



ICT Sector Focus Report

Printed Electronics

April 2010

Disclaimer

The information and opinions in this report are based upon information available to the public. The content of this report has been prepared as a result of the desk research done via existing literature and publicly accessible web pages, as well as expert interviews. The information herein is believed by the authors to be reliable and has been obtained from sources believed to be reliable. The report was refereed by an expert panel. The publisher, the authors and supporting organisations make no representation as to the accuracy or completeness of such information. The information given in this report is intended to be as accurate as possible at the time of publication. Opinions, estimates and projections in this report constitute the author's judgment and are subject to change without notice.

This report is provided for informational purposes only. It is not to be construed as an offer to buy or sell or a solicitation of an offer to buy or sell any financial instruments or to participate in any particular trading strategy in any jurisdiction in which such an offer or solicitation would violate applicable laws or regulations. The information contained in this document is published for the assistance of recipients but is not to be relied upon as authoritative or taken in substitution for the exercise of judgement by the recipient. The publisher, authors and all supporting institutions assume no responsibility for any losses or damages that might result because of reliance on this publication. The publication is not intended to be used as a legal or accounting advice, nor should it serve as corporate policy guide.

The copyright of this document is reserved by the authors.

Contents

1	Executive summary.....	4
2	Introduction	6
2.1	Definition	6
2.2	Overview	7
2.3	Methodology.....	9
3	Science and Technology Aspects	14
3.1	State of R&D	14
3.2	Printed electronics with nanoscale features	15
3.3	Additional demand for research.....	17
3.4	Applications and perspectives	20
3.5	Current situation within the EU.....	25
4	Economic aspects.....	27
4.1	General market description	27
4.2	Drivers and barriers	28
4.3	Selected company profiles.....	29
5	References	31
5.1	Selected list of experts.....	31
5.2	Other References	31

1 Executive summary

Printed electronics creates electrically functional devices by printing on variety of substrates. Compared to conventional manufacturing of microelectronics, printed electronics is characterized by simpler and more cost-effective fabrication of high and low volume products. Despite its many benefits, to date the performance of printed electronics in terms of the actual function and reliability is less than that of conventional electronics.

This report considers two aspects of printed electronics that relate specifically to nanotechnology. First, printed electronics can use different so-called nano inks. This report deals with the state-of-art of metal nano inks and carbon nanotube inks but will not go into detail of the methodology of nanomaterials, for these the reader is referred to the Materials report .

Secondly, at least in laboratory scale, printed electronics can be printed at nanoscale features. Experts currently believe that nanoscale features will be possible to print with Flexography printing, Gravure printing Inkjet printing and Nanoimprint lithography. It is also possible to create nanoscale features using different laser methods, but those are beyond the scope of this report.

One of the biggest current challenges facing printed electronics lies in the materials used for printing: currently there are only few substrates available. There are many nanomaterials and nanoparticles but few researchers are formulating these into printable solutions (functional ink).The use of functional materials and nanoparticles in inks has broaden the scope of applications that printed electronics enables. Suppliers formulating novel functional inks and setting up high-volume ink manufacturing facilities will in the near future have an important role in the development and commercialisation.

Another challenge lies in developing the processes themselves for real mass-manufacturing. Currently they are mostly “hand-made” prototypes with many parameters that need to be optimised. The price of the system is also still too high. Yield is another big question mark in mass-manufactured real applications. Experts believe that it will be a combination of different methods that will finally be used for manufacturing printed electronics. More application focused research on combining different methods is needed. Some experts believe that inkjet and nanoimprint has the highest potential for the creation of nanostructures - but time will tell.

The biggest bottleneck of all is the definition of what kind of value adding applications are needed. Currently, the vast majority of current information and communication technology (ICT) applications do not require nanoscale patterning. However, according to our web-based questionnaire answered by 33 experts, there is an ICT market need for printing of nanoscale features with the assessed technologies. The experts do not believe that the first nanoscale featured products have entered the market yet.

Printed electronics enables applications in almost all industry sectors. According to expert opinion, RFIDs and sensors are so far the most interesting targets but biocompatible electronics, batteries, displays and LEDs are also soon to be seen.

From an economic point of view, printed electronics is one of the current fields where the hype in R&D should be turned into business. According to expert opinion the use of flexographic and gravure printing for making nanoscale features is still at the fundamental research stage. Experts believe that products using nanoimprint lithography will enter markets at the same time as those using inkjet technology, in approximately 4 years. Furthermore, our questionnaire shows that experts believe that mature markets for printing of nanoscale features are expected to be reached in 7-10 years. According to a recent UK report (2009), made by the Department for Business Innovation & Skills (BIS), the market value is forecast to rise from \$2 billion in 2009 to \$120 billion in 2020.

If successful, new types of multidisciplinary cooperation will emerge to drive renewal of industry with printed electronics. Because printing usually makes the whole device at once, changes are also expected to be seen in the manufacturing value-chain as well. Identifying companies working with printed electronics is difficult as it still the technology is at such an early market phase.

To conclude, it is important to remember that the end users will not care about the printing processes used as long as the product price and functionality satisfy their needs. First, it is important to understand whether there is a need for printed nanoscale features.

2 Introduction

2.1 Definition

Printed electronics creates electrically functional devices by utilising of traditional printing processes and broad range of substrates. So far the most common substrates are polymer films, ceramics, glass and silicon. Printing of functional devices on paper is also possible. In contrast to the terms organic electronics, printed electronics can utilise any solution-based material, including organic semiconductors, metallic conductors, nanoparticles, nanotubes etc.

In other words, printed electronic devices comprise solution-processable electronic materials deposited with a printing method. Printing processes include processes well known from the graphics art industry such as screen printing, flexography, gravure, offset lithography and inkjet. With printed electronics functional electronic or optical inks are used to print active or passive devices, such as transistors or resistors.

Examples of printed electronics components include e.g. electrodes comprising printed metal particle ink, carbon ink or conductive polymers or diodes and transistors comprising printed organic semiconductor and dielectric layer(s).

2.1.1 Benefits and trade-offs

Compared to conventional microelectronics, printed electronics is characterized by simpler and more cost-efficient fabrication of both high and low volume products. It enables roll-to-roll fabrication and the processes employed to manufacture printed electronics also are more flexible, enabling shorter production runs. Very small series, customised or even unique products are possible through a digital printing process. Another advantage is its processing at low-temperatures. The substrate is a solution which is printable and coatable enabling also flexible products. The additive processes might prove to be more environmentally friendly.

Despite its many benefits, to date the performance of printed electronics in terms of the actual function and performance is reduced compared to that of conventional electronics. It is therefore believed that printed electronics will complement, rather than compete with silicon based electronics.

Printed electronics is expected to be useful for applications for low-performance but also low-cost electronics. The applications will be also new electronics products for traditionally non-electronic applications such as smart labels, decorative and animated posters, and active clothing. They are also targeting large area products, flexible products, non-flat shaped products such as flexible displays and sensor walls.

2.2 Overview

Printed electronics can be divided into two subtopics. First is the material used for printing: the inks. These can either be conductors, dielectrics, resistors or semiconductors. Second is the printing technology used, the most common being inkjet, screen printing, gravure, offset and flexographic printing. Some examples of each of the subgroups are shown in the list at the end of this section. Because the scope is wide, the rest of this report will primarily deal with printing intelligence from a nanotechnology perspective. The applications focus on ICT.

Inks – Material for printing

Conductors

- Conducting polymers
- Metal flakes
- Metal nanoparticles (e.g. Silver, Copper, Gold)
- Metal-organic/metal-salt precursors
- Carbon nano tube inks

Dielectrics => capacitors

- Inorganic oxides
- Polymers
- Self-assembled monolayers
- Heterogeneous organic/inorganic mixtures

Resistors

- Carbon films

Others include e.g. Catalytic materials, Optical materials, and functional polymer materials.

