

# Revisiting the a-Si Backplane for the Next Generation of AMOLED Displays

A Florida-based startup has a new approach to AMOLED manufacturing that may soon drive costs down and adoption rates higher in many markets.

by Ian Hendy and Max Lemaitre

## Development of the OLED industry

After growing by fits and starts through the early 2000s, the active-matrix OLED (AMOLED) industry has picked up steam in the last decade to reach \$40 billion in annual revenue. The market is now forecast to grow to \$60 billion by 2025, with most of the value coming from only two market segments: smartphones (80 percent) and TVs (20 percent). The business case for OLED smartphones is strong because of their energy efficiency, wide color gamut (WCG), and excellent dynamic range, with adoption rates today at around 40 percent and moving toward 50 percent of all units. For TV, the percentages are much lower, at around 2–3 percent of units, while the TV market remains dominated by large volumes of lower value LCD sets. In other markets, such as automotive, tablets, and notebooks, OLED plays only a niche role, for cost and performance reasons. Now a Florida-based startup, Matrix Technologies (see the "History of Matrix Technologies" on [informationdisplay.org](http://informationdisplay.org)), has a new approach to AMOLED manufacturing that may soon drive costs down and adoption rates higher in all the markets mentioned.

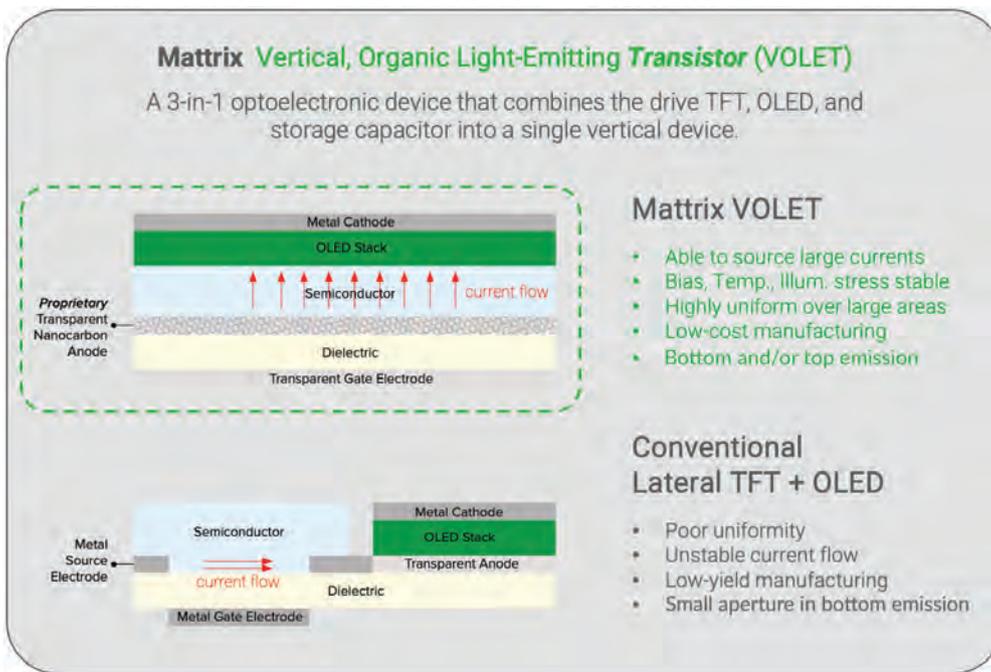
## A Pain in the Backplane

AMOLED displays are made up of emissive diodes that directly

convert electrical current into visible light. This means that OLED displays need a reliable current source to produce a stable and uniform image. While thin-film transistors (TFTs) make fantastic voltage switches for LCDs, they are not as adept at current sourcing and tend to drift in response to a voltage applied over a long period of time. The magnitude of this so-called threshold voltage shift is a measure of their bias-stress stability.

