3D PRINTING

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[redacted]			Simon Wardley	Sept 2005
Wohler Reports			Wohler	2003-2006
Printed Electronics			IDTechX	2006
Organic Electronics			IDTechX	2006
Castle Islands WorldWide guide to Rapid Prototyping			Ed	2005
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2.3 Terms

The use of fabrication technologies is widespread and complex. For the purposes of clarity the following terms will be used throughout this document.

Additive Fabrication System – the process of building an object through addition of multiple layers of material.

Subtractive Fabrication System – the process of removing layers of material from a large mass to produce a smaller mass object e.g. CNC milling.

Printing – image controlled application of a material onto a substrate

3D printing – in an additive fabrication system the use of any printing like techniques that involves directly depositing material onto a substrate.

NB

- *The term 3DPtm is MIT's proprietary 3-D printing like process.*
- *Other equivalent terms exist, for example*
    - *Functional Solid Free Form Fabrication*
    - *Digital fabrication*
    - *Direct printing*
    - *Digital manufacture*

Inkjet 3D printing – the use of an inkjet based technique in a 3D printing system.

Macro Printing – the use of additive fabrication techniques for the production of large-scale items. These techniques are normally used in rapid prototyping (**RP**) or the rapid manufacture (**RM**) of short runs of objects.

Rapid Prototyping (RP) – the creation of an object for the purpose of prototyping a new design.

Rapid Manufacture (RM) – the creation of an object for the purpose of end use.

Micro-Electronic Printing – the use of additive fabrication techniques for the production of small size items or electronics. These techniques are normally multi-material; they may only provide a subset of the manufacturing process and may exist in some form of hybrid manufacturing process.

Hybrid manufacture – the use of additive and subtractive techniques or the combination of multiple printing techniques to produce an object either at the Macro or Micro-Electronic range or both.

Hybrid Objects – objects that contain elements formed by both Macro printing and Micro-Electronic printing.

2.4 A history of manufacture

The following table examines the history of inkjet, Macro printing and Micro-Electronic Printing. The coloured section highlights how quickly the first commercial systems appeared.

Year	Bubble Jet (Thermal Inkjet)	Macro Printing	Micro-Electronic Printing
Year Zero	Mid1960 – various papers on inkjet theory	1967 – first example of using lasers to create a solid object from a photopolymer, Battelle Memorial Institute. 1974 – first proof of concept machines for prototyping with lasers.	2000 – first inkjet printed organic transistor. 2003 – first organic transistor with mass printing techniques 2005 – first organic circuit with mass printing technique 2006 – first commercial systems released
+ 15	1979 - Canon employee unintentionally pressed a hot soldering iron to an ink-filled syringe – Bubble Jet is born.	1980's – various papers on Solid Freeform printing (3D printing) 1980's – Establishment of new companies to exploit the growing 3D potential. 1987 – Steliography (SL) process released by 3D systems and commercialisation of process began.	
+ 20	1985 – Canon introduces first B&W commercial bubble jet printer (BJ80)	1988 Sony releases Solid Creation System. 1991 – Further additive systems released including FDM, LOM and SGC.	
+ 25	1990 – Inkjet printer market is growing, rapid improvement made in technology – though the market is still "skeptical". "Rosborough says the market for inkjets is growing, but there has been an argument building in the printing industry as to whether inkjets will ever be able to stand up to dot matrix and laser printer sales."	1996 – ZCorp launches first printer based upon 3DPtm techniques. 2001 – 3D printing market is growing, multi-material printers become available – mainly used in commercial applications (prototyping) 2001 – Concept Laser Gmbh introduces first hybrid machine that combines laser sintering and laser machining.	
+ 30	"In recent years the sales of inkjet printers have quietly been growing by leaps and bounds. In fact, in 1993 the number of sales of inkjet printers almost caught up to that of laser printers." March 1994 – Smart computing		
+ 35	"These days, a reasonably equipped inkjet costs less than $200. For that price, you can buy a printer with capabilities virtually unimaginable less than 10 years ago" August 2001 – Smart computing		

2.5 Manufacture 2.0

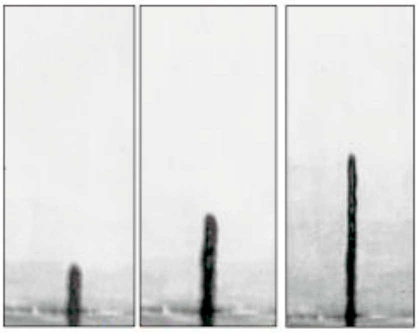
When people talk of printing, the most common idea is ink on paper. In reality this is two-dimensional printing using a particular suspension (ink) added as a single layer to a substrate (paper). Three-dimensional printing is simply the addition of further layers, an additive process to create a three dimensional structure.

This means that you can create physical objects – both in the macro and micro scale, comprised of single or many materials (Figures 1 & 2)

Figure 1 - Printing examples .

(Image from MIT web site)

Figure 2 - Inkjet printing on a Micro Scale



(30 x 500 µm tower)

(Image from TTP, 2006)

Additive techniques are not new – they've been around a reasonable time, for example the first use of lasers and photopolymers to produce physical shapes was achieved in 1967 at Battelle Memorial Institute and the first inkjet printed organic transistor demonstrated in 2000 by H.Sirringhaus[1]

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[1] *H.Sirringhaus, T.Kawase, R.H.Friend, T.Shimoda, M.Inbasekaran, W.Wu & E.P. Woo. High resolution inkjet printing of all-polymer transistor circuits, Science 2000.*

The technology is constantly being refined, and new methods of additive fabrication are being discovered. Today's commercial systems vary from lasers to heated grids to inkjet-based technology.

