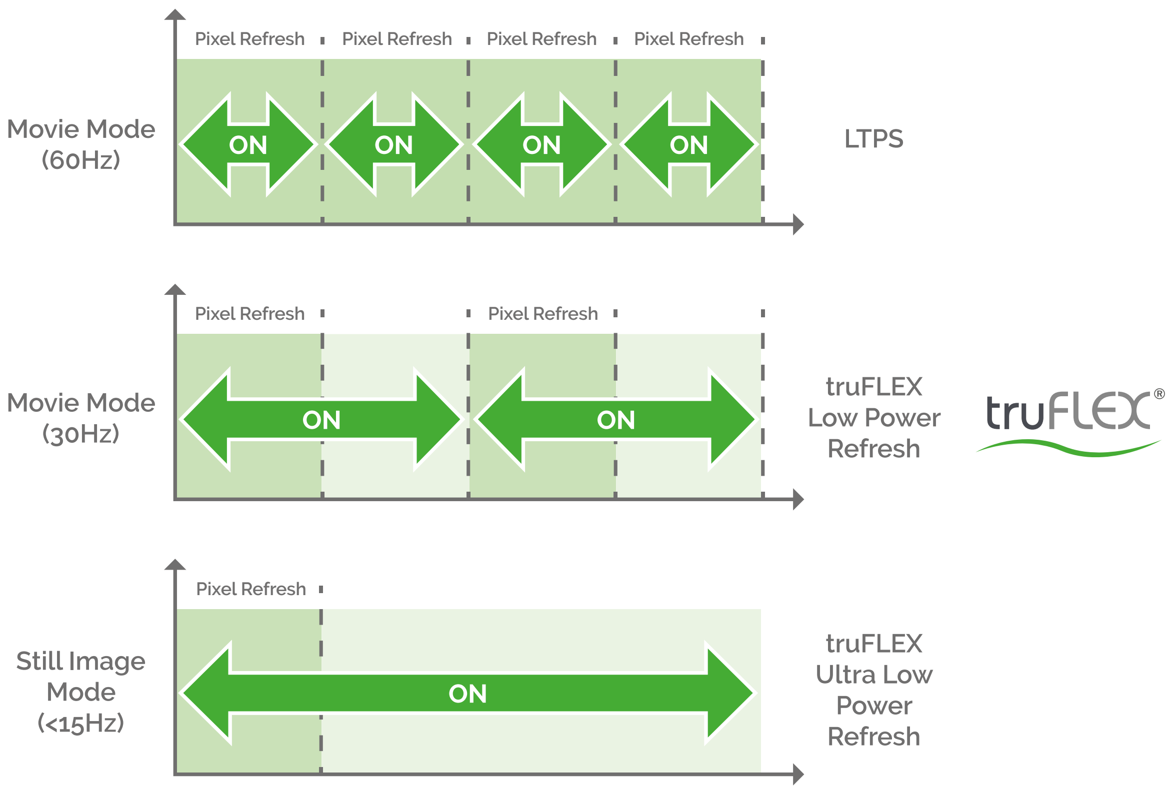

Figure 4
Illustration of low power and ultra low power refresh rates with truFLEX oTFTs

Current Leakage Mechanisms

So, what factors contribute to TFT drain current leakage and how do the competing semiconductor materials compare? Figure 5 illustrates the two primary contributions to off-state drain-current leakage, where the key leakage mechanisms in a typical TFT are leakage in the semiconductor channel ('channel leakage') and leakage through the gate insulator ('gate leakage').

These leakage mechanisms are dependent on a number of factors including the transistor architecture (transistor width and length), the gate insulator thickness, gate area and voltages across the channel and gate. However, a significant factor is the physical and electrical nature of the semiconductor material, the material type (amorphous or and polycrystalline) and the nature of the interface between the semiconductor layer and the gate dielectric material.