Amorphous-silicon (a-Si) TFTs have long been considered too unstable to drive AMOLED displays because of excessive shifts in threshold voltage. So, more complex and expensive backplanes solutions have been developed, including metal oxide (indium gallium zinc oxide, IGZO) backplanes for TVs and low-temperature polycrystalline silicon (LTPS) backplanes for mobile phones. However, both solutions require more factory capital expenditures (capex) and cannot match the high manufacturing yields that can be achieved with a-Si backplanes.

Moreover, IGZO and LTPS still often require compensation circuitry built into each subpixel to guarantee uniformity and stability, but this adds cost. Devoting pixel real estate to the drive circuit reduces the area that can be used for emission or forces the use of a top-emission structure, which is more costly and technically challenging. The alternative is to drive a higher current density through the OLED, but this results in unacceptably short product lifetimes. This trade-off means that OLED displays top out at a peak brightness in the 800–1,500 nits range, far lower than miniLED-backlit LCDs (LED-LCDs).

**Fig. 1.**

Matrix's vertical, organic light-emitting transistor (VOLET) architecture compared with the traditional lateral thin-film transistor (TFT) + OLED configuration.

for mobile phones but with a fraction of the mask steps.

In TV, LG Display currently uses WOLED (white OLED plus color filter [CF]) technology. Here, VOLET technology makes a compelling case by employing a high-yield a-Si backplane process, rather than IGZO, a quaternary material with a famously narrow processing window for acceptable device reliability. The VOLET also preserves the more

## How Matrix's VOLET Eases the Pain

Matrix Technologies has developed a new transistor architecture that it believes will address these issues: the carbon nanotube-enabled, vertical, organic light-emitting transistor (CN-VOLET or VOLET for short). **Fig. 1** shows a schematic of the new device architecture, as compared with the usual drive-TFT plus OLED configuration.

The vertical orientation confers several key benefits in the context of a display pixel. Because the integrated transistor now occupies the same area as the OLED itself, the current density in the channel is lower by nearly 1,000-fold. As a result, the vertical current flow is decoupled from the charge traps in the dielectric interface and thus is less susceptible to bias-stress instabilities. The implication of these two features is that even with an a-Si switching-TFT, there is no need for additional in-pixel compensation. The resulting complexity is lower, and the cost of the device—both in terms of capex and operating expenditures (opex)—is meaningfully reduced.

The integrated structure also means that less of the pixel is devoted to the non-emitting backplane components. A larger emissive area means lower current densities are required to achieve equivalent brightness levels. Therefore, a VOLET panel can reach a higher brightness without further degrading the OLED materials and can achieve a longer product lifetime.

There are two early market opportunities for VOLET-based displays: mobile phones and TV. In mobile phones, the top-end technology today is called low-temperature polyoxide (LTPO), in which manufacturers combine an LTPS transistor for sourcing the current to the OLED and an oxide transistor for the switching operation. This implementation saves power compared to LTPS alone by reducing leakage currents and drive voltages, and enables a variable refresh rate (VRR) display. A display based on an oxide-switching TFT plus a VOLET could accomplish the same

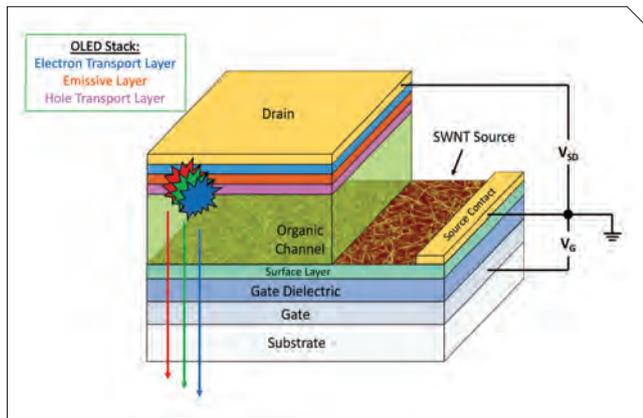
cost-effective bottom emission configuration for all TV sizes even at higher (up to 8K) resolutions. Improvements to the lifetime and peak brightness could also prove to be key differentiators.

