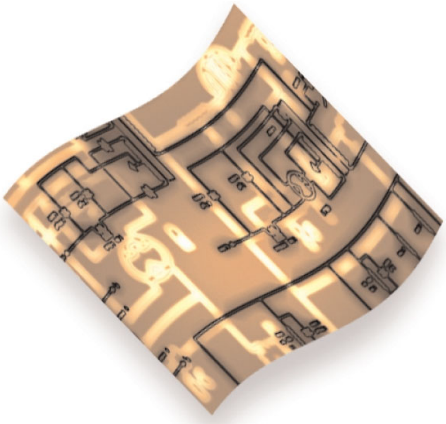

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IDTechEx

Printed Electronics White Paper

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Technology Overview and Applications

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Printed Electronics, typically being thin film silicon or inorganic or organic semiconductors, can be used to form Thin Film Transistor Circuits (TFTCs), such as replacing the functionality of simple silicon chips. TFTCs also employ thin film conductors and dielectrics and the ultimate objective is to make many different components at the same time – such as displays, batteries, sensors and microphones – using the same materials or at least the same deposition techniques thus saving cost and improving reliability.

Some TFTCs will be capable of covering large areas to affordably form electronic billboards, smart shelves and so on. They will be lightweight, rugged and mechanically flexible. Often they will be made by rapid, high-volume, reel-to-reel processing – even forming a part of regular printing processes for graphics. These circuits will be cheap enough to permit electronics where envisaged silicon chips are almost always too expensive, where multiple components are needed, and where silicon is impractical, i.e. when it's not flexible, too brittle or too thick.

Applications of Printed Electronics

Less than six decades from its discovery in Bell Labs, the use of silicon as a semiconductor for electronic components has indeed been impressive, now applied ubiquitously from computers to telescopes, and from spacecraft to toys.

The volume of silicon-based components is increasing, as is its performance, following the famous Moore's Law theory for computing – the number of transistors on a silicon chip doubles every 18 months. However, challenges that this demand brings can no longer be ignored: R&D spend is increasing at approximately the same rate as Moore's law too. New silicon fabrication plants cost in excess of $3 billion; the cost of the cheapest silicon chip for the past twenty years has been typically 5-10 US cents; and despite developments in computers-on-chips, external power, resistors, capacitors and other components are still needed, meaning interconnects are required and hence more cost, process stages and areas of failure.

Other semi-conductive materials

Now over 50 companies, from start-ups to blue chips, are working on an alternative by using the semi-conductive properties of other materials such as organic semiconductors (e.g. conductive plastics) and inorganic semiconductors (e.g. carbon nanotubes). Organic semiconductors, the most popular of the flexible electronic options so far, are based on large or small molecule plastics which are conductive. They can be deposited to form a functional transistor, and ever more functional and complex circuits. They can be printed using high resolution printing processes such as inkjet printing, lithography, gravure; and unlike silicon, other components such as batteries, sensors, displays, etc, can be printed using similar materials and processes.

Other than these, two key benefits of printed electronics are:

1. Materials and manufacture costs are very low
2. Circuits can be deposited onto flexible substrates such as plastic film and foils.

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HIGH COST HIGH FREQUENCY	→		LOW COST LOW FREQUENCY
Continuous grain polysilicon, nanoparticle structures or microcrystalline silicon	Conventional polysilicon	Amorphous silicon, other inorganic (e.g. carbon nanotube or metal particles) or insoluble (e.g. small organic molecule)	Soluble eg. polymer
			Source: IDTechEx

Figure 1 – The options for semiconductor materials to make TFTs on low- cost flexible substrates

However, their performance, being several magnitudes less than that of silicon, currently limits their capability – don't expect printed Pentiums any time soon.

Printed electronics instead offer the possibility of using electronics in applications where the cost of silicon would have made it impossible or where silicon properties – such as size or rigidity – are inadequate. Suitable applications include either "small area" electronics such as the electronic sensors and the changing use-by date on a pack of meat or medicines; "large area" electronics such as billboard size electronic displays, solar cells, lighting and sensors; or where flexible circuits are needed, for example: displays for computers, signage and posters where the flexibility of the display adds much needed robustness.

Technology Overview

Semiconductor choices

The options for semiconductor materials to make Thin Film Transistors TFTs on low-cost flexible substrates are shown in figure 1, as a function of cost and frequency.

The quest for higher frequency TFTCs

The frequency of Thin Film Transistor Circuits TFTCs is being improved for some applications where high speed data transfer is needed, such as RFID tags.

TFTC frequency is controlled primarily by the following three parameters:

1. Channel length (source to drain),
2. Voltage,
3. Carrier mobility.

Of these, there is some scope to improve the physical dimensions by improving low-cost ink jet or roll-to-roll printing. There is little scope to increase voltage because of need for insulation, compatibility with other components etc. With mobility there is scope for improvement of materials and constructions for TFTs and there are also compromises to be chosen. There is a spectrum of choice from a very-low-cost process but with poor mobility to the opposite. See table 2 for typical current performance.

