Beyond the curve to foldable displays

Lightweight, unbreakable, flexible and wearable; these are just a few of the development targets for contemporary consumer electronics. Over the past couple of years interest in flexible displays that meet these needs has increased significantly, with the market for this flexible display technology predicted to expand to more than $21billion by 2020[1]. Dr. Michael Cowin, Head of Strategic Marketing, SmartKem Ltd looks at the opportunities ahead.

FEW INDUSTRIES have the same rate of development as the electronics sector. Buoyed by consumer demand for fresh innovation and fierce industry competition, electronics development exists in a rapid cycle of continuous improvement. One of the most exciting and eagerly awaited outputs from this process is the development of bendable and flexible displays; a potentially transformative technology set to emerge over the next few years.

Curved displays are already available in the commercial space, with the more recent emergence of curved phones and television screens. Yet despite their novelty, the real 'wow' factor in the consumer experience has yet to be achieved. The value in the next generation of smart and wearable technology will come with the introduction of flexible and foldable devices such as smartphones, tablets and watches. However, this demands a new semiconductor platform with entirely new physical properties and form factor capability which in turn raises a unique set of challenges for traditional and new thin-film transistor (TFT) technologies to overcome.

Significant developments in electronic devices almost always require a corresponding advance in their functional components and materials. Leaps in processing power, for instance, have often occurred due to the emergence of increasingly smaller and denser transistors. In contrast, the rise of thin-film electronics has relied on the development of TFT technology with increasingly stable and uniform properties over wide areas.

These properties are in increasing demand; however the challenge now lies in ensuring the transistors also demonstrate true physical flexibility. This is set to become a key market driver, with organic semiconductors beginning to change the landscape of traditional TFT based platforms.

Organic semiconductors now deliver similar, and in most cases superior, properties to traditional inorganic devices, but with much improved physical flexibility.

Organic based TFTs (OTFTs) are already starting to penetrate the supply chain for the development of truly flexible Active Matrix Organic Light Emitting Diodes (AMOLED) displays and Electronic Paper Displays (EPD).

Indeed OTFT technology is now being seriously considered as a straight replacement in amorphous silicon (a-Si) lines for the manufacture of plastic, lightweight and ruggedised LCDs.

Figure 1: The evolution of flexible electronic devices has required a new approach to development, typified by the emergence of high performance organic semiconductors.

Furthermore the utility of organic semiconductors as a platform technology is set to play a pivotal role in how we see, touch and sense information in every aspect of our lives. This combined with the shift towards Big Data, The Cloud and the Internet of Things will drive flexible and adaptable technology fully into the mainstream in the form of a new generation of displays, touch screens and sensors.

Understanding organic semiconductors: Smart chemistry for smart electronics

Traditional inorganic TFT semiconductors are formed from amorphous or polycrystalline structures and as such are unable to meet the market demands of robust flexibility. In the case of Low Temperature Polycrystalline Silicon (LTPS), for example, the poly-crystalline network is partially responsible for the semiconducting properties but is also the root of the material's inflexibility.
Organic semiconductors are fabricated from small organic molecular species, polymers or a combination of both which allows them to overcome this fundamental limitation through their intrinsically flexible nature; offering the potential of ultra-flexible displays that can be folded to a sub-millimetre bend radius with no change in TFT performance.