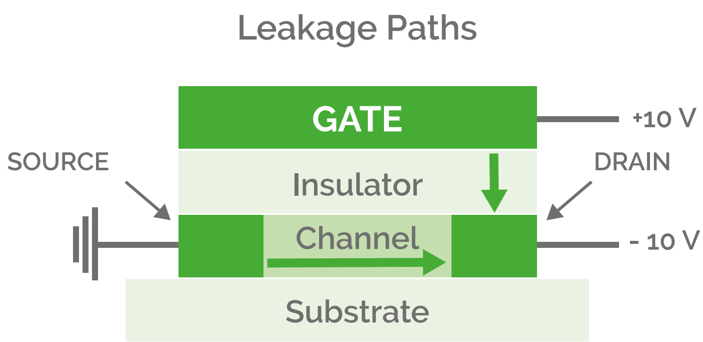

Figure 5.
TFT Leakage current paths; Arrows indicate the directions of electron flux for the primary leakage paths giving rise to the off-state drain-current leakage in a top-gate TFT. The horizontal (vertical) arrow corresponds to channel (gate insulator) current leakage paths.

A summary of the most common thin film semiconductor materials and their type and qualities is illustrated in Table 1.

Property	a-Si:H	LTPS	IGZO	truFLEX oTFT
Microstructure	Amorphous	Polycrystalline	Amorphous	Polycrystalline
VT uniformity	Good	Fair	Fair	Good
VT stability	Poor	Good	Poor	Good
Mobility (cm2/V.S)	1	50-100	10-30	5-10
Mobility uniformity	Good	Fair	Fair	Good
Device type	NMOS1	CMOS2	NMOS1	PMOS3
Process complexity	Low	High	Low	Low
Process Area	Large	Small	Large	Large

[1] NMOS = n-channel metal-oxide-semiconductor TFTs; [2] CMOS = complementary metal-oxide-semiconductor TFTs (i.e. combined n and p channel); [3] PMOS = p-channel metal-organic-semiconductor TFTs.

Table 1:
Key comparisons of a-Si:H, LTPS, IGZO and truFLEX oTFT AMLCD for AMLCD and AMOLED applications.

Channel leakage is mostly dependent on the electrical nature or energy bandgap (Eg) of the semiconductor, where the lower the bandgap the easier it is for charge carriers to be activated and contribute to the channel leakage current. IGZO and truFLEX have bandgaps that are larger than both LTPS and a-Si resulting in a reduced channel leakage contribution to the total drain leakage current.

Gate leakage current occurs when the TFT device, whilst under reverse bias, contributes to the overall leakage current by conduction between the gate and drain contact. Gate leakage is dependent upon the quality of the gate insulator and semiconductor interface such that a uniform electric field is created at this interface to minimise variations in the electric field presented to the underlying source and drain contacts.

IGZO TFTs have a low gate leakage since they employ a high quality SiO2 gate insulator that has smooth surface interface such that a uniform electric field develops across the gate insulator and the amorphous IGZO interface.

By comparison, polycrystalline LTPS gives rise to a pronounced roughness at the insulator/ LTPS interface resulting in higher gate leakage. IGZO is also superior to that of SiNx used in a-Si:9H TFTs. But whilst IGZO presents a low gate leakage than both LTPS and a-Si, it has a major issue with electrical stability and cannot be implemented with simple 2T1C circuits. IGZO therefore requires far more complicated TFT circuits to stabilise and compensate for voltage drift in the TFTs.

The industrialisation of polycrystalline organic semiconductors, such as truFLEX in combination with much simplified 2T1C drive circuits, offers lower leakage current than can be achieved with IGZO, LTPs or a-SI as illustrated in Figure 6 and 7. This is due to the high electrical stability of the truFLEX organic semiconductor combined with the extremely smooth, high uniformity interface that is achieved between the organic semiconductor and the organic gate insulator materials.

This is the key to the improved 'off state' current that can be achieved with truFLEX oTFTs and is a characteristic unique to truFLEX-type materials.