Manufacturing methods

Note: It is likely that a combination of those mentioned below will be used

Mass-printing methods/ Roll-to-roll: currently throughput of several 10.000 m ² /h	Flexographic printing	<ul style="list-style-type: none"> • Relatively cheap start-up due to use of rubber plates. • Incompatibility problem. Conventional plate materials (polymers) are not very compatible with “new” solvent systems used in printed electronics
	Gravure printing	<ul style="list-style-type: none"> • Allows printing of films with a wide range of thicknesses from 50nm to 5 μm • Good scalability of line width • Achievable high layer quality, high resolution/W
	Offset printing	<ul style="list-style-type: none"> • Excellent control, fast high-volume production. • High-resolution • High start-up cost and start-up waste volumes • Very specific ink formulations are needed
Sheet-fed printing methods	Inkjet printing	<ul style="list-style-type: none"> • Most widely used today • Possible to use a wide range of substrates • Dominates research into printed transistors • Manufacturing viability still unclear • Throughput ~ 100 m²/h and limited resolution (micro scale) <ul style="list-style-type: none"> ○ using multiple heads in parallel => yield problems • Drying phenomena important • Much cheaper than photolithograph process or vacuum processes. • Does not require any masks or template and can realize on-demand manufacturing • Low viscosity and low concentration ink formulations
	Screen printing	<ul style="list-style-type: none"> • Rather inexpensive • Highly flexible

		<ul style="list-style-type: none"> • Print layers ~20-100 μm • Limited resolution and throughput and line roughness compared to R2R • Most mature, has been used in some limited applications such as printing interconnections • Can be roll-to-roll as well
Step-by step printing/New methods	Stamping / nanoimprinting	<ul style="list-style-type: none"> • Similar to gravure printing • Patterned master is used to transfer a pattern onto a substrate • “Too early to comment their manufacturability”
	UV Lithography	

2.3 Methodology

Printed Electronics is an additive processing method, whereby a functional material is deposited in a controlled manner to print the desired pattern without wasting the material. In contact printing methods (flexography, gravure, offset lithography, and screen printing) the image carrier has direct contact with the substrate. These methods are the most commonly used.

In the following the methodology and components of each of the most commonly used methods are described shortly [the following is adapted from Caglar,2009]

Flexography – see Fig 1

- 1. Printing plate: Prints in rotary fashion using a relief image pattern
- 2. Impression cylinder: helps transfer the ink from the printing plate and the image on to the printing substrate
- 3. Anilox roll: transfers ink to the printing plate; ink transfer can be controlled
- Printing substrate runs between Printing plate and Impression cylinder
- Similar to traditional rubber-stamp techniques
- The image plate cylinder is usually made of polymer material

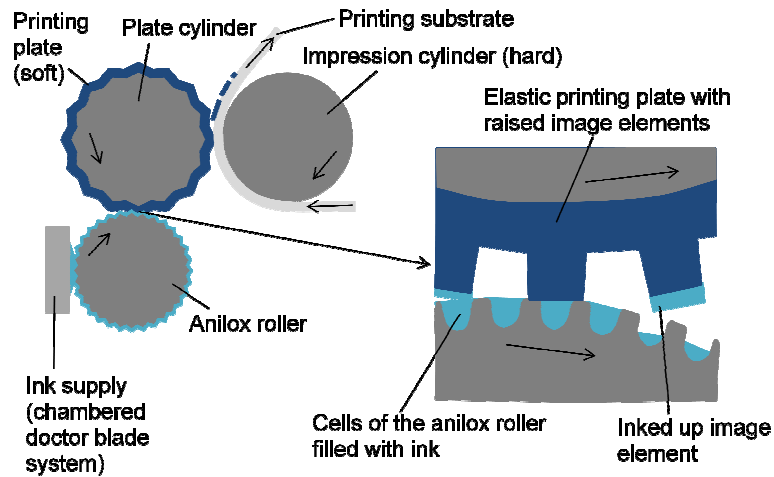


Figure1: Schematic Figure of how flexography works.

Gravure printing – see Fig 2

- Ink transferred from ink reservoir to rotogravure cylinder.
- Image is engraved on rotogravure plate.
- Doctor blade removes extra ink
- Substrate runs between rotogravure plate and impression cylinder.
- Surface of substrate must be smooth for successful printing
- Reverse of flexographic printing in terms of wetting ink on printing plate.

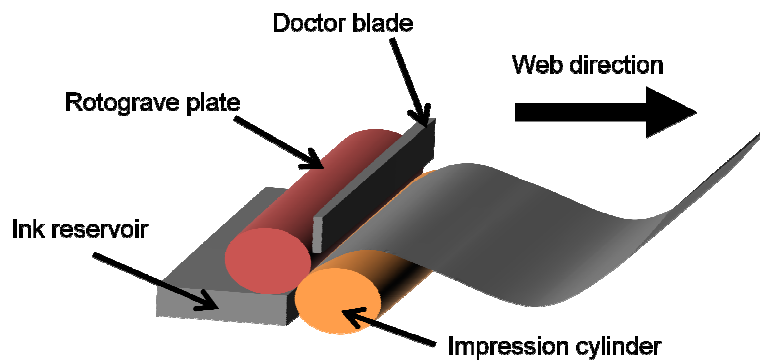


Figure 2: Schematic Figure of how Gravure works.

Offset Lithography see Fig. 3

- Printing plate has hydrophobic and hydrophilic areas
- hydrophobic ink is transferred to the hydrophobic areas on the printing plate.
- Printing image is on surface of anilox roller

- Offset plate: transfers ink the image on to the substrate with the help of the impression cylinder
- Wetting printing plate is very complex

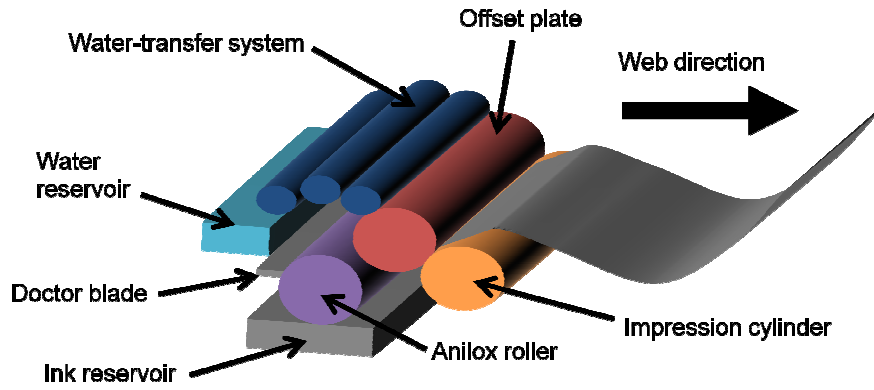


Figure 3: Schematic Figure of how Offset Lithography works.

