Vertical Organic Light Emitting Transistors for Large Screen AMOLED Displays

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ABSTRACT

The carbon nanotube enabled vertical field effect transistor technology further demonstrates its promise to allow cost effective manufacturing of large screen AMOLED displays. Formed essentially by directly stacking an OLED onto the vertical channel layer of the vertical field effect transistor, the resulting vertical organic light emitting transistor combines the driving transistor, storage capacitor and light emitter into a single integrated device. A QVGA AMOLED prototype using this technology was demonstrated at the 2016 San Francisco SID Display Week, winning the I-Zone award for best prototype.

We discuss the important desirable benefits obtained from this novel device structure for AMOLED display applications. The naturally obtained and well controlled sub-micron channel length makes a broad range of low mobility, amorphous organic semiconductors useful as the channel material. This permits material choices (unconstrained by the high mobility required by lateral TFTs) that minimizes bias stress instability, as demonstrated by enhanced bias illumination stress stability of vertical field effect transistors in both positive gate bias stress conditions (PBIS) and negative gate bias stress conditions (NBIS).

1. Objective and Background

In recent years, AMOLED displays have achieved successful market penetration in small to medium size handheld devices like smart phones and tablets. Because of their performance advantages, AMOLED displays have been adopted in high-end products and enabled distinctive features such as the curved edge screen. Foldable AMOLED display prototypes have also been demonstrated by research laboratories and panel manufacturers. These advances would suggest an eventual dominance of the market by AMOLED technology.

On the other hand, AMOLED displays have had less success in penetrating the large screen display market, which continues to be dominated by LCD panels. The numerous advantages of AMOLED displays: faster response times to eliminate motion blur; wider color gamut to reproduce more vivid images; higher contrast ratios to display true black; a 180-degree viewing angle without brightness or color distortion; as well as a thin form factor to realize the so-called Wallpaper TV, should virtually guarantee the success of large screen AMOLED TVs, but only if they can be manufactured cost-effectively without compromising performance.

Among the manufacturing challenges, a key issue arises from the thin film transistor (TFT) backplane. Within each pixel the driving TFT need not only supply large current to drive the OLED at high brightness, but it must also provide fine control over that current to achieve a well-defined grey scale. The successful LTPS TFT technology used to manufacture small size OLED panels suffers from more severe uniformity issue for large screen panels, and the excimer laser annealing process generally limits the glass substrate size to maximum gen 6 which is not economical for large screen panel mass production [1,2]. The oxide TFT, such as the indium gallium zinc oxide (IGZO) TFT technology has admitted large screen AMOLED displays entry to the market, however, the manufacturing costs remain high. The oxide TFT exhibits high sensitivity to process conditions resulting in inconsistent and low yields [3,4]. It also exhibits instabilities that manifest as display artifacts during operation such as the image sticking issue [5].

We have taken a different track, evolving and improving our carbon nanotube enabled vertical field effect transistor (CN-VFET) technology [6]. Its architecture features a dilute carbon nanotube network source electrode and a vertical organic semiconductor channel. Unlike the traditional TFT in which the source and drain electrode lie side-by-side, with the channel length defined by the horizontal distance between them, in a CN-VFET the organic channel layer is stacked on top of a dilute carbon nanotube network source electrode, with the drain electrode stacked on top of the channel layer. Current flows vertically from the bottom nanotube source electrode, upward through the channel layer, to be collected by the top drain. The channel length is now simply the thickness of the organic channel layer which is easily made sub-micron thick. A comparable channel

