19-2: Stable AMOLED Displays using a-Si:H Backplanes

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Abstract

As a first demonstration of proven stability for a-Si, over 7000h of stability data for a high drive current a-Si AMOLED pixel driver circuit was presented at SID 2004. Also demonstrated was an AMOLED display operating at 6V using the IGNIS 4-T pixel driver circuit [1] and based on a top-emission reverse OLED architecture. In this paper, an update to that information is presented with test data that is representative of lifetime in excess of 25,000 hours taking into account pertinent acceleration factors, extracted from high current drive and high temperature stressing conditions. Lifetimes will continue to increase, given the high and ever-increasing OLED efficiency.

1. Introduction

Early organic light-emitting diodes (OLEDs) suffered from low device efficiencies, leading to current requirements that precluded the use of amorphous silicon (a-Si) backplanes for an active matrix solution. However, impressive advances in OLED materials and devices recently have led to much higher efficiencies [2,3], making the a-Si backplane a viable solution for a large number of display sizes [4]. The use of a-Si for the emerging AMOLED technology is highly desirable since it leverages the vast installed infrastructure of proven AMLCD production, promising much lower manufacturing costs and rapid commercial deployment, as opposed to a low temperature polysilicon (LTPS) backplane solution [5]. In fact, the application space for a-Si based AMOLED appears to be expanding rapidly into sectors once previously thought of as impracticable or impossible.

With a-Si, however, due to its unstable nature, a compensating pixel driver circuit is required to manage changes in thin film transistor (TFT) properties. Here, the threshold voltage shift (ΔV_T) is the obvious parameter. The circuit must also compensate for changes in temperature and other environmental factors. Recent results of the IGNIS 4-T circuit [1] are presented here, demonstrating stable operation over 8,000 real time hours at video display conditions for low and high temperature operation. Additionally the circuit can be designed to maintain a uniform display brightness taking into account an *a priori* specification of the OLED degradation over time so as to maximize the display lifetime.

2. Design Tradeoffs in a-Si Backplanes

Regardless of the compensation scheme, all AMOLED pixel circuits have at least one "drive TFT", in series with the OLED. The limits of a-Si pixel circuits can therefore be determined by examining the biasing conditions of the drive TFT. The brightness of the OLED is determined by the current through this TFT, which is controlled by the gate voltage, V_{DS}. The saturation current of the drive TFT is given by [6]

$$I_{OLED} = \frac{\mu_{eff}}{\alpha} \zeta C_G^{\alpha-1} \frac{W}{L} (V_{GS} - V_T)^{\alpha} \chi \qquad (1)$$

where μ_{eff} is the effective field effect mobility, ζ an amorphous silicon material parameter, C_G the gate dielectric capacitance, χ the channel length modulation parameter, and α a parameter that ranges between 2 and 2.4. Continuous operation of the TFT will cause the V_T to increase over time, causing the OLED current to drop. Therefore the V_{GS} needs to rise to maintain constant OLED current. However, to act as a current source, the drive TFT must remain in the saturation region which is given by

$$V_{DS} > V_{GS} + V_T. \qquad (2)$$

Here V_{DS} is the drain-source voltage across the drive TFT, V_{GS} the gate-source voltage, and V_T the threshold voltage. And since

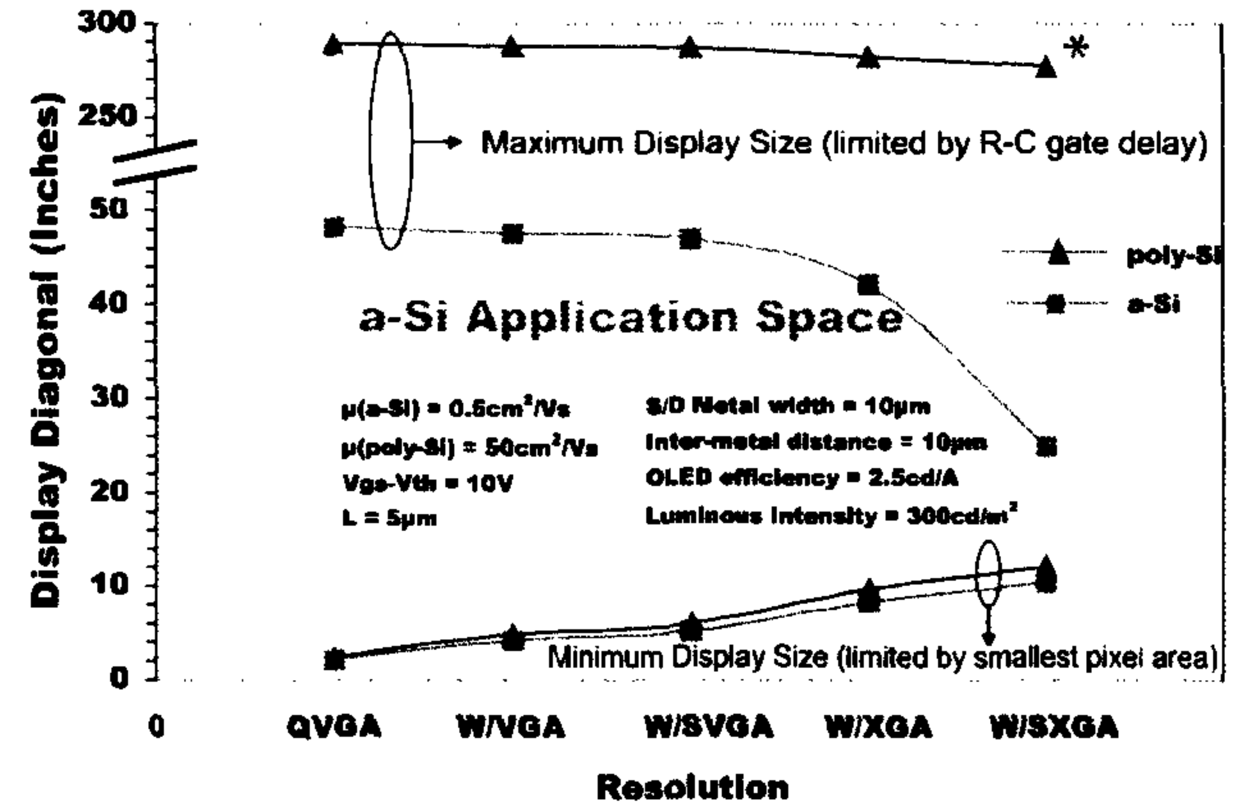
$$V_{DS} = V_{SUPPLY} - V_{OLED} \qquad (3)$$