Screen printing – See Fig 4

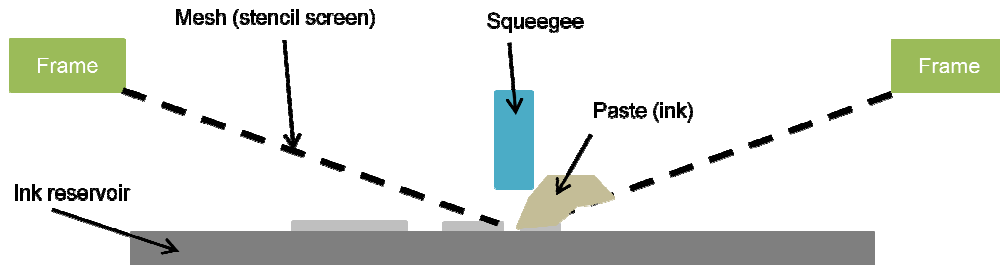


Figure 4: Screen printing principles

Inkjet printing – see Fig 5

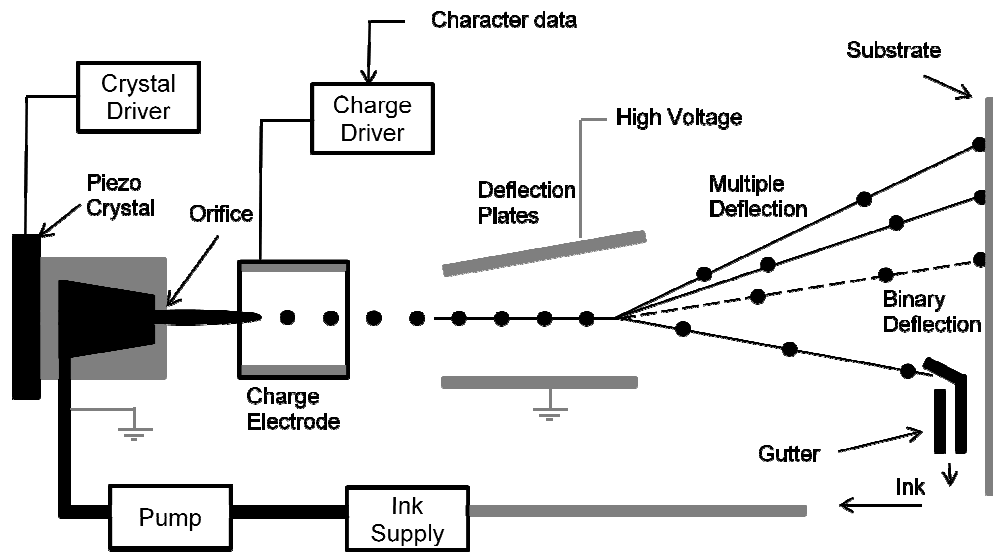


Figure 5: Schematic Figure of how one version of Inkjet printing works.

Nano imprint lithography (NIL)

There are many different types of nanoimprint lithographies, of which the two most important are thermoplastic and photo nanoimprint lithography.

Hot embossing:

- A thin layer of imprint resist (thermoplastic polymer) is spin coated onto the *sample substrate*.
- *The mold*, with predefined topological patterns, is brought into contact with the sample and they are pressed together.
- The pattern on *the mold* is pressed into the softened polymer film when heated up above the glass transition temperature of the polymer
- *The mold* is separated from *the sample* and the pattern resist is left on the *substrate* when being cooled down.

Photo nanoimprint lithography

- The mold is normally made of transparent material like fused silica.
- A photo(UV) curable liquid resist is applied to the sample substrate
- The mold and the substrate are pressed together,
- The resist is cured in UV light and becomes solid.
- After mold separation, a similar pattern transfer process can be used to transfer the pattern in resist onto the underneath material
- Notice: the use of a UV-transparent mold is difficult in a vacuum, because a vacuum chuck to hold the mold would not be possible.

Some of the current characteristic and ink requirements of the selected printing processes are shown in table 1.

	Flexography	Offset Lithography	Gravure Printing	Screen Printing	Inkjet Printing
Printing Form	Relief (polymer plate)	Flat (Al plate)	Engraved cylinder	Stencil and mesh	Digital
Typical Resolution (lines/cm)	60	100-200	100	50	60-250
Ink Viscosity (Pas)	0.05-0.5	30-100	0.01-0.2	0.1-50	0.002-0.1
Substrates	Paper, boards, polymers	Paper, boards, polymers	Coated paper and boards, polymers	All	All, 3D possible
Film Thickness (μm)	0.5-2	0.5-2	0.5-2	5-25	0.1-3
Line Width (μm)	20-50	10-15	10-50	50-150	1-20
Registration (μm)	<200	>10	>10	>25	<5
Throughput (m^2/sec)	10	20	10	<10	0.01-0.1
Printing Speed (m/min)	100-500	200-800	100-1000	10-15	15-500

Table 1: Characteristics and requirements of selected printing processes. Adapted from Caglar, 2008

The data in table 1 varies slightly depending on the expert interviewed. According to some experts, gravure printing can reach resolution up to 2000 lines/cm by extreme engraving. Film thicknesses for gravure printing are said to be 0.05-7 μm and for screen printing 1-25 μm by one run (the same applies to flexography and offset lithography, too). Ink-jet printing requires several, even dozens of runs in order to reach film thicknesses of 0.1-3 μm . The line width lower bound in table 1 is claimed to be optimistic for all methods. Typically the minimum linewidth is 50 μm for other methods than ink-jet printing for which it is 30 μm . Registration is claimed to be too optimistic as well for other methods than flexography.

2.3.1 Inks

Formulation of the ink is crucial. The use of functional materials and nanoparticles in inks has broadened the scope of applications that printed electronics enables. Suppliers formulating novel ink materials and setting up high-volume ink manufacturing facilities will in the near future have an important role in the development and commercialisation.

Inks are either water-based, solvent based or UV-curable. In addition to viscosity requirements, the different printing techniques set many requirements on e.g. surface tension, density, evaporation rate, particle size, solid content, shelf life and volatility.

More details on nanomaterials can be found in the Materials report.

3 Science and Technology Aspects

3.1 State of R&D

Currently the whole field of printed electronics is not considered a nanotechnology itself. However, printed electronics can use different so-called nano inks. We have also assessed whether printed electronics will be able to print nano-scale features. Experts currently believe that nanoscale features might be possible to print with Flexography printing, Gravure printing Inkjet printing and Nanoimprint lithography. The following chapter will only deal with those.

This section discusses the state of art in the nano particle inks. The state of art of printing nano-sized features is discussed in the following section.

3.1.1 Metal nano ink

Metal nano ink is conductive that uniformly disperses nanoscale metal particles in a solvent. Currently the market for this material is small and consists mostly of sample shipping. The main target of metal nano inks is not as a substitute for conventional materials or processes, but for new generation devices. The mass-markets will grow with the commercialization of new devices.

Semiconductor and insulating materials are under development for inkjet printing process. There are still some challenges on reliability, materials characteristics, and mass manufacturing process. Once these challenges are overcome production of this material for printed electronic will start growing. It is believed these challenges will be overcome by 2012.

3.1.2 Carbon Nanotube Ink

Conductive inks are made with noble metals such as gold and silver because they are good electrical conductors and do not oxidise, but there is a cost issue with using these materials. Copper would be cheaper but oxidises in contact with air. Norman Lüchinger at ETH Zurich has developed graphene coated copper nanoparticles, synthesising the nanoparticles and coating them with a graphene shell *in situ*. The ink itself was of similar viscosity to normal printing ink, and could be used in an inkjet printer. However, conductivity of this ink is still inferior to gold and silver.

SouthWest NanoTechnologies Inc. (SWeNT) claims to have nanotube-based ink available for commercial applications. This uses CNTs produced by SWeNT, dispersed in an ink formulation developed by their partner Chasm Technologies. The company states that viscosity of the ink can be controlled to maximise compatibility with a range of printing processes, and that drying takes place at under 100 C.

One of the challenges is to separate semiconducting nanotubes from metallic nanotubes. Researchers at DuPont and Cornell have produced a solution to this challenge by converting the metallic CNTs by adding fluorine molecules, in a process called cycloaddition.

A recent study from French and German researchers, reported in Nanotechnology, built a tuneable RF-receiver by printing CNT inks on paper. Researchers at the University of Helsinki have used copper nanoparticles, employing poly(ethylene imine) (PEI) or tetraethylenepentamine (TEPA) as a protective layer. The coated nanoparticles were able to be sintered at temperatures of 150 -200 C, and continued to demonstrate good electrical conductivity.