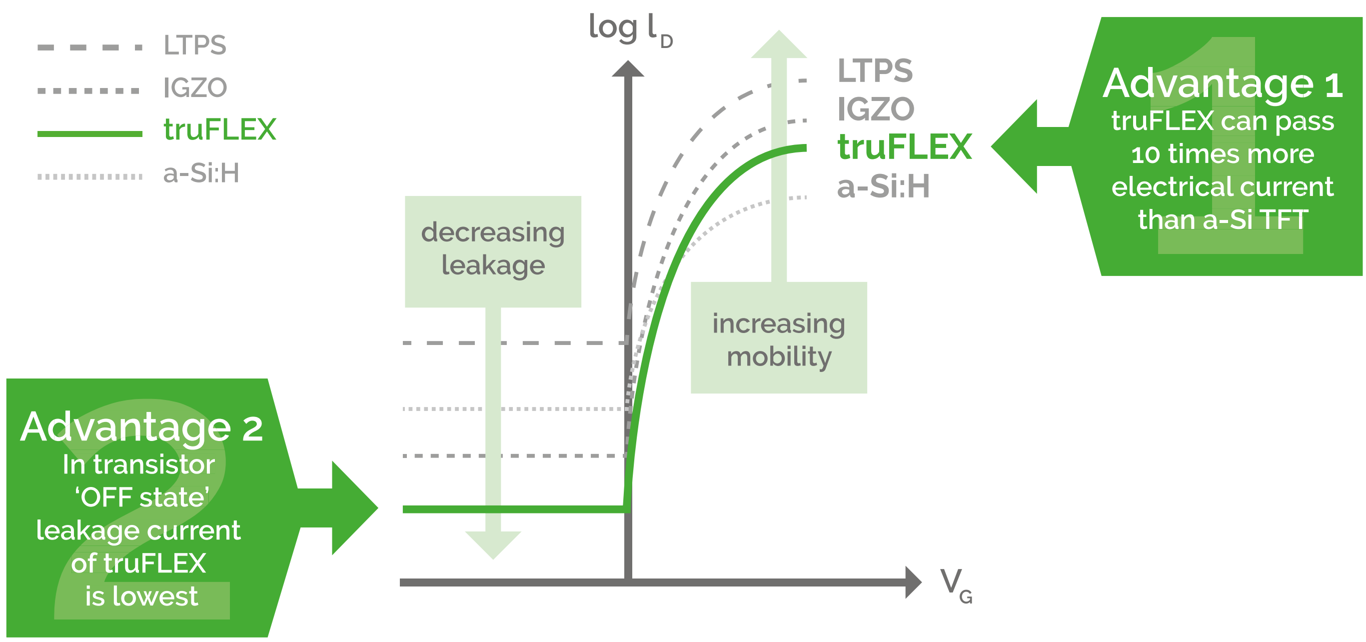

Figure 6.
Illustration depicting idealised drain-current or gate-voltage [log (I_D) – V_G] transfer-curve comparison of TFTs.