(2) can be rewritten as

$$V_{SUPPLY} > V_{GS} + V_T + V_{OLED} \qquad (4)$$

where V_{SUPPLY} is the supply voltage to the array, and V_{OLED} the voltage drop across the OLED. Eqn. (4) describes the upper bound on the lifetime of a-Si drive schemes. As the V_T increases, Vgs must also increase to maintain constant current. Eventually the TFTs will fall out of saturation, at which point the current begins to drop. A larger V_{SUPPLY} will allow for longer pixel lifetimes, however, this will increase power consumption. To keep the V_{SUPPLY} low while still maintaining long lifetimes, V_T, V_{OLED}, or V_{GS} should be minimized, according to Eqn. (4). The OLED and TFT process is usually fixed, so the only option is reducing V_{GS}. However, to do this the drive TFT must be made larger to conduct the same amount of current, and therefore the pixel size increases. Essentially, the design exercise reduces to a pixel size vs. driving voltage tradeoff. A smaller pixel can be made if the voltages are raised, or vice-versa [7].

One might expect that poly-Si would have a distinct advantage, since with a higher mobility, the pixel can be made smaller, or driven at a lower voltage. However, for most applications, the mobility of the TFT is not a bottleneck. Due to the increasing efficiency of OLEDs, the drive TFT is often minimum size for a-Si pixels, therefore there is no difference between poly-Si and a-Si pixel sizes or voltages. Therefore increasing the size of the drive TFT does not significantly affect the area of the pixel, due to the large interconnect overhead. As can be seen in Fig. 1, the difference in minimum display size for a-Si and poly-Si are insignificant (<10%) for typical applications.



* Note: Theoretical calculation, equipment does not currently exist to produce panels this large.

Fig. 1 Comparison of a-Si and poly-Si applications.

For very large display sizes, however, poly-Si has an advantage. For extremely large pixels, the interconnect area is no longer the dominating factor, and with large OLEDs, the a-Si TFT requires high W/L ratios, resulting in sizeable capacitances. Because of the high mobility, poly-Si can use much smaller TFTs, therefore leading to smaller capacitances. The smaller capacitances allow for less RC delay in charging the line. However a-Si is capable of producing displays with up to 50" diagonal, and even higher as the OLED efficiency increases. Fig. 7 shows the capabilities for a 20" a-Si HDTV application. We see that the a-Si backplane is clearly well within the specifications for the frame rate.