Applied Nanotech has also developed copper nanoparticle inks and printed them on paper substrates. The company is also developing inks which use Nickel.

3.2 Printed electronics with nanoscale features

The general consensus is that nanoscale manufacturing is a hard task for printed electronics. Currently, microscale features are acceptable. Mass-production of nano-scale printing, i.e., below 100 nm, is quite difficult even for nano-imprinting. Experts believe that gravure printing and flexography printing will never reach the nanometer scale in feature size at least not with the current technology. The benefits for the printed electronics market are elsewhere. Also it is very questionable whether inkjet printing reaches the nanometer scale feature sizes.

The vast majority of current ICT applications do not require nanoscale patterning. Most of these applications (especially displays) only require micro-scale patterning. The nanoscale patterning applications seemed to be mostly focused on the optics and bio side.

The authors used a web-based questionnaire to address experts in the printed electronics and nanotechnology field. We assessed four different printing methods: gravure, flexography, ink-jet and roll-to-roll nanoimprinting

The experts were asked to assess the state of printed electronics enabling printed nanoscale features for ICT applications. The results of the questionnaires are based on answers from 31 experts. For more information on who answered the questionnaire see the list of references.

In Figure 6 we compare the Technology readiness level of the four different technologies with the impact of this technology. The experts assessed the technology readiness level of each of technology based on several questions. The different technology levels are defined as follows:

- **TRL1: Fundamental research:** Physical laws and phenomena behind this structure is known and critical challenges regarding the application of structures are known.
- **TRL2: Applied research:** Proof-of-concept components utilising these structures are manufactured, integration is still a challenge
- **TRL3: Prototype:** Functional prototypes (e.g. integrated circuits) having components utilising these structures are manufactured.
- **TRL4: Market entry:** First products utilising these structures have entered the markets
- **TRL5: Mature markets:** Multiple vendors are providing products and technology utilising these structures

The assessed impact is the current status of technologies listed compared to the current state-of-the-art printed electronics manufacturing technologies. We assessed five aspects and the impact is the average of these:

- Manufacturing process enables novel features in nanoscale printed electronics ICT applications
- Performance (e.g. speed, line width, yield, reliability) of the manufacturing process
- Cost effectiveness of the manufacturing process
- Scalability of the manufacturing process
- Environment, Health and Safety (EHS) aspects of the manufacturing process

Impact is assessed as follows: 1) Very low 2) Low 3) Neutral 4) High 5)Very high

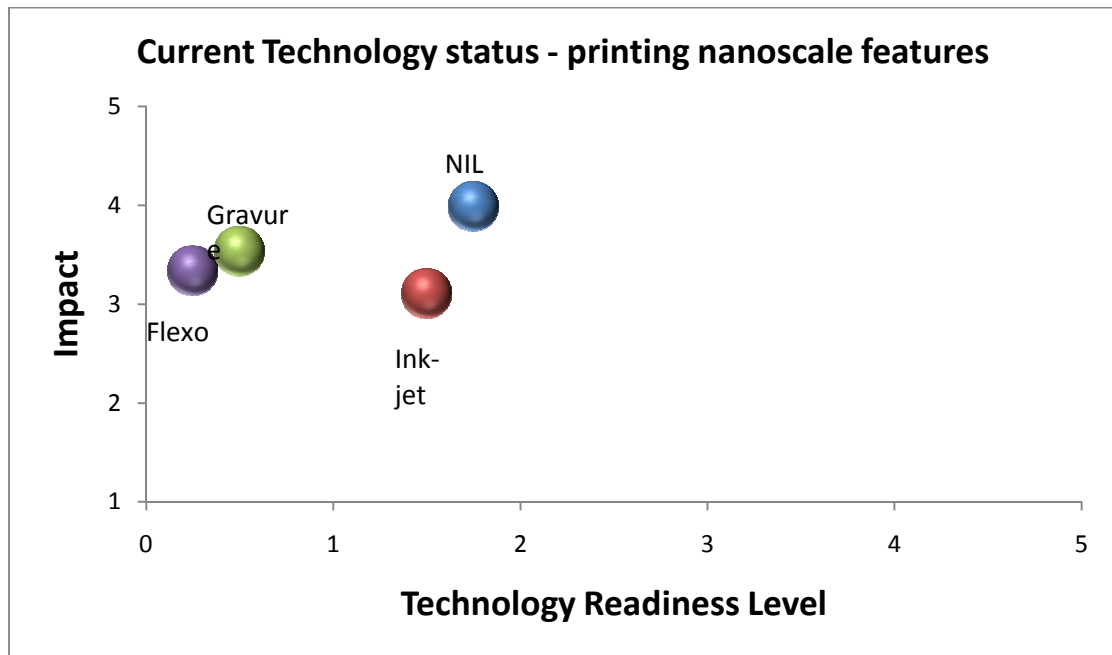


Figure 6: Current Technology status – printing of nanoscale features.

According to expert opinions, Figure 6 shows that nanoimprint Lithography is achieving applied research phase. Also its impact currently is highest in terms of printing nanoscale features. Both gravure printing and flexographic printing are still at the fundamental research stage. Some experts even believe that it will never be possible to print nanoscale features with these two methods.

3.3 Additional demand for research

The biggest challenge lies in the getting the whole process working. The technology is multidisciplinary, calling on skills from advanced materials to printing and systems integration, and so necessitating interaction between individuals and organisations that have not so far worked closely together.

3.3.1 Need for printed electronics and is computation possible?

As exemplified in the previous sections printed electronics manufacturing has several benefits compared to conventional electronics manufacturing for low-performance electronics. Its value lies in the simple process flow and integration as well as the relatively low capital costs. Currently the problem lies more in the technology-push vs. technology need aspect. What is really needed is the definition of what kind of value adding applications are needed.

Another greater problem is that IC's computational problems might emerge earlier than physical limits of Moore's law. More research on more efficient computation is needed.

One of the challenges of printing low-intelligence products lies in the lack of signal processing technologies. Currently the smallest unit of information is stored on a chip. However, chips with thousands of transistors include the same amount of intelligence as the first computer. Some future applications, such as storing your ID on a chip will only need intelligence stored in a few transistors but to date we don't have the technology to process data from only a few transistors.

3.3.2 Optimisation of parameters

Setting aside the larger needs of application driven research and computational problems, the challenges and limitations of the current state of art lies in the vast amount of parameters that need to be optimised and developed. Compatibility of all processes used in production is a real issue. Related to process, materials and compatibility of the methods at least the following parameters have to be optimised and developed:

- Line width, gap width
- Substrate distortion
- Registration
- Throughput
- Layer thickness and uniformity,
- Layer Edge quality
- Drying time
- Curing time
- Solvent compatibility, viscosity and wetting
- Materials performance

3.3.3 Is mass-manufacturing possible?

First, some compromises on the cost of device performance and size have to be made before we will have working printed electronics plants. Another bottle neck for mass manufacturing is how to make the devices last longer. Yield is yet another big question mark in mass-manufactured real applications.

Experts also believe that a combination of different manufacturing methods will be used. More application focused research into combining different methods is needed.

Huge challenges also lie in power use and heating problems. This is one problem that could be helped with new functional materials and nanomaterial solutions discussed in the following section.

3.3.4 Demand for Materials research

One of the biggest current challenges for printed electronics lies in the substrate materials used for printing: currently there are only few substrates available. There are many nanomaterials and nanoparticles but lack of people who are formulating it into ink or other printable materials that can be used. Thus, not all components can be printed and one has to add basic electronic components to the circuit. For example, for inkjet technology, the materials are immature. More development of functional materials is needed to be able to create more sophisticated electronic structures.