To achieve small channel length

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Table 1 – Market needs relevant to low-cost laminar transistor circuits

Application	Potential yearly	Comment
Active matrix drive circuits for OLEDs.	A few billion.	Usually rigid substrates but flexible opens up new markets. Organic LED (OLEDs) offer improvements in brightness, viewing ratio and power consumption over conventional TFT flat screens. Driver circuits require large numbers of transistors with the same design.
RFID tags.	Ultimately ten trillion.	Usually flexible substrates. Need to reduce the cost to one US cent or less by removing the silicon chip.
RFID interrogators.	Tens of millions.	Smart shelves etc. Flexible substrates would be useful.
Other	Ultimately perhaps one hundred billion.	Talking, singing, flashing and voice and event recording cards, toys and smart packaging etc. Patient compliance monitoring (blisterpacks), control of active packaging (fragrance emitted when you approach) and many other safety, fraud prevention, merchandising and other features. Flexible substrates preferred.
		Source: IDTechEx

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Table 2 – Typical carrier mobility in different TFTC semiconductors (actual and envisaged). Single crystal silicon may have a figure of up to 1,000 cm2/vs but it is not currently envisaged as a TFTC material.

Semiconductor material	Approximate Mobility (cm^2/vs)
Polysilicon thin film on polymer film	50
Amorphous silicon thin film on polymer film	2
Insoluble organic compound (usually small molecule) vacuum deposited on polymer film	2
Soluble organic compounds – usually polymer but small molecule precursors also studied – printed on polymer film or paper (lower mobility)	0.2
	Source: IDTechEx

Figure 2 – Options for high speed, low-cost printing of TFTCs

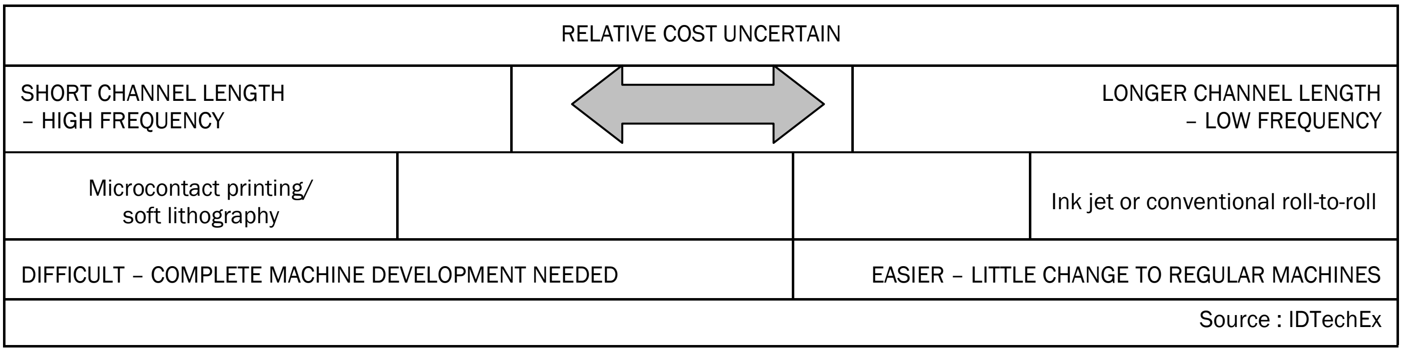
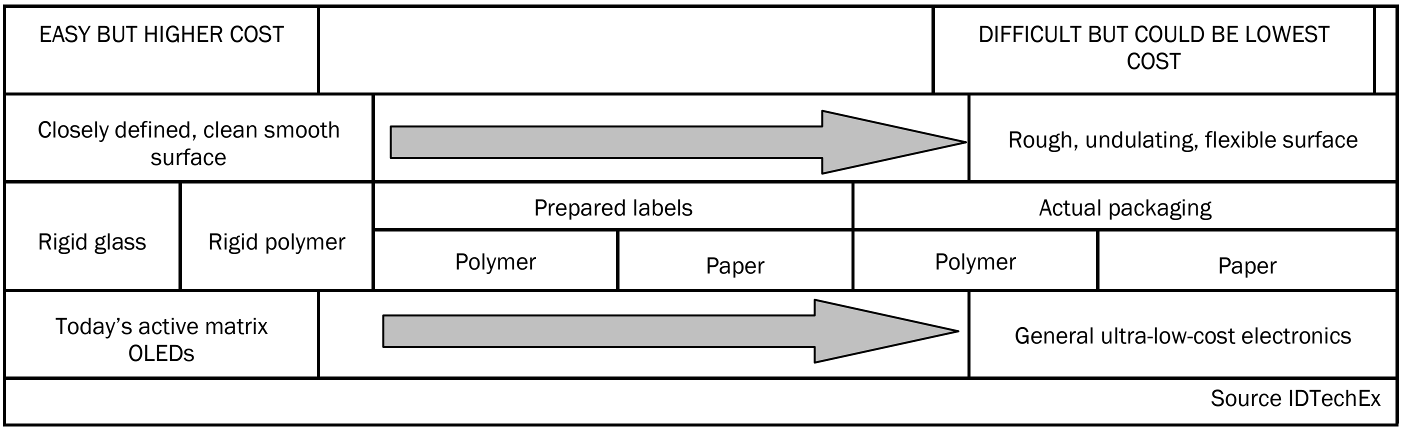


Figure 3 – Evolving level of difficulty of substrates in creating low-cost TFTCs



the primary options are shown in figure 2, given that photolithography is not likely to become a very low-cost roll-to-roll process.