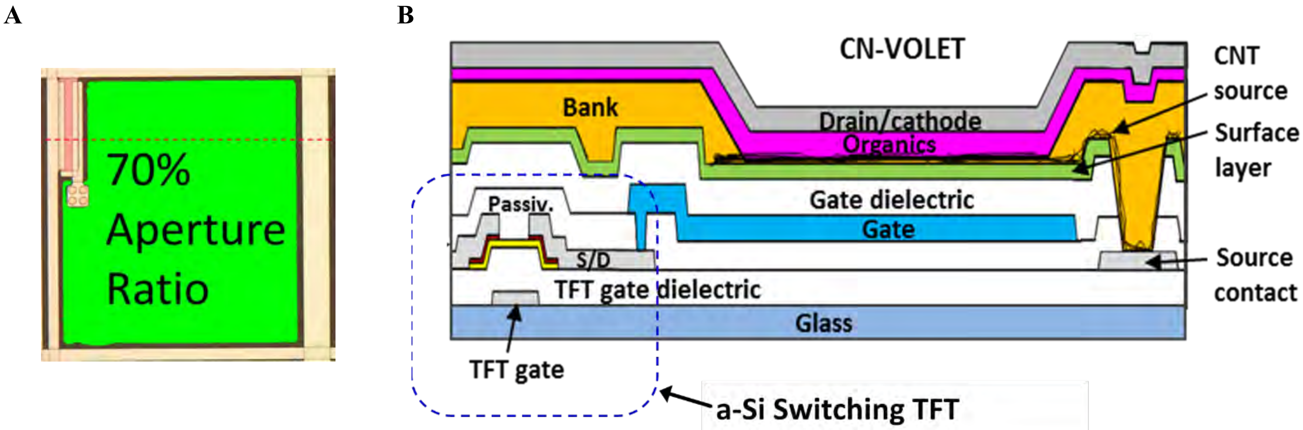

Figure 1. A) Microscopic image of the QVGA prototype pixel with a 70% aperture ratio (false colored green). The a-Si switching TFT is in the upper left corner of each pixel. **B)** Cross section of an active matrix CN-VOLET pixel along the dashed line in A. The layer labeled "Organics" includes the organic semiconducting channel layer and the OLED stack.

length in the lateral channel design would require high resolution patterning, something not even available over the latest generation large substrates. A critical benefit of such short channel lengths is that organic semiconductor channel materials with mobilities as low as 10^{-3}–10^{-4} $cm^2/(V{\cdot}s)$ can still source ON-state currents more than sufficient to drive even high current demand OLED stacks [7]. Since chemists have over decades steadily pushed organic semiconductor mobility to the range of 1 $cm^2/(V{\cdot}s)$ and higher, there exist a bounty of materials that possess more than ample mobility, allowing for material selection to be made based on other critically important properties like stability, processability, uniformity and cost. The CN-VFET architecture, by relaxing the constrains imposed by the previous need for high mobility materials, allows for transistors that are stable, uniform, simple to fabricate, and capable of driving large currents.

Moreover, by integrating the OLED stack directly into a CN-VFET we formed a carbon nanotube enabled vertical organic light emitting transistor (CN-VOLET) [8,9]. The CN-VOLET greatly simplifies the pixel circuit of an AMOLED display. The simplest AMOLED 2T+1C pixel circuit requires 4 components: the switching and driving transistors, the OLED stack and a storage capacitor to maintain the driving voltage over the refresh cycle. In the typical pixel design the other components limit the area available for the OLED reducing the aperture ratio. The CN-VOLET, in contrast combines the driving transistor, OLED and storage capacitor (by its intrinsic capacitance) into a single stacked device, reducing that component count to two: a switching transistor and the CN-VOLET. This both maximizes the aperture ratio and promises to simplify panel manufacturing [10].

A 2.5 inch mono-color AMOLED QVGA (320 x 240) prototype based on the CN-VOLET was demonstrated and won the 2016 SID Display Week's I-Zone Best Prototype Award [11]. Figure 1A shows a micrograph of a pixel (false color) from the prototype, the a-Si switching transistor is in the upper left corner, leaving 70% of the pixel area for the light emitting portion of the CN-VOLET, in a bottom emission display. Figure 1B shows a cross-section of the pixel. The contrast ratio of the prototype is close to 10^6 and the brightness is above 500 Cd/m^2. Figure 2 shows static images taken from the prototype. A video recording demonstrating its functionality, operating at 60 Hz, can be seen at http://www.nverpix.com/qvga-video/.