For Inkjet, gravure, and flexography printing technologies, one of the **largest challenges is the diffusion of printed materials** on the printed media, which can seriously degrade the printing resolution and precision. For roll-to-roll nanoimprint, the biggest concern is the lift-time of the templates, which uses mechanical deformation to define functional devices. In addition, the automatic separation between the patterned media and the templates is still an issue that demands more fundamental research in terms of surface chemistry/physics.

One important near future problem lies in recycling issues related to printed products. As the materials become more complex so does the recycling process.

3.3.5 Forecast of how the methods will develop

In the web-based questionnaire the experts are asked to assess the current status of technologies listed compared to the current state-of-the-art printed electronics manufacturing technologies for printing nano-scale features as well as the expected status when the products using this technology will hit the market.

Figure 7 shows the four technologies and the five aspects assessed. The impact is assessed as follows: 1) Very low; 2) Low; 3) Neutral; 4)High; 5)Very high. Experts believe that NIL will develop the most. The results can also read so that not all the methods will bring nanoscale features as nothing is expected to happen between now and the market phase. Most novel features will be brought by NIL and the performance of Inkjet printing is expected to raise most.

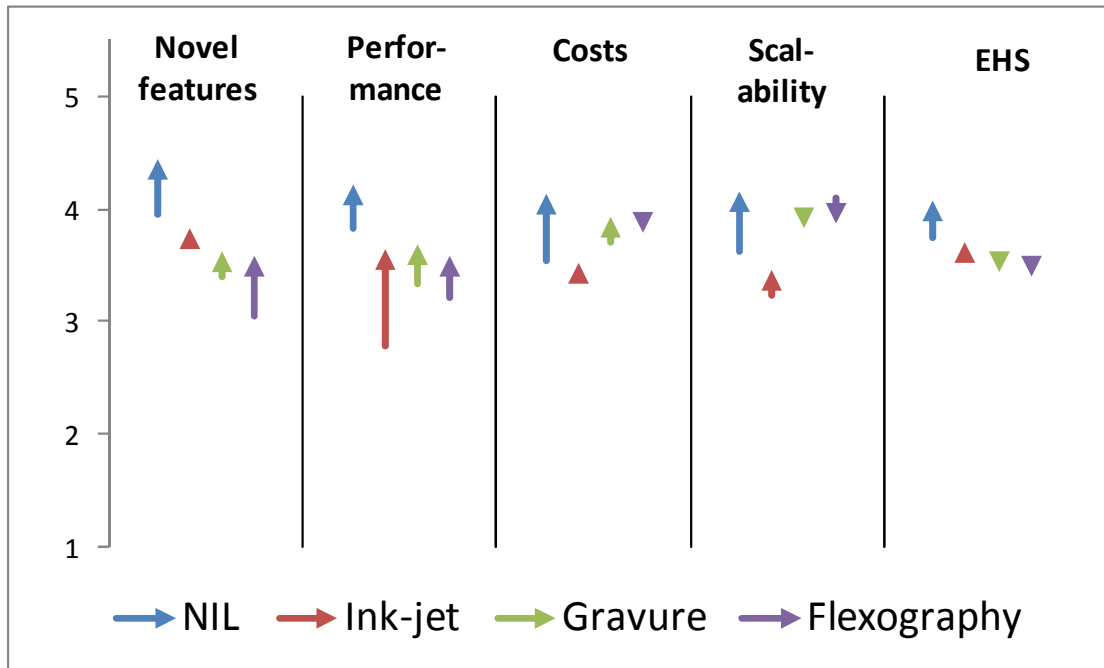


Figure 7: The Current status of technologies listed compared to the current state-of-the-art printed electronics manufacturing technologies for printing nano-scale features . Arrow moving to the status when the products using this technology will hit the market. The y-axis, impact scale: 1)Very low; 2) Low; 3) Neutral; 4) High; 5)Very high. (EHS=Environmental, Health and Safety aspects)

3.4 Applications and perspectives

Printed electronics enables applications in almost all industry sections. The bigger question is whether there is a need for the features that printed electronics enables for existing applications and what kind of new applications are really needed. This section deals with the different kinds of components that can be printed and then it takes a look at what kind of applications could need nanoscale-scale features.

According to the questionnaire experts believe there is an ICT market need for printing of nanoscale features with the assessed technologies. Figure 8 shows that experts on average strongly agree (=4) that there is an ICT market need for NIL. However, the experts are on average (filled circle) neutral for that of the other technologies. Notice that the deviation in the answers for the three other technologies is large. Some experts don't see a need for the technologies at all.

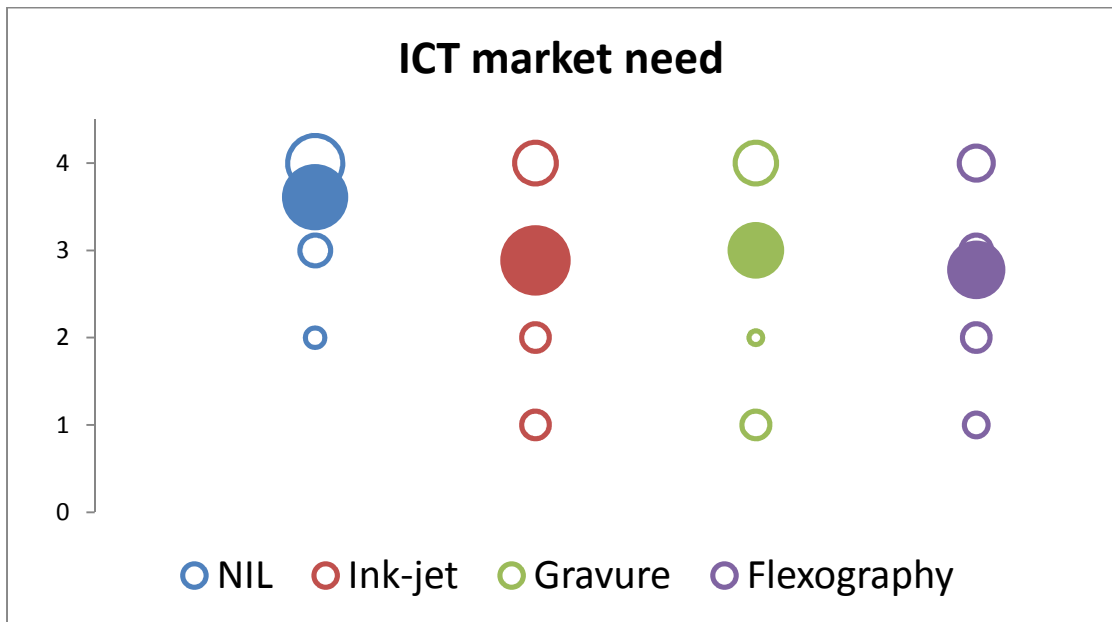


Figure 8: There is an ICT market need for printing of nanoscale features. In the Figure the whole circle correspond to the average of the answers. The empty circles show how the individual answers are distributed. The size of the circle correlates with the amount of experts answering. The y-axis scale: 4: Strongly agree; 3: Moderately agree; 2: Moderately disagree; 1: Strongly disagree;

3.4.1 What can be produced with the different printing methods

The following is a list of examples of possible components that can be printed with the different printing methods.

- | | |
|----------------------|---|
| Component categories | <ul style="list-style-type: none"> • Passive electrical and optical <ul style="list-style-type: none"> ○ Wirings, conductors ○ Resistors ○ Conductors (dielectrics) ○ Inductors ○ Diffractive optics, light guides ○ Optical Read-only memory • Active electronic and optoelectronic <ul style="list-style-type: none"> ○ Diodes ○ Transistors ○ LEDs ○ Solar cells • Sensors and indicators |
| Component | <ul style="list-style-type: none"> • OLED displays and signage |

integration

- Printed organic transistor circuits, multilayer electronic circuits
- Memory devices
- Solar cells, miniaturized fuel cells, etc

Component examples

- Gravure printed optical waveguides
- R2R manufactured optical MEMS-array
- Roll-to-roll hot embossed OROM element with mobile reader

Adapted from Kopola (2009).