The compromises in choosing substrates

With TFTC manufacture there is a progression from easy but relatively unsaleable substrates to difficult but biodegradable, widely useful lowest cost ones as shown in figure 3.

Value chain for TFTCs

The value chain expected for TFTCs, as they start to be sold, is shown in figure 4, where we also show how some parts suppliers are tempted to move downstream to increase their returns. This is particularly true where they already have appropriate activity. For example, Dai Nippon Printing and Toppan Printing have major packaging operations and seek to print electronic circuits in their packaging for various purposes.

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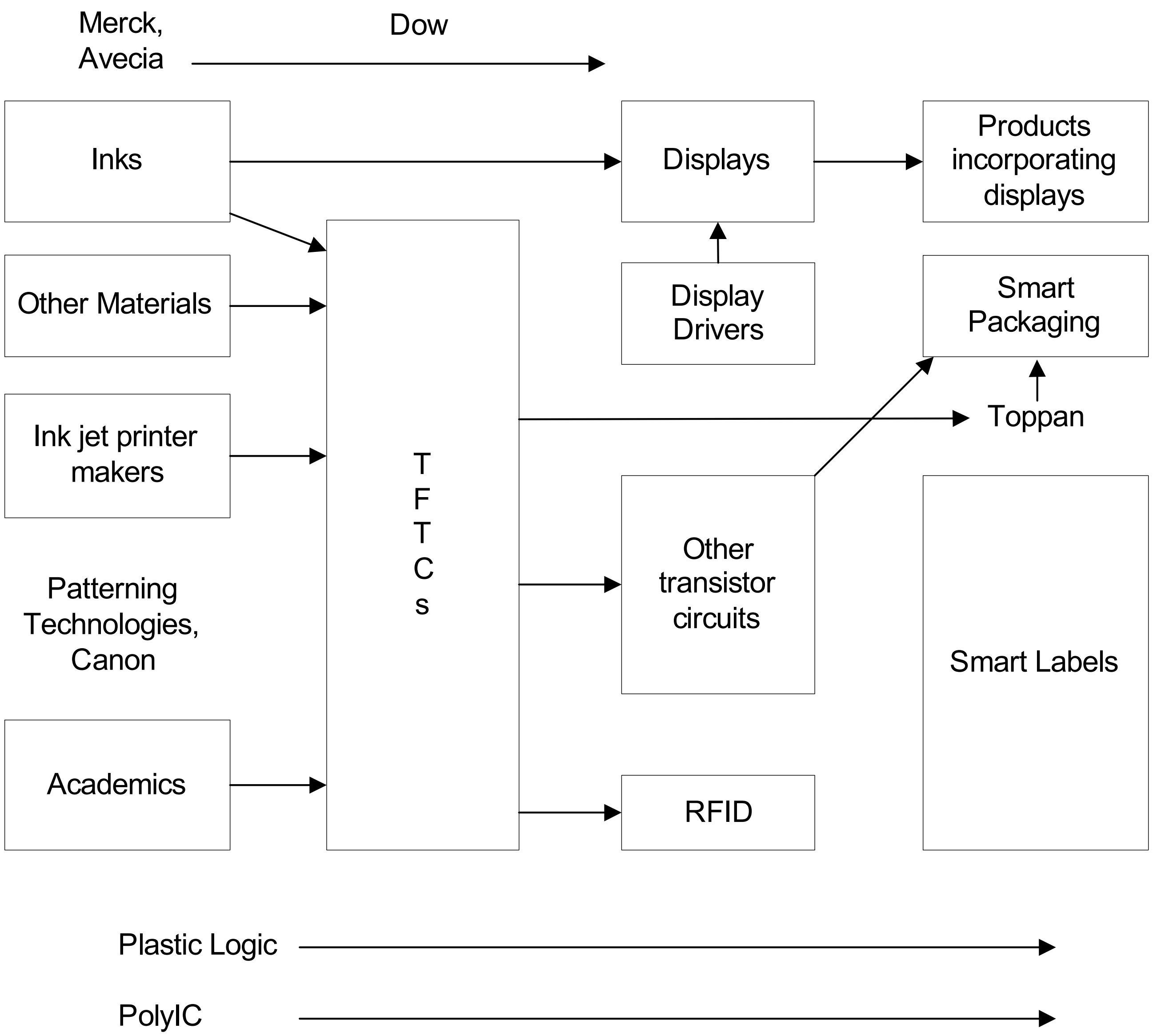
Figure 4 – Value chain for TFTCs and examples of migration of activity for players



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