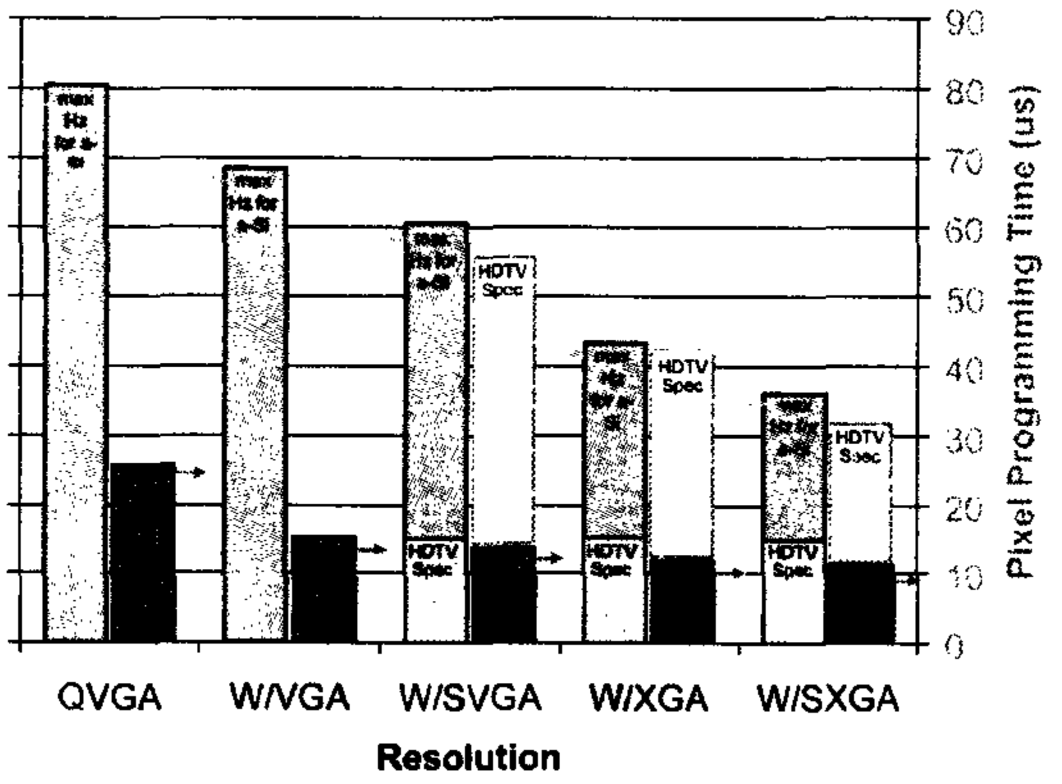


Fig. 2 a-Si capabilities for 20" HDTV applications.

3. Extreme Self-Compensating Pixel Circuit

The primary issue that should be addressed in a-Si backplane design is the compensation for V_T shift [8-10]. However, there are other factors that influence stability of operation: temperature, mechanical stress, and more significantly, OLED degradation. A design that incorporates V_T shift compensation alone will function well inside a lab, but will be unreliable in a real-world application. IGNIS' circuit architecture is such that the input data current is replicated at the OLED [11] (see Fig. 3). Therefore any factors that change the performance of the TFT will not affect the relationship of input current to output current. In addition, judicious choice of biasing conditions of the current mirror allows for a controlled increase in OLED current to compensate for OLED degradation.

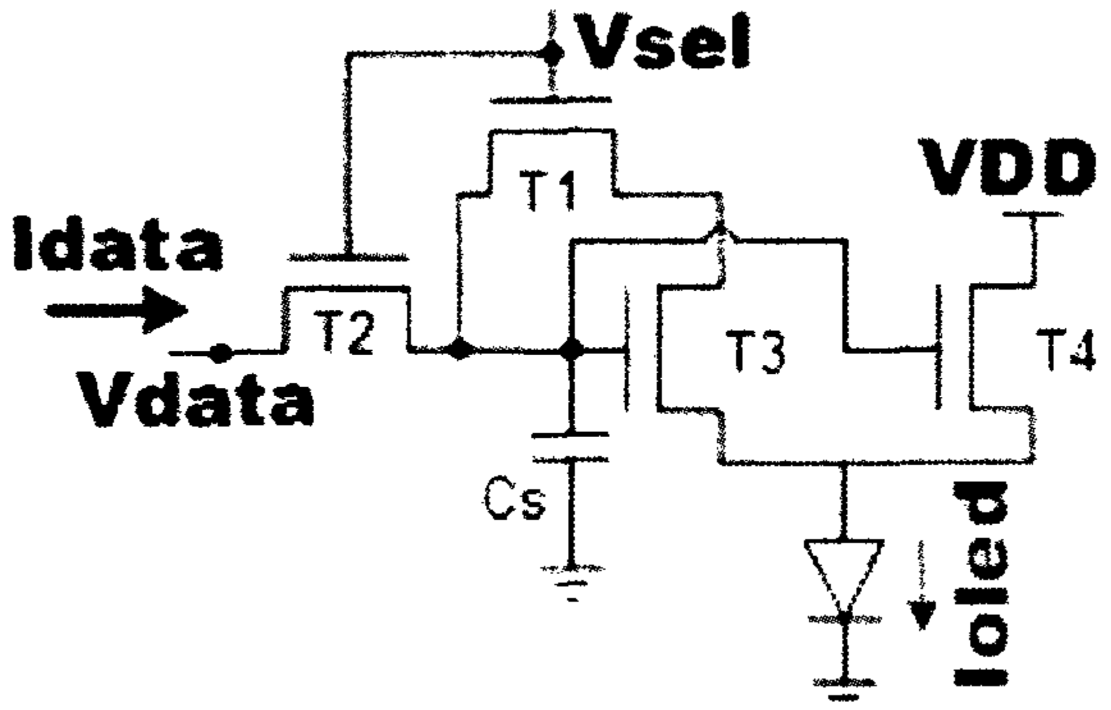


Fig. 3 4-TFT current programmed V_T shift compensated circuit.