Flexographic printing is mainly used for inorganic and organic conductors.

Gravure printing is especially suitable for quality-sensitive layers like organic semiconductors and semiconductor/dielectric-interfaces in transistors, but also for inorganic and organic conductors when high resolution is needed.

Inkjet printing is mostly used for organic semiconductors in OFETs and OLEDs. Some OFETs completely prepared with this method have been demonstrated. Other components prepared with inkjet printing include, frontplanes and backplanes of OLED-displays, and integrated circuits.

The **screen printing** method is used mainly for conductive and dielectric layers and also organic semiconductors, e.g. for OPVCs. Some complete OFETs have also be printed.

Nano imprint lithography has been used to fabricate MOSFETs, Organic-TFT and single electron memories.

3.4.2 What kind of ICT applications could need printed nanoscale features?

According to experts nanoscale features could be needed in several different applications. The following is a list of ideas gathered from experts. RFIDs and sensors are at present the most interesting targets of for nanoscale printing.

Components

- Transistors
- O-FET
- (Cheap, simple) Circuits
- RFIDs
- Circuits and devices for sensors
- Memories and memory devices (e.g. smaller linewidths)

Component integration

- Biocompatible electronics
- Integrated elements as a part e.g. in packages
- Batteries
- Displays
e.g. Active matrix backplanes
- LEDs
- Nanoscale photovoltaics

The bigger picture

- Applications (sensors, displays etc.) which form added value or functions for the main product.
- All high volume consumer products which can benefit from the hybrid manufacturing.
- Manufacturing of memories and logic ICs will be greatly affected by these technologies. Most part of them will be replaced.
- Medical areas will be of importance.

As shown in Figure 9 experts do not believe that the first nano-scale featured products have entered the market (2: Moderately disagree; 1: Strongly disagree). However it is noticeable that a small amount of experts do see some products already available.

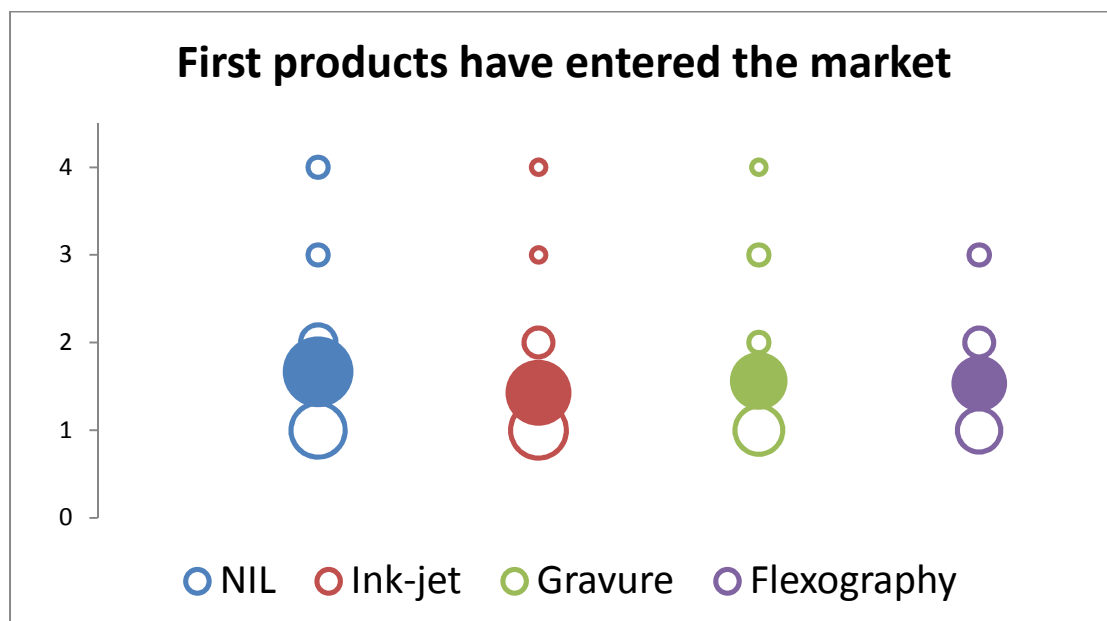


Figure 9: In the Figure the whole circle correspond to the average of the answers. The empty circles show how the individual answers are distributed. The size of the circle correlates with the amount of experts answering. The y-axis scale: 4: Strongly agree; 3: Moderately agree; 2: Moderately disagree; 1: Strongly disagree;

3.4.3 Example of applications

Organic EL has wider view angle, higher contrast, quicker response as well as being thinner and lighter than conventional LCDs. In 2008, only sample shipping and prototypes of OELs could be seen because a vacuum deposition process was needed. To overcome this, many companies are developing printing technologies to open large panel productions. It is expected that OEL will open a new market, which will start growing from 2010 onward.

E-Paper is an electrically rewritable thin display that can be used as paper. Printing TFTs of organic semiconductors on the back panel for E-paper are under development. In 2008 this was in a prototype phase. The use of printing technologies might enable the formation of device elements on flexible boards. The E-paper market is expected to gradually grow from 2010.

3.4.4 How the Technology readiness level is expected to progress

Figure 10 indicates how experts believe the TRLs are expected to progress. For making nanoscale features, flexography and Gravure printing are expected to still be in the fundamental research stage. Whilst some experts express scepticism that these technologies

will ever be used to produce nanoscale features, others believe that prototype products with these technologies will be made in 3-5 years. Experts believe that products using NIL will enter markets at the same time as inkjet in approximately 4 years. Mature markets for printing of nanoscale features are expected to be reached in 7-10 years.

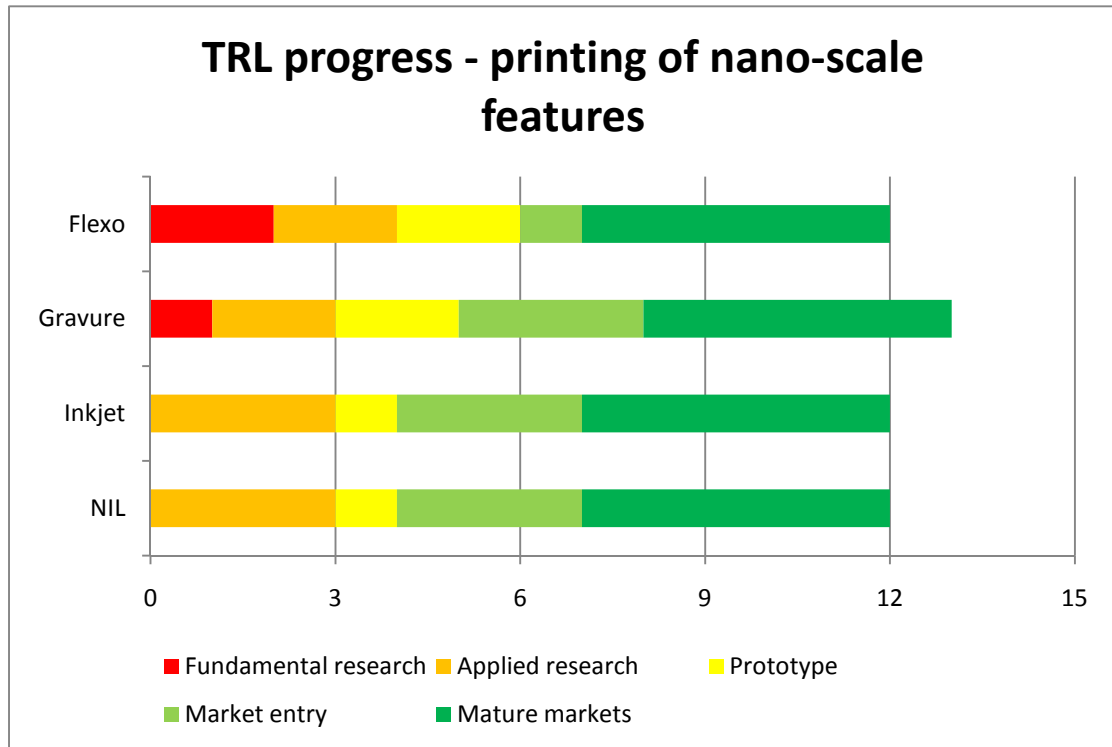


Figure 10: TRL progress – printing of nano-scale features. The scale on x-axis is years from 2010.