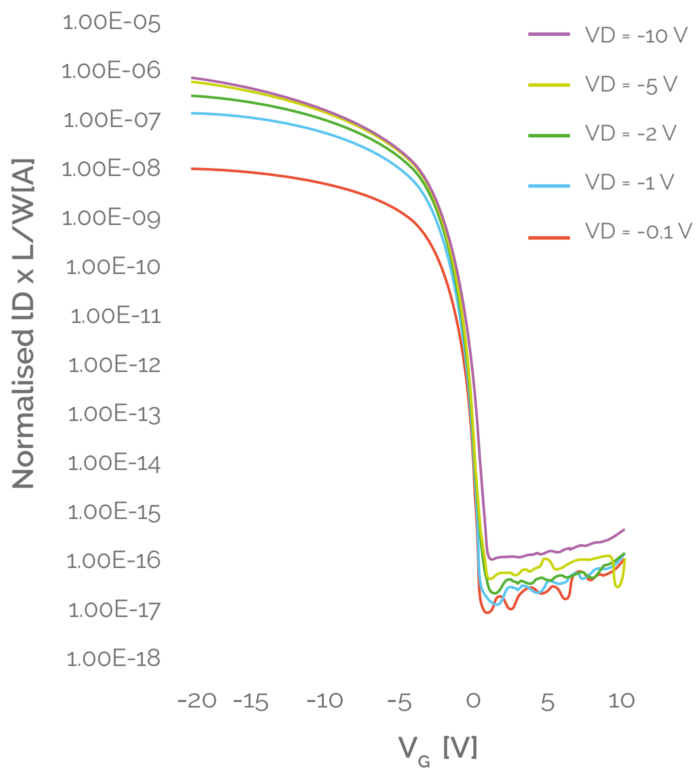

Figure 7
Normalised Leakage current measurement for truFLEX® semiconductor TG TFT

Case Study – Power Reduction in a Typical Smartwatch

In an attempt to demonstrate the power-consumption benefit to an end-user application, the power consumption of a typical Smartwatch active matrix OLED (AMOLED) display has been analysed.

The effect of using low leakage oTFTs, rather than LTPS TFTs, has been simulated. A typical Apple Watch display specification was used as the baseline for the display definition as shown in Figure 8 below.

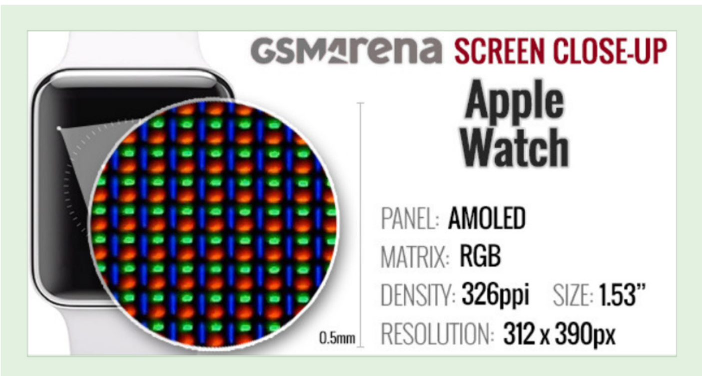

Figure 8
AMOLED Apple Watch specifications for power consumption case study

The AMOLED panel driving assumptions are detailed in Table 2 below.

Parameter	Assumed Value
Ppi	300
Outdoor luminance after polariser	200 cd/m2
Indoor luminance after polariser	60 cd/m2
RGB split	3:6:1
Power efficiency of the Red OLED	30 cd/A
Power efficiency of the Green OLED	60 cd/A
Power efficiency of the Blue OLED	10 cd/A
Reverse leakage of p-Si transistors	1pA
Reverse leakage of oTFT transistors	0.1fA
Display diagonal	42mm/1.665"

Table 2.
AMOLED panel driving assumptions for Smart Watch display; power consumption calculations using truFLEX low power frame refresh.

The power consumption for indoor and outdoor illumination levels at varying frame refresh rates were calculated for varying percentages of 'active' (switched on) pixels and compared to the power consumption of the same display driven by LTPS at 60Hz. Thus, the difference in power consumption between truFLEX and LTPS was derived.

Figure 9 below shows the reduction in relative power consumption (compared to LTPS operating at 60 Hz) of a smartwatch sized AMOLED display assuming a range of pixels switched 'ON' and for 1 and 30Hz frame refresh rates.