## VOLET Technology's Background

VOLET technology has been built upon several earlier innovations and years of steady development. The first piece was the invention of transparent, conductive, thin films made from dilute networks of single-walled carbon nanotubes (CNTs) by Andrew Rinzler and his team at the University of Florida. This work was first published in 2004 in *Science*<sup>1</sup> and showed promise as a replacement for indium-based transparent conductive oxides (TCOs). At the time, concerns about worldwide indium reserves, paired with the proliferation of touchscreen mobile devices, such as the iPhone, motivated the search for alternatives. Although these CNT-based films had advantages for applications demanding high flexibility, it proved challenging to match the combination of transparency and electrical conductivity of ITO (indium tin oxide).

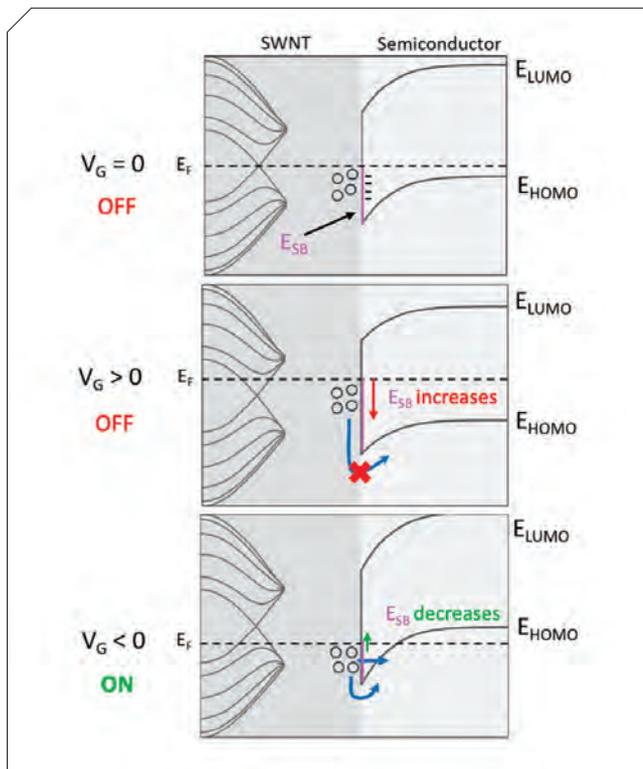
Faced with these challenges, Rinzler and his team returned to the drawing board, looking to take full advantage of the unique features of their CNT films. While most of the research community was busy trying to find ways to isolate semiconducting CNTs, the Florida team focused on the low-density of electronic states, which conferred to the films a Fermi level that could be tuned dynamically by coupling to an electric field.

It occurred to the team that if the quasi-metallic CNT film was placed into intimate contact with a semiconducting material, a Schottky barrier would form at the interface. Furthermore, applying a voltage to a near-lying gate electrode could then modulate the barrier to charge injection across the interface. This novel method for transconductance was demonstrated in a 2008 paper by lead author and Matrix co-founder, Bo Liu.<sup>2</sup>



A special feature of this new device was that it permitted the source and drain electrodes to be oriented vertically above the gate, rather than in the conventional lateral TFT architecture (see Fig. 2). In this new orientation, the channel length is defined by the thickness of the semiconducting layer. This, in combination with the quasi-3D channel, alleviates the need for a high-mobility semiconductor that typically would be required to source large currents.

This areal structure was the final piece of the puzzle. It allowed for an OLED stack to be placed directly on top of the semiconducting layer, resulting in a device that effectively combined the drive TFT, storage capacitor, and light emitter into a single, highly stable device. In 2011, the VOLET “breakthrough” was published in a paper in *Science* that demonstrated red, green, and blue (RGB) single-pixel operation.<sup>3</sup>



**Fig. 2.**

Cross-section of the carbon-nanotube VOLET (not to scale). The single-walled carbon nanotube (SWNT) network plays a central role in the operating mechanism of this novel transistor.