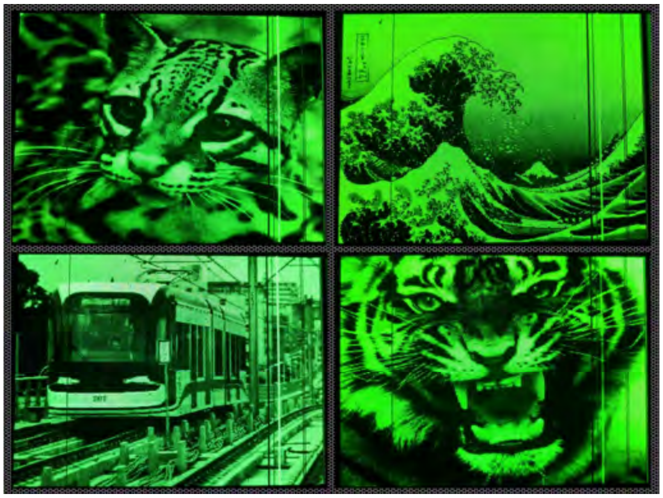

Figure 2. Sample static images displayed by the CN-VOLET QVGA AMOLED prototype.

Video rendering, free of image artifacts, requires high stability in the driving transistor of AMOLED displays. Electrical stress from the gate voltage bias can induce shifts of the threshold voltage (V_T) in the driving transistor, leading to the image sticking issue. IGZO TFTs are sufficiently stable when the gate bias is applied to stress the device in the dark. However, when IGZO TFTs are stressed with a negative gate bias under illumination (NBIS stress), the V_T

shifts toward more negative gate voltages [5, 12]. That the CN-VFET can be configured (through engineering and materials selection) to avoid this illumination stress issue is demonstrated here for both negative bias illumination stress (NBIS) and positive bias illumination stress (PBIS) conditions.

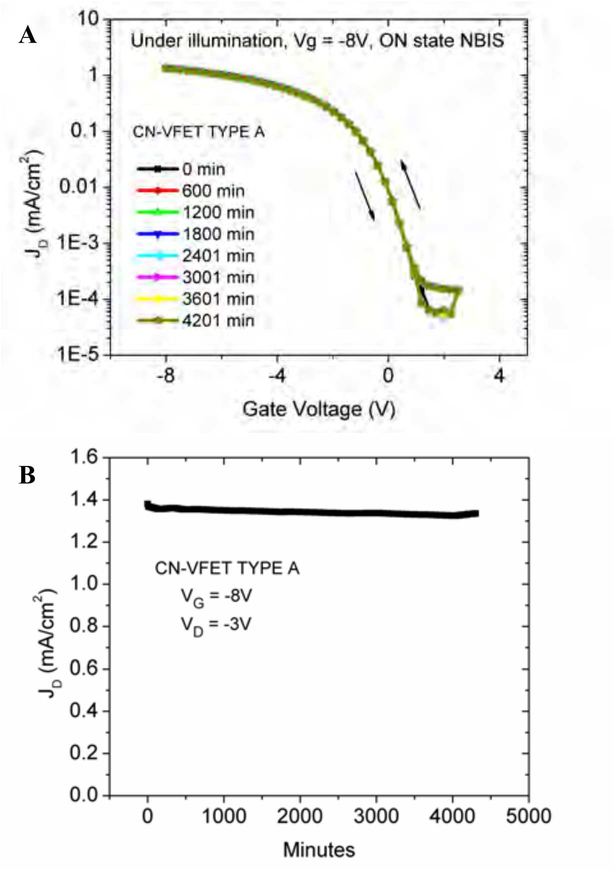

Figure 3. NBIS stability data of CN-VFET type A. **A)** Transfer curves taken periodically during the stress showing negligible V_T shift. **B)** ON state current density of the device for the stressed period.

2. Results and Discussion

Bias illumination stress stability measurements on CN-VFETs were carried out in an argon glovebox. A Keithley 2612 dual-channel SourceMeter controlled by a Labview program supplied both the gate voltage (V_G) and drain voltage (V_D) to the CN-VFETs. A fluorescent lamp was used to provide around 650 lux (typical indoor lighting) for the illumination. During the stress measurements, the gate voltage was applied continuously, except for occasional, short duration bi-directional transfer scans to record the transfer curves and V_T of the device. The regular operation gate voltage range of the CN-VFET was from -8V fully ON to 2.5V fully OFF. Since the tested CN-VFETs are p-channel devices, the NBIS measurements correspond to an ON state stress, and the PBIS measurement corresponds to an OFF state stress.