4. Test Conditions

TFT circuits were fabricated using a 300°C process, designed for glass substrates, and a 150°C process, designed for plastic substrates [12]. The circuits were then diced and bonded into ceramic packages. Testing the circuits in discrete form allows access to all nodes for diagnostic purposes. Due to the large parasitic capacitances involved with packaging a discrete pixel circuit and using a current driver based on discrete ICs, the pixel was operated at 8.3 Hz instead of the targeted 60Hz which would be easily achievable in an array, due to lower parasitics.

A state-of-the-art test system was developed in-house to allow for stressing and real-time monitoring of pixel circuits. The test system replicates the conditions the pixel would experience in any display configuration; in this case, a (320 x 240) QVGA array running at 60 frames/s. A microcontroller was used to generate precise timing signals, a level shifter to apply the V_{SELECT} signal, and a voltage-controlled current source (VCCS) to supply an I_{DATA}. The I_{OLED} current was measured in real-time using a high-precision current sensor.

The voltage at the I_{DATA} node (i.e. V_{DATA}) was also monitored and plotted on the same figure. Over time, the voltage necessary to allow I_{DATA} to flow into the pixel increases. This voltage gives a good indication of the "life" left in the pixel. Following eqn. 4, once V_{DATA} approaches the supply voltage, the pixel stops compensating.

The value of V_{DATA} for all tests is higher than for an actual application. First, all the tests are accelerated by running at higher currents, therefore the voltage is correspondingly higher. Second, the high voltages are in part due to the limitations of the fabrication process. The process uses large gate lengths (23μm). An industrial process with more typical 5μm gate lengths would allow for a larger drive TFT in an equivalently sized pixel.

Therefore the same output current would be achieved with a lower V_{DATA}. This lower V_{DATA} would also result in less V_T shift, further extending the pixel lifetime. Calculations, in addition to the prototype display described in Section 6, show AMOLED displays based on IGNIS' pixel architecture will run with a V_{SUPPLY} of 5-8V, depending on the configuration.

Finally, the large gate lengths and overlaps also result in high parasitic capacitance. The parasitic capacitor between the $V_{ADDRESS}$ node and the gate of T3 (as seen in Fig. 3) causes the voltage on C_S (and consequently the output current) to drop when the $V_{ADDRESS}$ line switches from high to low [7]. This causes the OLED current to drop 20-30%, therefore the pixel must be programmed with a higher current. Clock feedthrough would also be much smaller with a tighter design rule process, thus further reducing I_{DATA} and V_{DATA}.

5. Test Results

The first test was launched early July 2003 and is still operating after over 8500h of continuous stress. For the first 2500h, the average current was 11.2μA. For convenience we present a recent window of data that contains the last 6000h, shown in Fig. 5.