### More on the VOLET’s Novel Operating Mechanism

The operating mechanism of the VOLET is distinct from that of a conventional TFT. Rather than controlling the conductivity of a semiconducting channel between source and drain electrodes, in the VOLET, the gate-field modulates the amount of charge injected across a Schottky barrier formed between the source electrode and semiconducting channel.

In this device, the key to maximizing transconductance (i.e., high dynamic range, HDR) is to have good electrostatic control of both the height and width of the Schottky barrier.

The essential role played by the CNT film as a source electrode was first fully elaborated in a 2012 paper,<sup>4</sup> motivated by Mattrix CEO and co-founder Max Lemaitre. As fully demonstrated there, only a gate-field porous source electrode with a high conductivity and a low density of electronic states—a peculiar combination unique to sub-monolayer CNT films or perforated graphene—is suitable for this role.

The low density of electronic states permits the gate field to tune the work function of the CNTs, thus raising or lowering the Schottky barrier height (a feature not available to conventional metals, which possess a high density of electronic states).

The porosity of the sub-monolayer nanotube film also allows the gate-field to permeate the film and affect the charge accumulation in the semiconductor, resulting in a bending of its energy bands and thus providing control over the Schottky barrier width. In the transistor’s off-state, the barrier to charge injection is high and wide, preventing carriers from traversing the barrier. However, in the on-state, the barrier is lowered and thinned, promoting both thermionic emission over the barrier, as well as quantum tunneling through it, resulting in an Ohmic contact between the CNTs and the semiconducting channel. Fig. 3 depicts this operating mechanism.

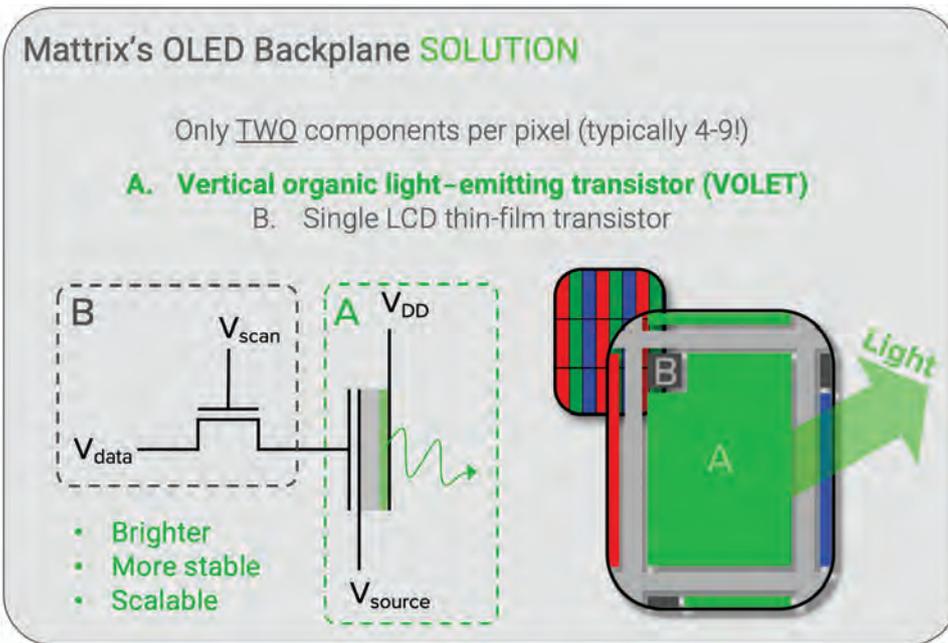
This combination of the two mechanisms enabled by the CNT source electrode and the short, vertical semiconductor channel length allows the VOLET to source large currents suitable for driving an OLED pixel and enables the more than six orders of magnitude of contrast required for HDR displays.

### Why a-Si Failed in the Past as a Backplane for OLED

As early as 2003, several groups were producing RGB AMOLED prototypes based on a-Si backplanes. However, work by AUO and others rapidly concluded that a-Si TFTs could not source sufficient currents with the required stability to drive AMOLED pixels.

**Fig. 3.**

Energy band diagram illustrating the novel operating mechanism of the VOLET.