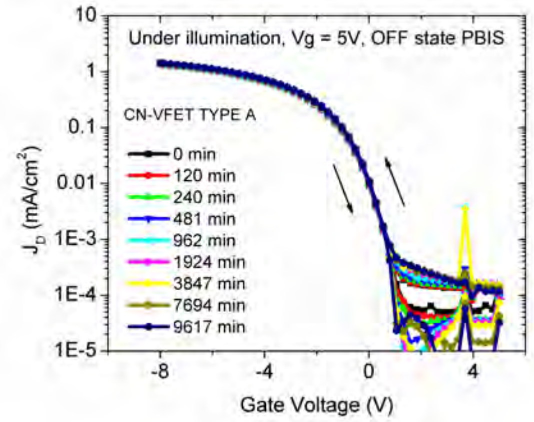

Figure 4. PBIS stability data of CN-VFET type A stressed at V_G = 5V for more than 160 hours. Transfer curves taken periodically during the stress showing a small shift $\Delta V_T < 0.05$V.

Figure 3 shows the NBIS measurement result for a CN-VFET pixel with a commercial but proprietary organic semiconductor channel layer (CN-VFET type A) stressed at V_G = -8V and V_D = -3V under illumination. As seen from the periodically recorded transfer curves during the 4200 minutes of stress shown in Fig. 3A, there was negligible V_T shift in the device, while as shown in Fig. 3B the ON state drain current was remarkably stable over the long stress period. Figure 4 shows the PBIS measurement result of CN-VFET type A for an even longer term of more than 9600 minutes under illumination stressed at V_D = -3V. Experience has shown that PBIS stability is more challenging to achieve for the p-channel CN-VFETs because electron trapping at the gate dielectric/channel interface can (for some channel materials) readily shift the V_T in this condition. Although the device is fully OFF at a gate voltage of 2.5V, here to prove the stability at a more severe condition, V_G = 5V was used for the entire stress period. The V_T shift in this severe long term stress is less than 0.05V, demonstrating its remarkable stability here, as well.

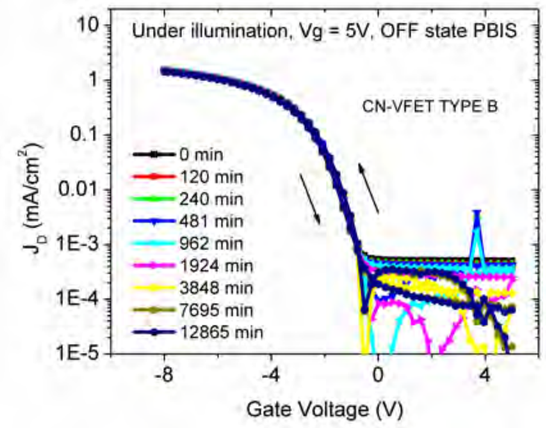

Figure 5. PBIS stability data of CN-VFET type B stressed at V_G = 5V for more than 200 hours. This is a particularly severe test since the device is already OFF at V_G = 0V. Transfer curves taken periodically during the stress show a small shift $\Delta V_T \sim 0.13$V.

Figure 5 shows the PBIS transfer curves at the indicated times for a CN-VFET pixel using a distinct, commercial but proprietary, organic semiconductor that we designate CN-VFET type B. This was also stressed at $V_G = 5V$ and $V_D = -3V$, under illumination. Over a duration totaling more than 12800 minutes of stress time it demonstrated a V_T shift of 0.13V, which is more than that of the CN-VFET type A, but still relatively stable. Figure 6 plots the stress results for both CN-VFET type A and type B. It is worth noting that these two devices have quite distinct threshold voltages. At $V_G = 0$, CN-VFET type B is already completely OFF, making it possible to drive this device with a single polarity of V_G and avoid stressing the device with positive gate voltage at all during operation, further benefiting its stability.

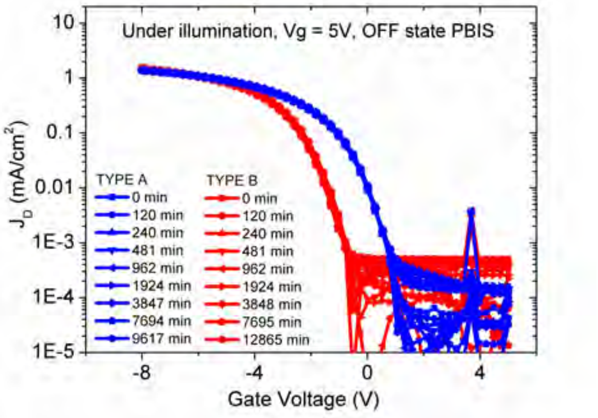

Figure 6. Comparison of PBIS stability data. Blue curves: CN-VFET type A. Red curves: CN-VFET type B. Note the distinctive V_T of device type A and type B.