3.5 Current situation within the EU

The EU funded PriMeBits project is developing a printable electronic memory for use in RFID tags and other applications. This project is led by VTT, Finland and includes a number of other research centres.

Currently the UK is among the world’s leading players in Plastic Electronics. UK is a world leader in many fronts related to Printed electronics. These include: 1) **Materials**, such as the light-emitting polymers developed by Cambridge Display, 2) **Technology** (CDT), and the flexible plastic substrates produced by DuPont Teijin Films, 3) **Processing and manufacturing equipment**; for example Plasma Quest’s thin-film deposition kit and Timson’s highquality printing on unsupported flexible plastic films, 4) **Device design and manufacture**, including Plastic Logic’s flexible displays and Thorn Lighting and CDT’s OLED lighting panels, and 5) **Product design and integration**, such as Hewlett Packard Labs’ reflective colour display and

Polymer Vision's rollable eReader. The UK also has five centres of excellence working on this topic. The Printable Electronics Technology Centre (PETEC) is a national Printed Electronics prototyping centre.

Finland, and especially the Oulu Area, has extensive facilities for prototyping printed products. PrintoCent in Oulu is a center for business development in the area of Printed Intelligence, and is a world class production environment with special focus on R2R- and hybrid production, optical measurements and multiple applications ranging from printed passive and active electronic components to microfluidic solutions, printed indicators and Point of Care diagnostics. Printocent is working in close contact with the technical research centre, VTT in Oulu.

According to the Strategic Research Agenda (SRA) of Organic & Large Area Electronics by a leading European organisation on the area, Europe is the leading R&D and innovation powerhouse in organic and large area electronics. The SRA covers 5 topics on the area, which are lightning, organic photovoltaics, displays, electronics and integrated smart systems. For more information, please see the references section of this report.

The Tyndall National Institute was established to bring together activities in photonics, electronics and networking research at the National Microelectronics Research Centre (NMRC), UCC academic departments and Cork Institute of Technology. The objective is to create a focal point of Information and Communications Technology in Ireland, to support industry and academia nationally and to increase the number of highly qualified graduates for the 'knowledge economy'. The strengths of the institute lie in photonics, electronics, materials and nanotechnologies and their applications for life sciences, communications, power electronics and other industries. For more information, please see www.tyndall.ie.

4 Economic aspects

4.1 General market description

Printed electronics is one of the current fields where the hype in R&D should be turned into business. Several different research institutes in Europe custom-tune their printing machines and are testing printing of different component on small scale. There are only a few commercial products available. Experts believe that currently there is not a single profitable printed electronics company available world-wide.

According to our questionnaire, as shown in Fig. 11 on average experts do not agree that multiple vendors are providing the technology. However, some of the answerers believe that for NIL, Ink-jet and Gravure printing, vendors are already providing printing of nano-scale features.

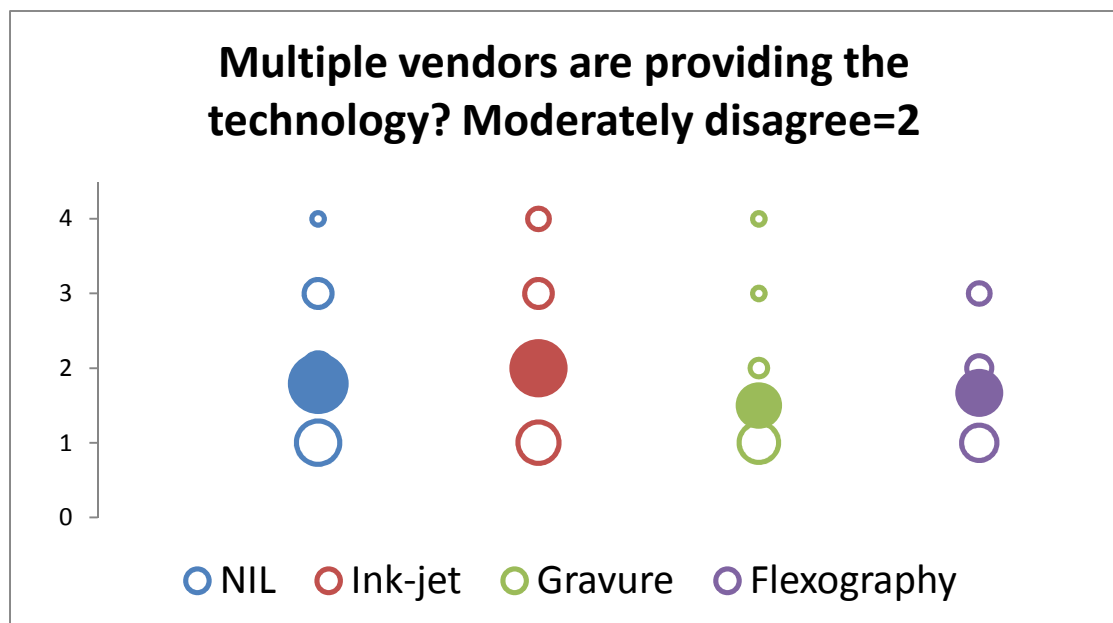


Figure 11: On average experts do not believe that multiple vendors are providing these technologies. However, especially for Ink-jet some experts believe that vendors do exist. In the figure the whole circle correspond to the average of the answers. The empty circles show how the individual answers are distributed. The size of the circle correlates with the amount of experts answering. The y-axis scale: 4: Strongly agree; 3: Moderately agree; 2: Moderately disagree; 1: Strongly disagree;

4.1.1 Forecasts

A UK report (BIS, 2009) forecasts that the plastics electronics market value will rise from \$2 billion today to \$120 billion in 2020. This is based on the assumption that within the next few years printed electronics will become an industry addressing huge application markets with sophisticated products, much as the semiconductor industry does now. The opportunities in this sector will vary considerably from application to application.

According to Harrop and Das (2009) "Printed and thin film transistor circuits will become an \$8 Billion market in 10 years, from just \$10 Million in 2009." According to the same book, already, over 500 organisations are developing printed transistors and memory, and the first products were being sold commercially in 2009.

4.1.2 Printed electronics changes the value-chains

In traditional electronics manufacturing somebody designs a product. All parts are manufactured separately by different vendors and somebody puts it together. With printed electronics, in the same phase you can produce the circuit (card) and the components. Thus the vendors are not needed. The manufacturing value-chain will be different and some players will not be needed.

Also new types of multidisciplinary cooperation will emerge to drive renewal of lighting, displays, signage, electronic products, medical disposables, smart packaging, smart labels and much more besides. The chemical, plastics, printing, electronics and other industries need to cooperate to make it happen.

4.2 Drivers and barriers

One of the biggest drivers is that several non value-added process phases and materials will be eliminated with printed modules. Improvements provided by the technology include reduction of HW size, possibilities to achieve next level in IC pad size and reductions in lead-times.