**Fig. 4.**

New VOLET architecture. The simple Matrix pixel has higher brightness, longer product life-time, elimination of image burn-in, and flexible and transparent capabilities.

mobility semiconductor or a short channel to meet this requirement. Because submicron patterning is a nonstarter in large generation manufacturing, the industry was forced to turn to more costly measures to manufacture high mobility alternatives, such as LTPS or IGZO.

**VOLET Technology Circumvents a-Si Weakness**

The VOLET operating mechanism enables it to remain quite stable when sourcing large currents. This allows Matrix to pair a VOLET with an a-Si or IGZO-switching TFT to make a stable (two-component) pixel (Fig. 4). Matrix has not overcome the issues of a-Si mobility, stability, and uniformity, but rather circumvented them by limiting the use of these TFTs to switching. This is possible because the VOLET is essentially a gated OLED that controls the current flow, and thus light emission, in a highly stable way (Table 1).

**Adoption of VOLET in Mass Production**

The VOLET architecture requires only two additional mask steps after the a-Si backplane. Neither of these processes are novel. They require only standard equipment available in any LCD line.

The low mobility of a-Si requires a large drive TFT, which leaves little room for additional in-pixel circuitry that is required to compensate for the large threshold voltage shifts observed under prolonged bias stress.

The key distinction between those early demonstrations and the VOLET pixel architecture is that the a-Si TFT backplane is used only for the pixel-switching operation. This means that the TFTs are used as simple voltage switches rather than current sources. Conventional TFTs are generally quite good at these voltage-switching operations and have been used successfully in LCD displays for decades.

In contrast, the stability, mobility, and uniformity requirements on the drive and compensation TFTs in an OLED backplane are much more severe. To begin with, drive-TFTs must be capable of sourcing a large dynamic range of currents to the OLED stack. Conventional lateral channel TFTs require either a higher

TYPE	CONVENTIONAL APPROACH	VOLET PIXEL
Backplane used	Indium gallium zinc oxide (IGZO) or low-temperature polycrystalline silicon (LTPS)	Amorphous silicon (a-Si) or IGZO
Emitters used	<ul style="list-style-type: none"> <li>- Phosphorescent and fluorescent OLEDs</li> <li>- Quantum LED (QLED)</li> <li>- Blue OLED with quantum-dot (QD) conversion</li> <li>- MicroLED</li> </ul>	All the emissive technologies can be used.
In-pixel compensation circuit	6T+ pixel circuit (smartphone) 4T pixel circuit (TV)	No additional compensation circuitry is needed.
Type of emission	Top (cell phones and tablets); bottom TVs	Top or bottom
Typical bottom emission apertures	30-40 percent	60-80 percent

**Table 1.**

Comparison of OLED driving techniques.



**Fig. 5.**

White VOLET (WOLET) demonstrator with a color filter (CF).

The proprietary CNT source electrode and surface layer are new, but these layers will be deposited via a conventional slot-die coater. The functional material set and deposition processes have been jointly developed with partner and Matrix investor, JSR Corporation. The VOLET also has a slightly modified drive scheme, but Matrix is working with panel drive circuit suppliers to embody this modification.

### Product Demonstrators and Technology Roadmap

Matrix has worked on two different demonstrators of their technology. The first is a white VOLET (WOLET) plus CF demonstrator for TV applications,<sup>5</sup> although at a smaller size to show proof of concept. The demonstrator is a 4.7-inch 320 × 240-pixel demo at resolution of 85 dpi. This was built based on a standard a-Si LCD backplane from a small Japanese contract fabrication plant. **Fig. 5** is a still image of the first WOLET prototype operating video.

A second demonstrator is currently in the works to illustrate a replacement for LTPO in mobile phone applications, which is currently monochrome. It is being produced in collaboration with the Samsung Advanced Institute

**Fig. 6.**

Economics of implementing the VOLET for TV and mobile applications.

of Technology in Korea and aims to demonstrate lower-power operation and variable refresh capability for high-end AMOLED applications.