3. Conclusion

With its easily formed and precisely controlled sub-micron channel length, the CN-VFET makes relatively low mobility, amorphous organic semiconductors useful for high current, high performance transistor applications. The broad availability of organic semiconducting materials provides opportunity for selecting channel materials that make the CN-VFET highly uniform, stable and efficient. As shown here, that freedom of choice also permits an adjustment of the threshold voltage to a more desirable region. With these advantages afforded by the CN-VFET and the successful demonstration of active matrix CN-VOLET display prototype, these devices continue their steady march toward benefitting display manufacturing.

REFERENCES

[1] S. Utsugi, N. Nodera, T. Matsumoto, K. Kobayashi and T. Oketani, "67-1: Novel LTPS Technology for Large Substrate", SID Symposium Digest of Technical Papers, 47, (2016).

[2] P. van der Wilt and S. Passinger "30-2: The Crystallization Monitor: Enabling Accurate Metrology of Excimer-Laser Annealed Si Films", SID Symposium Digest of Technical Papers, 48, (2017).

[3] K. Nomura, T. Kamiya, M. Hirano, and H. Hosono, "Origins of threshold voltage shifts in room-temperature deposited and annealed a-In-Ga-Zn-O thin-film transistors", Appl. Phys. Lett. 95, 013502 (2009).

[4] J. Bang, S. Matsuishi, and H. Hosono, "Hydrogen anion and subgap states in amorphous In–Ga–Zn–O thin films for TFT applications", Appl. Phys. Lett. 110, 232105 (2017).

[5] Y. Rim, W. Jeong, B. Ahn, and H. Kim, "Defect reduction in photon-accelerated negative bias instability of InGaZnO thin-film transistors by high-pressure water vapor annealing" Appl. Phys. Lett. 102, 143503 (2013).

[6] B. Liu, M. McCarthy, Y. Yoon, D. Kim, Z. Wu, F. So, P. Holloway, J. Reynolds, J. Guo, and A. Rinzler, "Carbon-Nanotube-Enabled Vertical Field Effect and Light-Emitting Transistors", Advanced Materials, 20, p. 3605 (2008).

[7] M. McCarthy, B. Liu, and A. Rinzler, "High Current, Low Voltage Carbon Nanotube Enabled Vertical Organic Field Effect Transistors", Nano Letters, 10, p. 3467 (2010).

[8] M. McCarthy, B. Liu, E. Donoghue, I. Kravchenko, D. Kim, F. So, A. Rinzler, "Low-Voltage, Low-Power, Organic Light-Emitting Transistors for Active Matrix Displays", Science, 332, p. 570 (2011).

[9] B. Liu, M. McCarthy, B. Iheanacho, W. Wong and A. Rinzler, "Recent Developments of Carbon Nanotube Enabled Vertical Organic Light Emitting Transistors for OLED Displays", SID 2013 Digest, p. 21.4L (2013).

[10] M. McCarthy, B. Liu, M. Mativenga, J. Jang and A. Rinzler, "The CN-VOLET Based AMOLED: Manufacturing Considerations", IMID 2014 Digest, p. 58-2 (2014).

[11] M. Mccarthy, B. Liu, D. Cheney, M. Lemaitre, R. Jayaraman, M. Mativenga, D. Geng, J. Kim, H. Kim, J. Jang and A. Rinzler, "P-206L: QVGA AMOLED Displays Using the Carbon Nanotube Enabled Vertical Organic Light Emitting Transistor", SID Symposium Digest of Technical Papers. 47. 1796-1798. (2016).

[12] Y. Chen, T. Chang, H. Li, W. Chung, T. Hsieh, Y. Chen, W. Tsai, W. Chiang, and J. Yan, “Dependence of Light-Accelerated Instability on Bias and Environment in Amorphous Indium-Gallium-Zinc-Oxide Thin Film Transistors”, ECS Journal of Solid State Science and Technology 2: Q74-Q76. (2013).