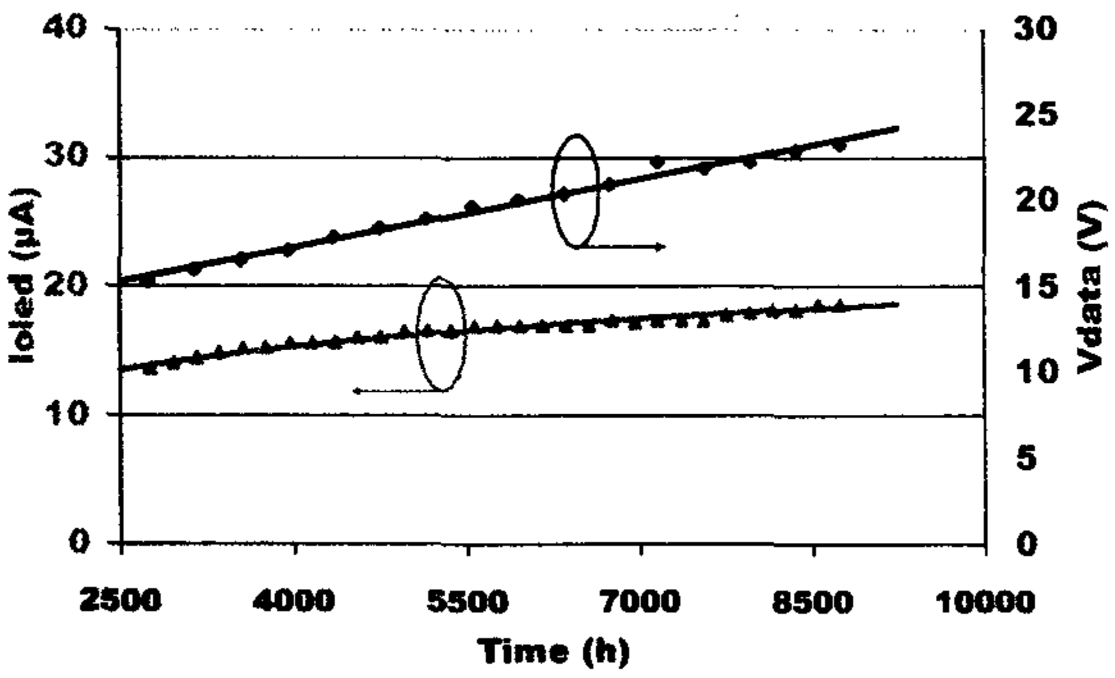


Fig. 5 Average OLED current for 4-T pixel – high-current test. This figure shows the last 6000h of 8500h test (circuit averaged 11.2μA for the first 2500h). This is equivalent to over 27,000h at 1.5μA.

To accelerate the test, the current is approximately 10 times higher than necessary for a present-day $300\mu m^2$ OLED (we are assuming 1.5μA as an average OLED current). An acceleration factor of 3.16 can be applied, using the acceleration factor calculation presented in [13]. Therefore this test represents over 27,000h of operation at 1.5μA.

This circuit, by design, shows a slow increase of the output current over time – this overcompensation is intrinsic to this circuit, and stems from several different factors that affect the balancing of the current mirror in the pixel circuit. By control of these factors, the pixel can be designed with a specific rise over a period of time. This allows the pixel circuit to compensate for OLED degradation, and maintain a constant brightness.

Test results for a circuit without this compensation (i.e. a circuit designed to provide zero current rise over time) are shown in Fig. 6. This test is operating at 8μA, providing an acceleration factor of approximately 2.3. Therefore this test represents over 5,000h of performance data.

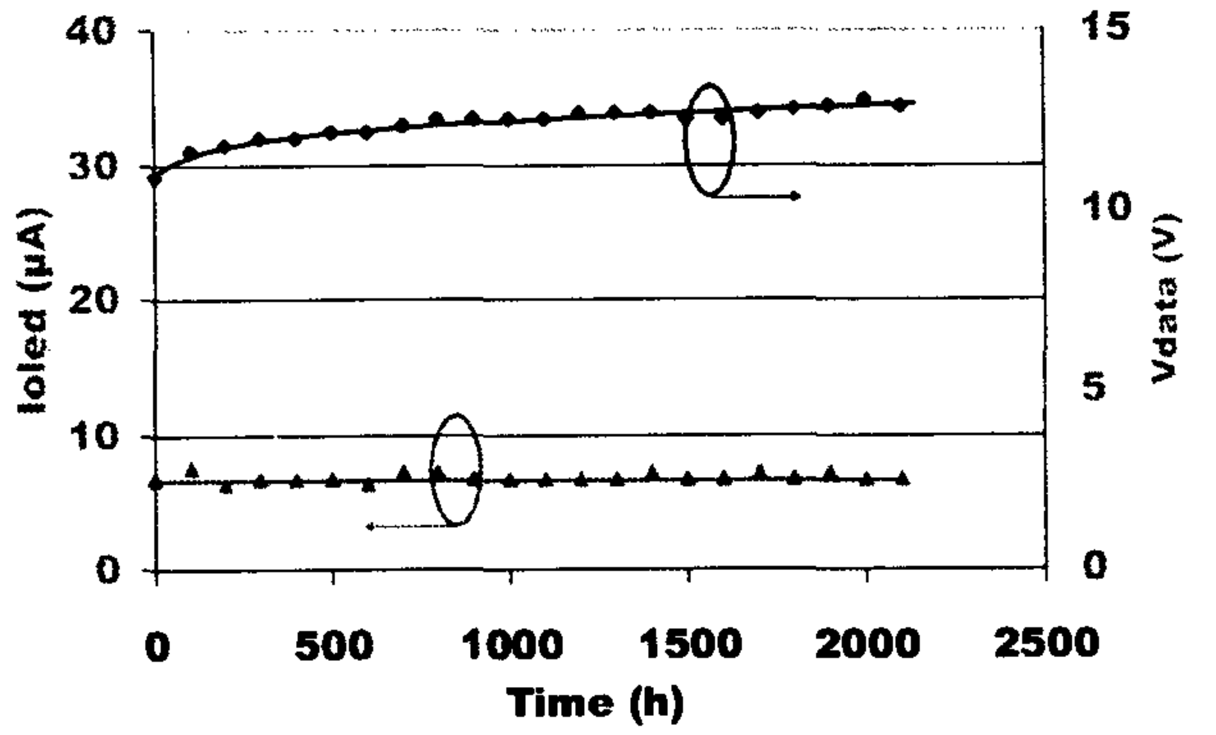


Fig. 6 Average OLED current over 2000h for a 4-T pixel designed to have zero current rise. This is equivalent to over 5,000h at 1.5μA.

A more recent test running at lower current levels is shown in Fig. 7. Correspondingly V_{DATA} is lower. This test more closely represents the typical conditions for phosphorescent OLEDs [2] and is indicative of the performance that can be expected. An acceleration factor of 1.8 can be applied to this circuit; therefore this test is equivalent to over 11,000h of data.