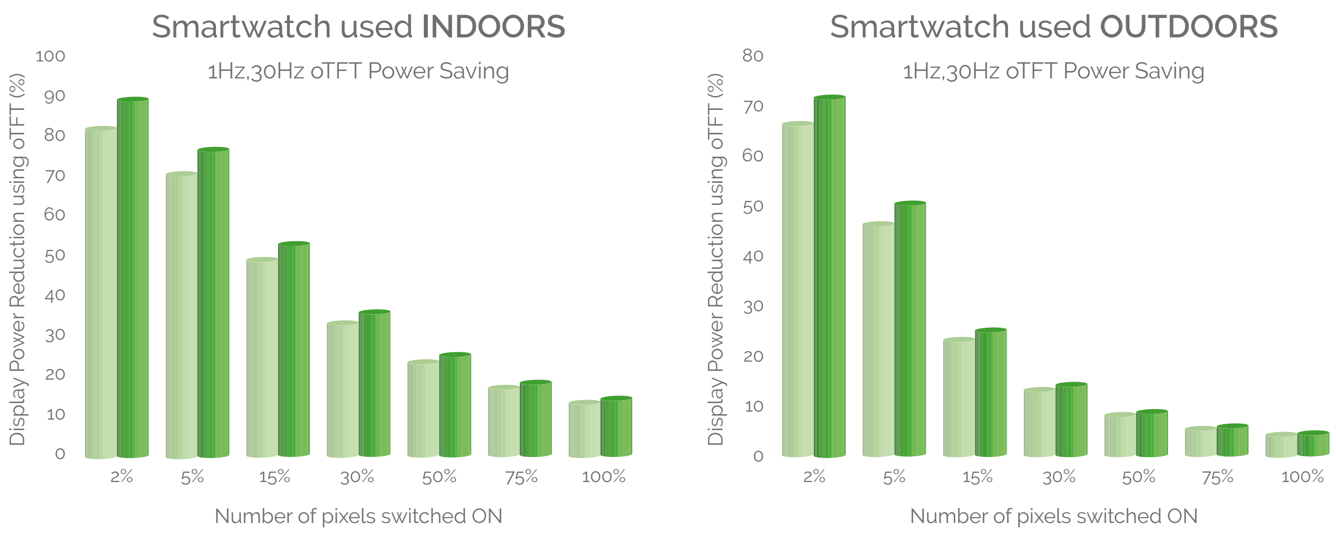

Figure 9

Normalised (to LTPS operating at 60Hz) AMOLED smart watch display power consumption using truFLEX® at different frame frequency refresh rates (1Hz: ■ , 30Hz: ■) for indoor (LHS) and outdoor (RHS) at differing rates of pixel usage from 2% to 100%.

The power consumption calculations are normalised against the power consumption for 60Hz LTPS to give an indication of the percentage reduction in display power. It can be seen that using oTFTs reduces AMOLED display power consumption by a significant amount for both indoor and outdoor use.

The range of potential power saving is from 5% to 90%, dependent upon the ambient conditions (indoor or outdoors) and the number of pixels that are active.

Conclusions

It has been shown that truFLEX offers the display industry a semiconductor TFT platform that enables the manufacture of extremely low leakage current backplanes for low power AMOLED and LCD displays. Low leakage oTFTs combined with the use of 'low power frame refresh' to reduce the frame refresh rate offers an immediate route to extended battery life in all mobile display based consumer electronic products.

It has been shown that for a typical smartwatch application the display power consumption can be reduced by as much as 90% when displaying a simple static image indoors as compared to a similar smartwatch display driven by LTPS TFTs.

Given that the power consumption of a high-quality display can account for as much as 70% of the total device power consumption, this offers a potential extension in (battery running times) periods between device charging of 3 to 5 times over current a-Si and LTPS technology platforms.

truFLEX oTFTs thus represent a market-leading route for the manufacture of wearable, mobile and portable displays having greatly extended battery life. Coupled with the additional advantages of excellent bias stress stability, simplified drive circuits and low temperature processing, truFLEX oTFTs present a significantly more attractive business proposition than LTPS and IGZO from a production, yield and most importantly end-user display performance perspective.

SmartKem

SmartKem Ltd.
Manchester Technology Centre,
Hexagon Tower, Delaunays Road,
Blackley, Manchester, M9 8GQ UK

t +44 (0)161 721 1514
e enquiries@smartkem.com

smartkem.com

Company Registration No. 06652152