Both demonstrators show that this technology is feasible and promising. The WOLET demonstrator shows off the technology well, and there are no anticipated technical issues for scale-up to Gen 8 or Gen 10 for full-scale TV panels. For the LTPO replacement demonstrator, the next step would be a full-color version. The roadmap then is to complete the equipment and process engineering, and work on driving schemes to provide a turnkey solution for adoption by the industry.

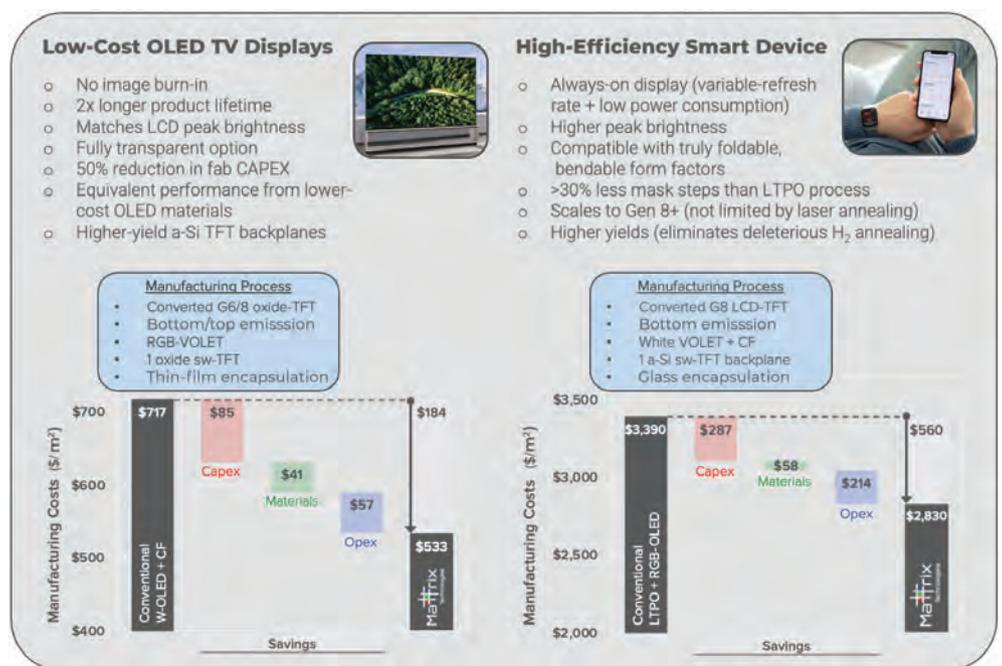
### Key Economic Benefits of the Technology

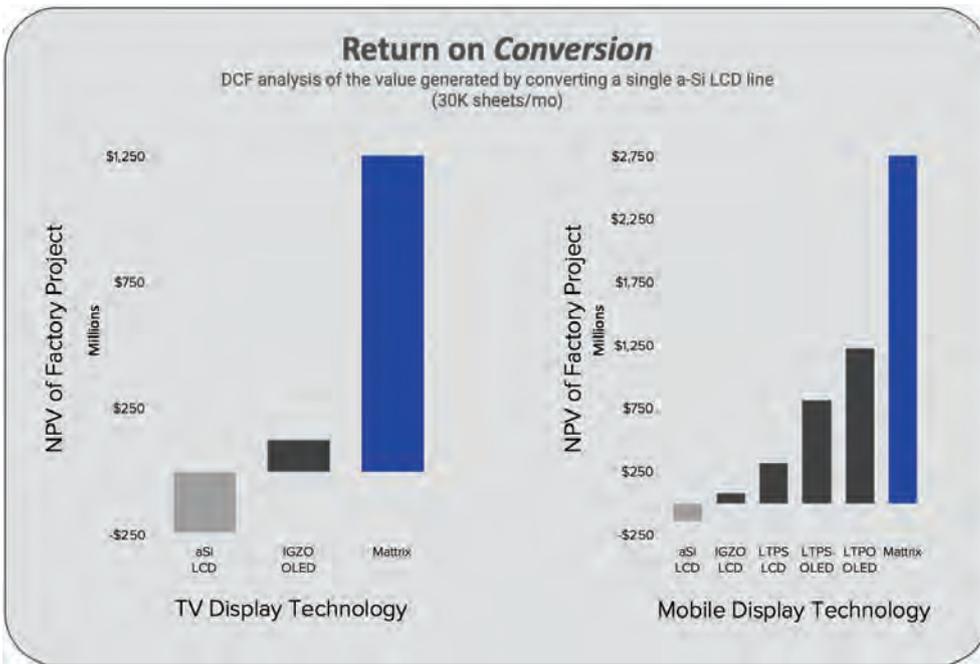
The economic benefits of this technology are striking. There are substantial cost savings in both capex (through backplane simplification and the move to lower cost backplanes in each case), as well as opex (factory overheads and material cost savings).