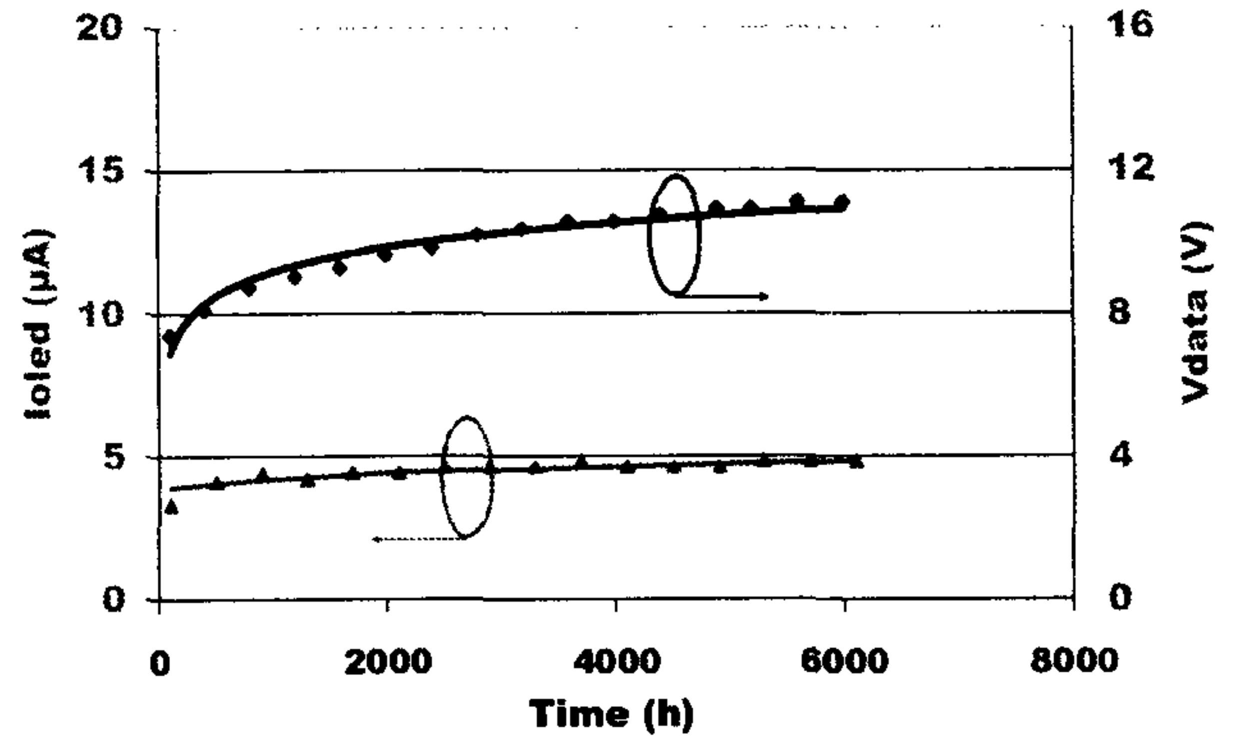


Fig. 7 Average OLED current over 6000h for a 4-T pixel – low-current test. This is equivalent to over 11,000h at 1.5μA.

Testing pixel circuits at high temperatures is another way to accelerate the degradation. At the same time, it qualifies the pixel for operation at higher temperatures. Pixel circuits tested at 75°C in an environmental chamber are shown in Fig. 8. The pixel circuit maintains normal operation at the higher temperature, and continues to compensate after 3000h. The temperature provides an acceleration factor of 1.8, and the higher current adds a factor of 2. Therefore the data shown is equivalent to a pixel circuit operating at 1.5μA and 25°C for over 11,000h.