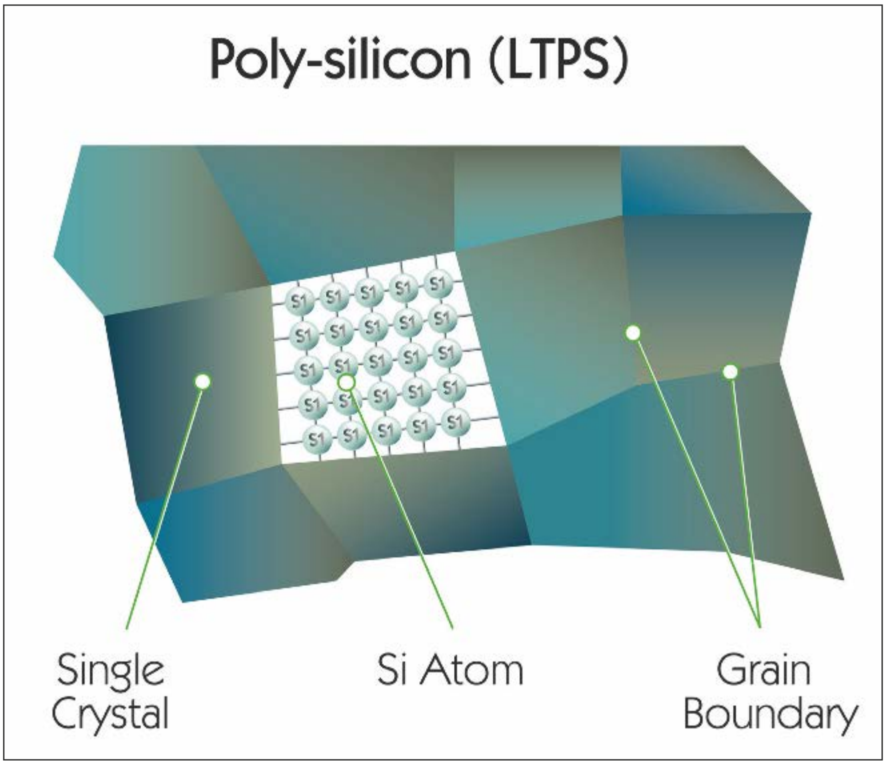

Image courtesy of AUO

This end product advantage is further complemented by a range of additional benefits such as a high mobility performance and a potential cost down proposition to manufacturers through ease of processing, higher yields and increased throughput achieved via low temperature processes such as Sheet-to-Sheet and eventual Roll-to-Roll (R2R) print techniques.

Organic semiconductor technology generally fits within two main material categories: polymeric and distinct molecular materials. A common feature of both is that they are types of conjugated systems, meaning they consist of alternating single and double bonds which lower the overall energy of the molecule and increase stability.
Efficient device operation can be ensured by matching the highest electron energy level of the organic semiconductor to the work function of a metal contact. For high performance TFTs, high charge carrier mobility is required which naturally favours crystalline small molecule semiconductors; molecules that are closely packed with regular arrangement in a crystal lattice increase good π-bonds and therefore efficient charge carrier mobility.

A new class of organic semiconductor materials eliminate such issues by designing into solution based semiconductor 'inks' the preferred features of chemically stable, high mobility, single-crystal organic semiconductors and combining them with amorphous semiconducting polymers or 'binders'. This material combination offers the electrical performance of single crystals but with the uniform processing characteristics required for high mobility.

As such the key benefits of organic semiconductors are realised with a technology platform that offers ease of production coupled with superior physical and electrical semiconductor performance in end-product form.
Although organic semiconductors can be stable up to 300°C the ease by which these solution-based materials can be processed at low temperatures offers manufacturers a wide range of cost effective stack materials and substrates, and easier bond/de-bond and inter-

Characteristic	a-Si	LTPS	OTFT	Oxide
Flexibility & Fold Capability	✗	✗	✓✓	✗
Route to stretch-ability	✗	✗	✓✓	✗
Low Temperature Process	✗	✗	✓✓	✗
Print Compatibility	✗	✗	✓✓	✗
Mobility	✗	✓✓	✓	✓
Bias Stress Stability	✗	✓✓	✓✓	✗
Low Cost of Ownership	✓✓	✗	✓✓	✓
Established Supply Chain	✓✓	✓✓	✓	✓
Suitable for Wide Area	✓✓	✗	✓✓	✓
Reproducibility	✓✓	✓✓	✓	✗

Figure 2: The different TFT characteristics

layer alignment due to less expansion and contraction. This all adds up to significantly improving production yield (over high temperature processing) and thereby reducing production costs over any area of substrate.