Other drivers are the positive environmental implications. Printing is waste-free electronics manufacturing, therefore reducing material usage and logistics operations. It is also believed that the R&D cycle times will be significantly improved. Manufacturing flexibility cannot be disregarded as one of the drivers for this technology development.

The near future will focus on printing different kind of sensors. Despite high hopes, it is generally believed that it will take another 5-10 years before we are able to print whole

circuits. According to expert feedback, currently by printing the yield of transistors is 97 %. As one circuit needs thousands of transistors the yield is too low to be able to function in mass-manufacturing.

One interesting growing area is printing of Pi materials. Cohio, USA has produced transistors which perform much better than normal printed transistors (and are perform almost as well when made with amorphous Pi). The benefit is that they can be put very many different boards, which makes the manufacturing cheaper in the long run.

Within five years it is believed that we will get more commercial applications to market but that the markets will still be small. New commercial applications will also be developed. The integration of different processes (e.g. roll to sheet) will be carried out and we will have greater understanding of materials, from modelling, to ink formulation. With growing market size a commercial market for manufacturing of printing machines will also emerge.

Many experts believe that paper machines will not be the ones implementing printed electronics. Current electronics manufactures have the process and technology knowledge and can more easily change to printed electronics than paper printing manufacturers learn electronics.

4.3 Selected company profiles

4.3.1 Printable Electronics Technology Centre (PETEC)

The Printable Electronics Technology Centre (PETEC) at CPI is the national Plastic Electronics prototyping centre. Opened by the Secretary of State in March 2009, PETEC develops manufacturing processes at pre-production volumes to bridge the gap between small scale laboratory demonstrators and high volume production runs. As well as having this process expertise, PETEC also provides support in semiconductor materials integration and the vital barrier layer technologies. The recent investment into PETEC of £20m by BIS and One North East will support and fund a state-of-the-art manufacturing facility, enabling the development of new innovations in markets such as ultra-efficient lighting and photovoltaic solar cells. The expanded PETEC facility will also accelerate the establishment of units for incubating start-up businesses within the centre.

4.3.2 Hewlett-Packard Laboratories

Hewlett-Packard Laboratories' European base is in Bristol, where work on Plastic Electronics is aimed at developing 'Information Surfaces' – plastic sheets that can display paper-like, print-quality information as well as interactive and video media.

4.3.3 Cambridge Display Technology

Cambridge Display Technology (CDT) is heavily involved in the development and commercialisation of OLED technologies – particularly those based on solution-processable materials. The company is a spin out of the University of Cambridge's Cavendish Laboratory. The main focus of the company is on the development of materials which would be suitable to produce high-definition displays with low-cost, inkjet printing. The company is also developing thin film transistors and solar cells. CDT participates in several projects funded by the UK's Technology Strategy Board, including MOET – which focuses on optical enhancement of OLED lighting and displays – and TOPLESS.

4.3.4 De La Rue International Limited

De La Rue is the world's largest security printer, producing national currencies, passports, and travelers checks. The company is investigating printed electronics with applications envisioned to include displays and interactive features on documents, as well as security enhancing interactions between documents and inspection equipment.

5 References

5.1 Selected list of experts

The questionnaire was answered by 31 experts around the world. See Fig. 1 for places of experts. The report was sent for peer-review for the same group of experts.



Fig 1: Distribution of experts locations.

5.1.1 More details on selected experts

Prof. Jim Greer, Electronics Theory Group, Tyndall National Institute, Ireland. More info at: www.tyndall.ie

Dr. Enrico Gili, Cavendish Laboratory, University of Cambridge, United Kingdom. More info at: <http://www.phy.cam.ac.uk/>

Dr. Jumana Boussey, Senior Scientist, Laboratory of Microelectronics Technologies, CNRS. More info at: <http://www.ltm-cnrs.fr>

Marian Rebros, PhD., Center for the Advancement of Printed Electronics, Western Michigan University, USA. More info at: <http://www.wmich.edu/engineer/cape/>

5.2 Other References

P. Beecher et al. Ink-jet printing of carbon nanotube thin film transistors. Journal of Appl. Phys., 102, 043710, 2007:

http://www-g.eng.cam.ac.uk/nms/publications/pdf/Beecher_JAP2007.pdf

BIS-report -Department for Business Innovation & Skills, UK: Plastic electronics : A UK Strategy for success, Realising the UK Potential, 2009.

Umur Caglar: Studies of Inkjet Printing Technology with Focus on Electronic Materials, PhD Thesis, Tampere University of Technology, Finland.

<http://dspace.cc.tut.fi/dpub/bitstream/handle/123456789/6446/caglar.pdf?sequence=3/>

Peter Harrop and Raghu Das, Printed and Thin Film Transistors and Memory 2009-2029:

http://www.idtechex.com/research/reports/printed_and_thin_film_transistors_and_memory_2009_2029_000221.asp

Mandakini Kanungo et al. Suppression of Metallic Conductivity of Single-Walled Carbon Nanotubes by Cycloaddition Reactions, Science 323: 234-237, 2009

Harri Kopola et al. Printed Intelligence – Sensors and Smart Packaging, Symposium “Finnish Paper Research Community Serving Europe”, 23 Jan., 2007:

<http://www.kcl.fi/tiedostot/Kopola.pdf>

Harri Kopola et al. Printed Intelligence Enabling Technologies – Route to Disruptions: Presented at FinNano and Functional materials annual seminar, Helsinki Fair centre, 28.5.2009:

http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/Materiaalit/fi/Dokumenttiarkisto/Viestinta_ja_aktivointi/Seminaarit/2009/Annual_seminar/Kopola_PrIntelligence_FinNano28052009.pdf

T. Mäkelä. Towards printed electronic devices – Large-scale processing methods for conducting polyaniline, PhD Thesis, VTT, Finland, 2008:

<http://www.vtt.fi/inf/pdf/publications/2008/P674.pdf>

Rost and Mildner: On the Way to Printed Electronics - Latest Advance, PolyIC, Special reprint from Kunststoffe international 6/2008:

http://www.polyic.com/upload/wwwKL%20PolyIC%20PE%206_08_.pdf

Petri Pulkkinen et al. Poly(ethylene imine) and Tetraethylenepentamine As Protecting Agents for Metallic Copper Nanoparticles; ACS Appl. Mater. Interfaces 1(2) 519-525, 2009.

Strategic Research Agenda: Organic & Large Area Electronics:

http://opera-project.eu/uploads/OLAE%20SRA%20FINAL%20VERSION%201_20%20DATED%2006%2001%2010.pdf

5.2.1 News and others

Carbon nanotube ink writes RF devices on paper:

<http://nanotechweb.org/cws/article/tech/40329>

Low-cost nanotechnology substitute for gold and silver in printable electronics, Nanowerk Spotlight, October 14 2008, <http://www.nanowerk.com/spotlight/spotid=7705.php>

SouthWest NanoTechnologies Introduces Carbon Nanotube Ink Technology for Commercial, High Volume, Printed Electronics Applications, 8th December 2009, [http://www.nanotech-](http://www.nanotech-now.com/news.cgi?story_id=35718)
[now.com/news.cgi?story_id=35718](http://www.nanotech-now.com/news.cgi?story_id=35718)

<http://www.printedelectronicsnow.com/>

5.2.2 Research institutes and selected companies

PETEC: Printable ElectronicsTechnology Centre, UK: www.uk-cpi.com/petec

FunMat: Printed Intelligence & Functional Materials, Åbo Academy, Finland:

<http://www.funmat.fi/>

Printed Intelligence centre, Oulu, Finland: <http://printocent.net/>

De La Rue International Limited, UK: www.delarue.com

Cambridge Display Technology, UK: www.cdtltd.co.uk