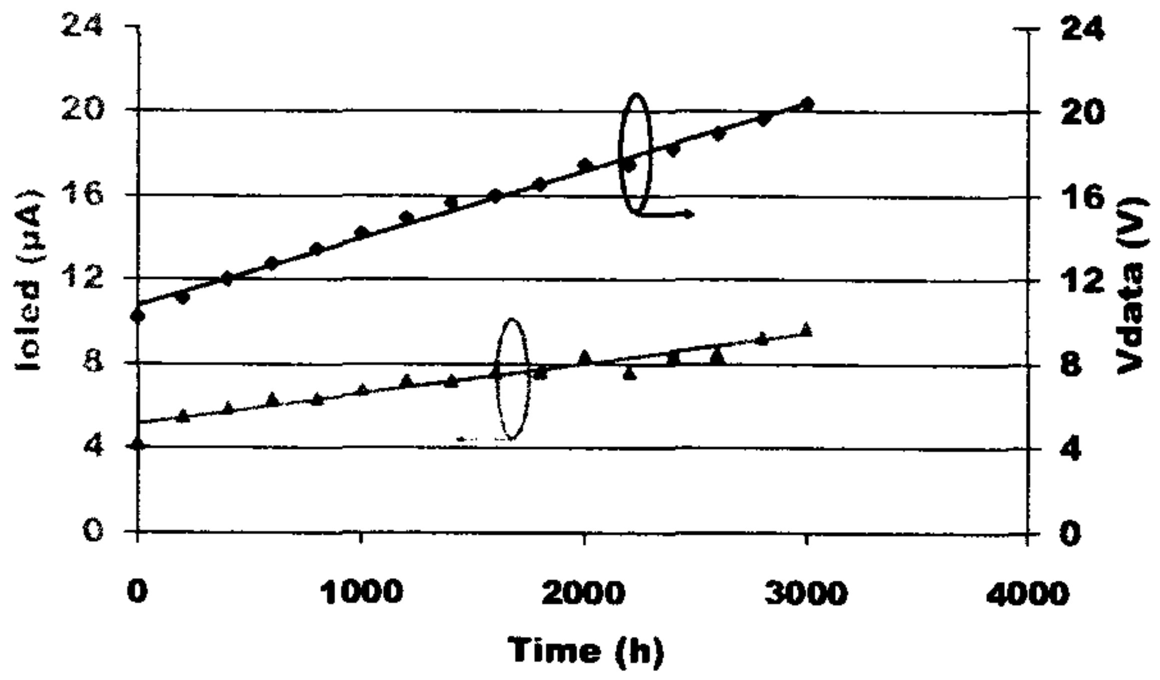


Fig. 8 Average OLED current over 3000h for a 4-T pixel – high-temperature 75°C test. This is equivalent to over 11,000h at 1.5µA and 25°C.

Using IGNIS' low-temperature fabrication process, pixel circuits were fabricated on plastic substrates, with maximum process temperature of 150°C [12]. The circuit is an ideal candidate for flexible backplanes given its compensating capabilities. The TFTs exhibit similar parameters as the devices fabricated at 300°C. The results in Fig. 9 show similar performance to the circuits fabricated at 300°C. Using an acceleration factor of 3, this test represents nearly 9,000h of operation at 1.5µA.

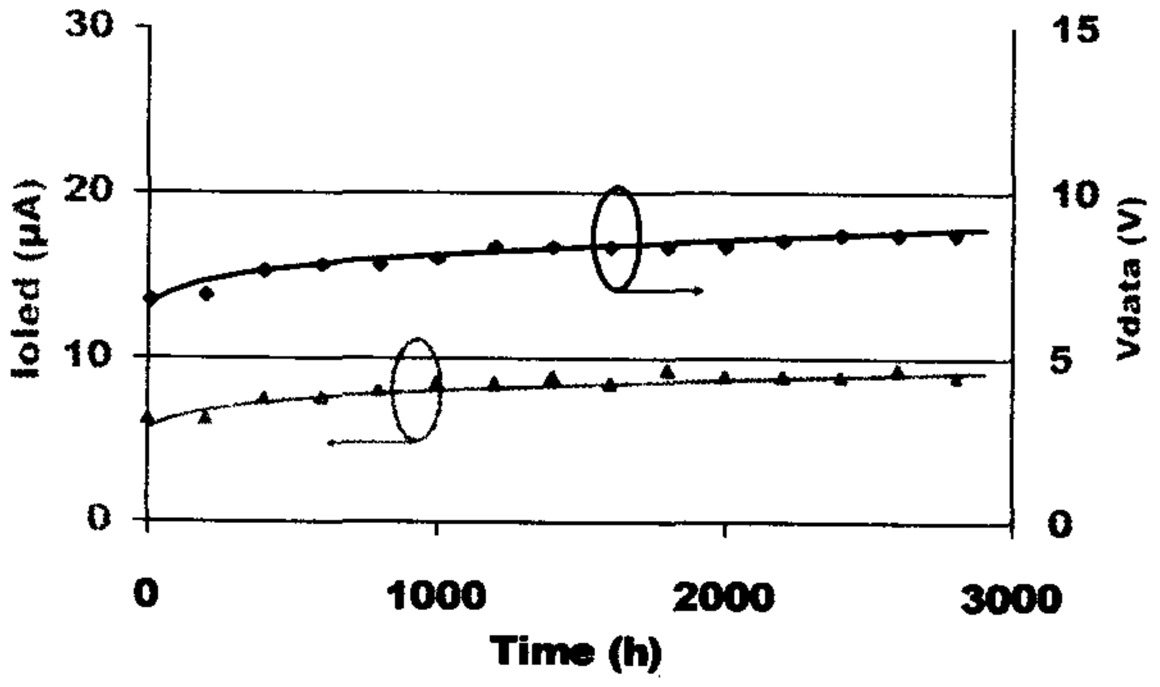


Fig. 9 Average OLED over 2800h for a 4-T pixel fabricated at 150°C. This is equivalent to 9.000h at 1.5µA.