One company leading the development of organic semiconductors is SmartKem with its product *tru*-FLEX™. While the electrical performance of *tru*-FLEX™ exceeds the need for applications such as AMOLED, LCD and EPD - more critically, the resulting TFTs are almost unbreakable, exhibiting flexibility down to a highly acute bend radius, thus eliminating the need for exotic and costly strain management layers. This offers original equipment manufacturers a high degree of confidence in product performance making the SmartKem *tru*-FLEX™ material a key component for highly rugged and reliable flexible display applications such as mobile and wearable devices.

Easing the printing processes

In addition to being the only truly flexible technology currently available, one of the major advantages of organic semiconductors comes from their ease of application. Solution based semiconductor inks can be applied to substrates through a range of additive processes and print production systems, including slot dye, spin coating and inkjet printing.

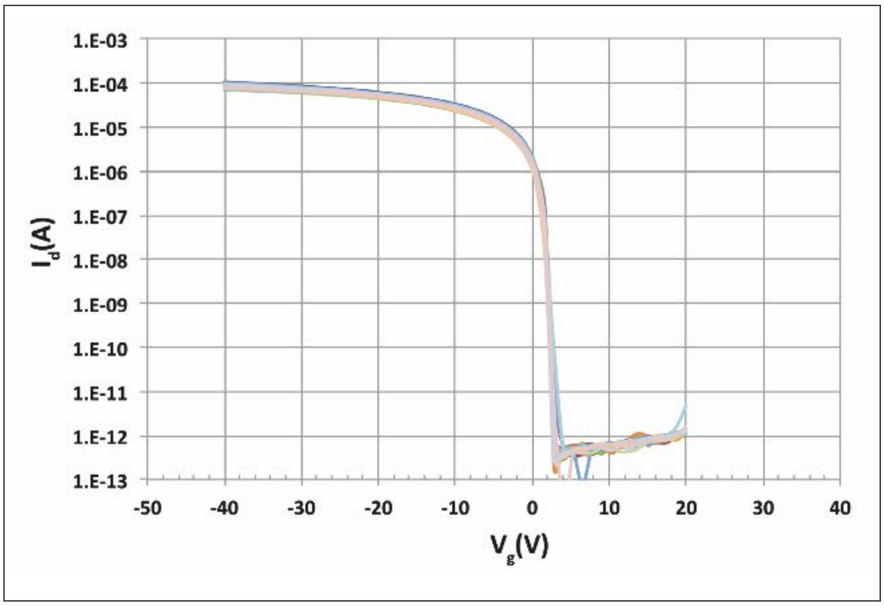

Figure 3: Typical linear transfer curves for SmartKem's tru-FLEX™ TFTs
x-axis : VG (V) y-axis : ID(A)

This application flexibility, along with the improvements in final product quality, process control and overall efficiency, make organic semiconductors an attractive prospect for manufacture. Organic semiconductor ink coatings are also compatible with R2R processing. Here, semiconductor materials are continuously or near continuously patterned onto a wide substrate area.

This high throughput process enables semiconductor fabrication and coating at a fraction of the time and cost of traditional manufacturing methods. Although still in its infancy, combining organic semiconductors with a scaled up R2R fabrication process is considered a realistic and incredibly lucrative prospect. For this reason many consider R2R processing the ultimate goal for electronics manufacture and organic semiconductors a critical component to achieving this.

The next generation of electronics

From displays and augmented touch screens to sensors, organic semiconductors are set to play a pivotal and diverse role in this new generation of electronics. Meeting the demands of this growing market requires developers of organic semiconductors to push boundaries in terms of the electrical performance and dynamic physical characteristics of these materials in TFT form. In response to this technological advancement the IEC standards for electronics are being re-written and re-defined to standardise every facet of this new industry.

Printable organic semiconductors have made the transition into pre-production and are enabling electronics manufacturers throughout the industry to make new and exciting form factor displays and products that will overhaul the current consumer world. And it's all a lot closer than you think.

Reference

[1] Flexible Displays technology and Market Forecast Report, September 2014, DisplaySearch