Here, we show two different cases: one based on WOLET + CF for TV applications and one based on the LTPO-replacement for the mobile product case (**Fig. 6**). The numbers are persuasive for both cases.

The WOLET TV plan delivers a 25 percent overall cost saving on a WOLED TV panel, built on a converted Gen 8 a-Si LCD fab. The product is produced using VOLET technology, which is higher performing with twice the product lifetime compared to today's WOLED displays.

Similarly, the economics for LTPO replacement panels are just as impactful, with a 15-percent reduction in total product cost (shown here on a per m<sup>2</sup> basis). The technology shown is a bottom-emission RGB-VOLET produced on an IGZO line converted from a Gen 6 a-Si LCD fab.





**Fig. 7.**

Net present value (NPV) of converting an a-Si line.

can be substantially increased up to 5-10x higher using VOLET technology (Fig. 7). The technology is relevant and adoptable in all types of fabs, since as demonstrated, it can use even a-Si backplanes (Table 2). Top emission or bottom emission does not matter. It can also be adopted for new QD-OLED-type technology from Samsung.

The VOLET approach uses a proprietary CNT source material, but this is available from a major, trusted industry materials supplier, JSR. The driving approach is a little

### Implications for the Industry

Implications for the industry are substantial. This represents a huge reduction in the cost of making OLED displays and in the level of manufacturing sophistication needed for entry into the OLED market. The improved economics in both capex and material cost results in substantially improved net present values (NPVs) for investment projects into fabs, as based on analysis and pricing in 2020.

Based on a common set of product assumptions in each case, the NPV of a single 30,000 substrate/month fab investment

different, but this will be implemented in available integrated circuits (ICs). From a factory fab perspective, the approach is straightforward, using only processes and equipment.

### Summary

VOLET technology offers a major simplification in the process of manufacturing OLED displays. For the first time, a-Si is a viable option for the AMOLED backplane. This means a radical cost reduction, as well as a reduction in the technical challenge for

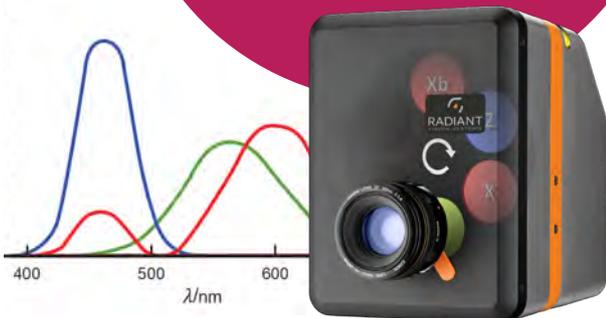
COMPARISON AREA	OLED TODAY	OLED IN FUTURE
Backplane needed.	IGZO or LTPS, both of which are challenging	a-Si; simple
Capex is needed (TV) for green-field fab and conversion (30,000 substrate/month Gen 8).	Gen 8 WOLED: \$1.8B	G8 WOLED VOLET: \$1.7B or about \$800M to convert from a-Si LCD fab
Capex is needed (mobile) for greenfield fab (30,000 substrate/month Gen 6).	Gen 6 LTPO: \$2.7B+	G6 IGZO VOLET: \$2.1B or \$1.7B from the IGZO LCD line
Overall complexity	Complexity in backplane and frontplane operations	Backplane much simpler. Frontplane challenge is the same.
Players	Only a small number are truly capable (2-4 globally), while Chinese players are working hard at the technology.	Could be much more pervasive, with almost anyone able to make an a-Si now potentially an OLED player.
Products	TV + Phone	TV + phone iPad and notebook

**Table 2.**

Implications for the industry.