6. Prototype AMOLED Array

To demonstrate the functionality of the 4-T circuit in an integrated array, a prototype AMOLED display was fabricated in collaboration with NOVALED GmbH. This represents the first a-Si AMOLED display with proven stability, as well as the first AMOLED demonstrated with a top-emission, top anode OLED. The photograph in Fig. 11 shows the prototype, which is divided into three sub-arrays. Each sub-array uses a different pixel architecture and driver circuit configuration. The region in the lower right contains various discrete pixels and test structures.

The upper right array, which uses the IGNIS 4-T pixel circuit architecture shown in Fig. 3, is shown displaying scrolling text. A microcontroller was used to generate the timing signals, and discrete components to apply the voltages and currents to the array. The display parameters are shown in Tab. 1.

Tab. 1 IGNIS/NOVALED AMOLED prototype

Backplane Process	a-Si standard process, 23µm gate length
Backplane Pixel Circuit	IGNIS 4-T
Pixels	40 x 40
Pixel Size	420µm
Supply Voltage	6V
Pixel Current	<1µA
OLED	NOVALED top emission, top anode red

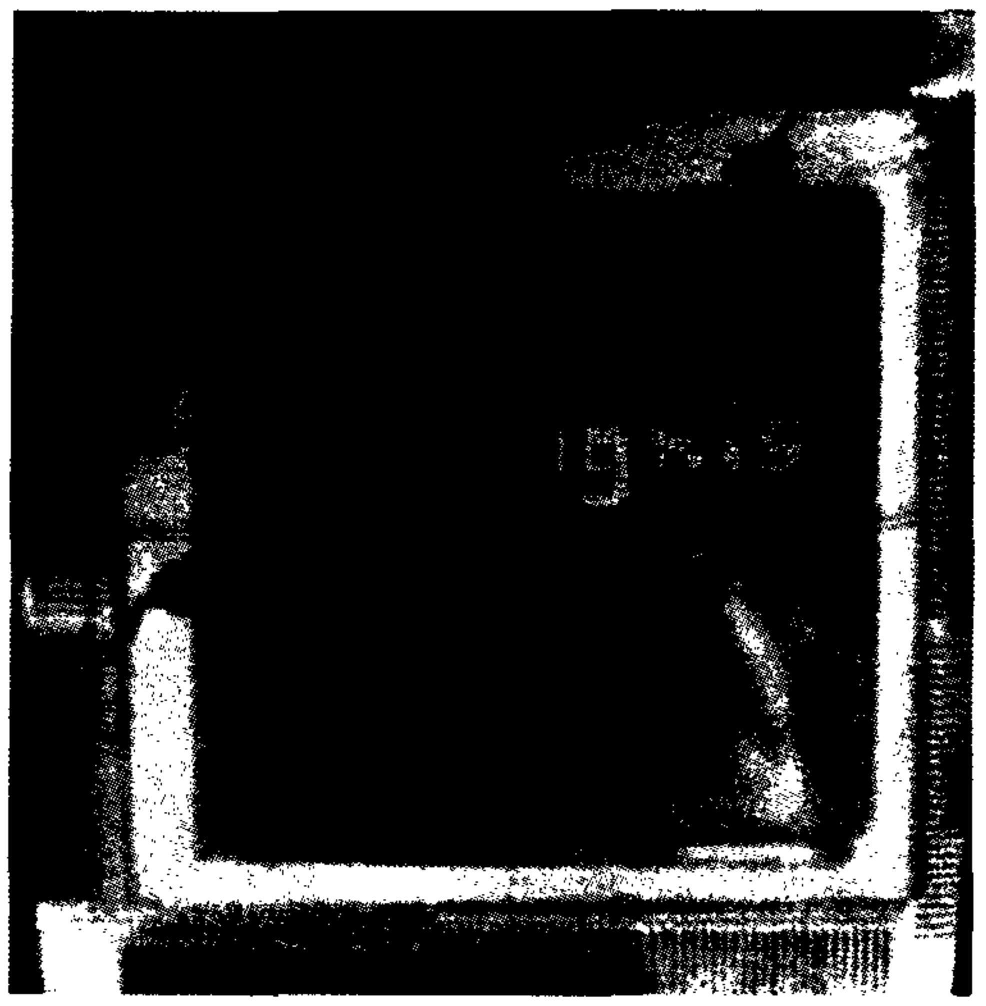


Fig. 10 Photograph of IGNIS/NOVALED test prototype AMOLED display.

7. Conclusions

The results presented here demonstrate that a-Si backplanes can maintain stable operation in excess of 25,000h. Indeed, this exceeds the current stability of the OLED, which now becomes the limiting factor in the lifetime of an AMOLED display. It is important to note that it is no longer sufficient for the pixel circuit to compensate for the TFT's instability; it must compensate for OLED degradation as well. Extending the usable lifetime of the OLED will allow AMOLED displays to exceed lifetime requirements for a broad range of application, particularly high definition television.

8. References

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