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industry participants in OLED. The addressable market is all fabs, installed and greenfield, and may well lead to additional OLED conversion for IT products.

As noted in the introduction, two categories of product—tablets and notebooks—in AMOLED adoption are constrained by cost and low brightness levels. Matrix technology addresses both issues and is scalable to the Gen 8 fabs typically used for these products. As such, the primary implication of this new technology may be further growth in smartphone, TV, and IT products. By reducing one of the main technological barriers to entry, many new market entrants may convert LCD fabs of all sizes to compete in the AMOLED space. 

### References

- Wu, Z., Chen, Z., Du, X., Logan, J.M., Sippel, J., Nikolou, M., Kamaras, K., Reynolds, J.R., Tanner, D.B., Hebard, A.F., & Rinzler, A.G. (2004). Transparent, conductive carbon nanotube films. *Science*, 305 (5688), 1273–1276. <https://doi.org/10.1126/science.1101243>.
- Liu, B., McCarthy, M.A., Yoon, Y., Kim, D.Y., Wu, Z., So, F., Holloway, P.H., Reynolds, J.R., Guo, J., & Rinzler, A.G. (2008). Carbon-nanotube-enabled vertical field effect and light-emitting transistors. *Advanced Materials*, 20 (19), 3605–3609. <https://doi.org/10.1002/adma.200800601>.
- McCarthy, M.A., Liu, B., Donoghue, E.P., Kravchenko, I., Kim, D.Y., So, F., & Rinzler, A.G. (2011). Low-voltage, low-power, organic light-emitting transistors for active matrix displays. *Science*, 332 (6029), 570–573. <https://doi.org/10.1126/science.1203052>.
- Lemaitre, M.G., Donoghue, E.P., McCarthy, M.A., Liu, B., Tongay, S., Gila, B., Kumar, P., Singh, R.K., Appleton, B.R., & Rinzler, A.G. (2012). Improved transfer of graphene for gated Schottky-junction, vertical, organic, field-effect transistors. *ACS Nano*, 6 (10), 9095–9102. <https://doi.org/10.1021/nl303848k>.
- Matrix Technologies, Inc. (2021, August 12). Matrix Technologies demonstrates the world's first WOLED display produced using LCD TV manufacturing technology. <https://www.einpresswire.com/article/548628383/matrix-technologies-demonstrates-the-world-s-first-wol-ed-display-produced-using-lcd-tv-manufacturing-technology>.



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He completed a Ph.D. degree from the University of Florida in 2013, where he co-founded Delta R Detection. His subsequent work on source-gated, vertical field-effect transistors helped unravel the novel operating mechanisms behind Matrix Technologies' CN-VFETs and VO-LETs. Lemaitre can be reached at [max@matrix.com](mailto:max@matrix.com).

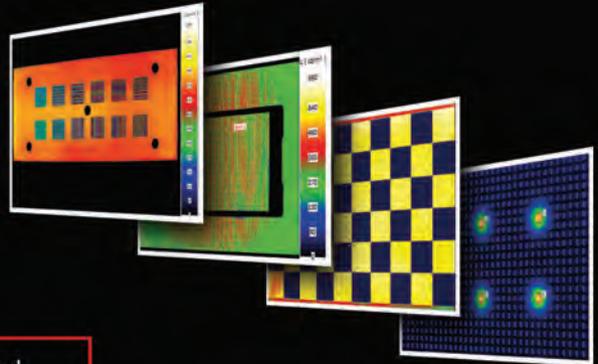




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