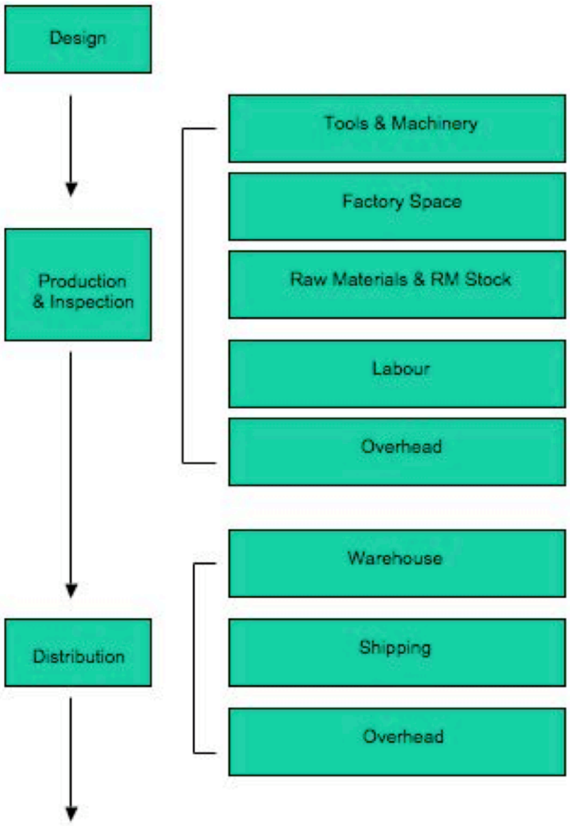
The key difference between these techniques and the traditional means of manufacture is their use of an additive principle, and as such they profoundly change the way we make things.

2.5.1 The process of making something?

Why would anyone be interested in printing an object as opposed to a traditional method of manufacture? What benefits are there?

If you consider mass printing systems, such as newspaper printers, the most obvious are high volume process, low cost manufacturing and reduced waste (additive vs subtractive). The power of this technology really stands out when you take a step back and consider the overall process of making something. I've provided a very simplified diagram below: -

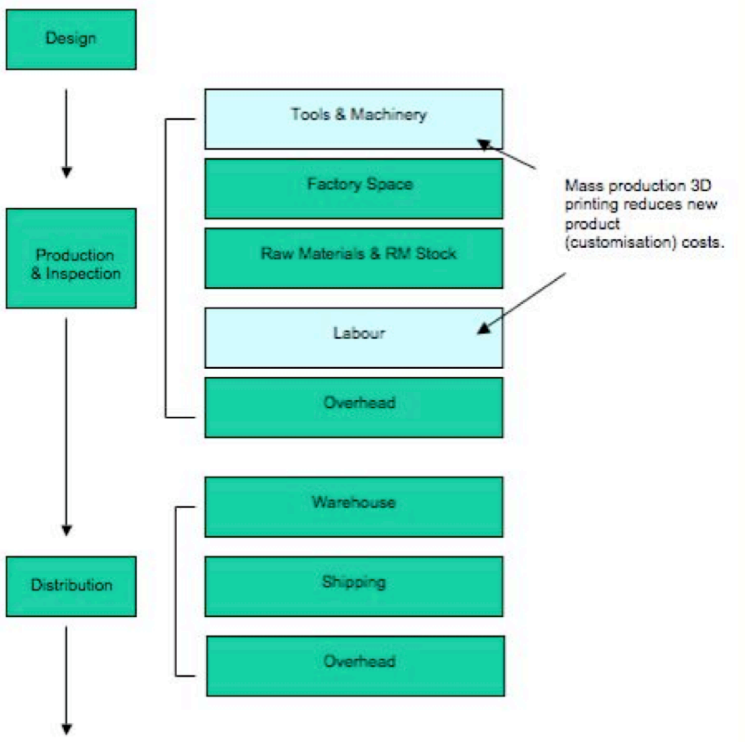
Figure 3 - Process of making something



Mass production is capital intensive – the requirements for tools and machinery, labour etc. One of the key advantages of 3D printing is in reducing the cost of retooling for a new product run.

In the case of flexographic techniques, a new product run may only require a new print drum. In the case of inkjet 3D printing, a new product run requires only a change in software. Possible cost reduction areas are shown in figure 4.

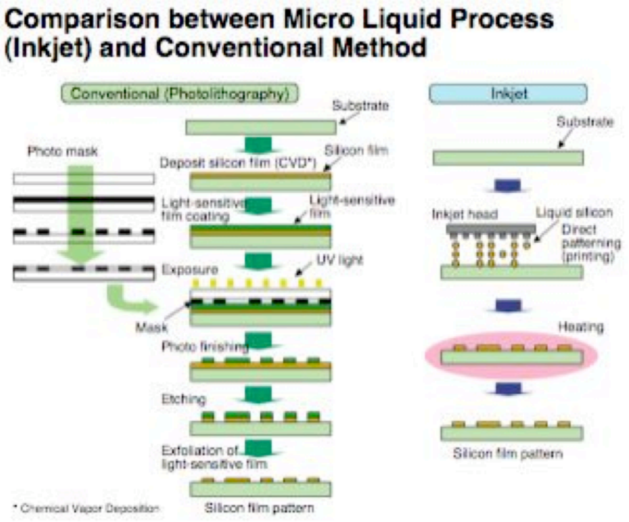
Figure 4 - Cost reduction in manufacture



However if you dive deeper, the nature of an additive process potentially saves other costs, for example.

The process of IC manufacture is outlined in the following steps – figure 5.

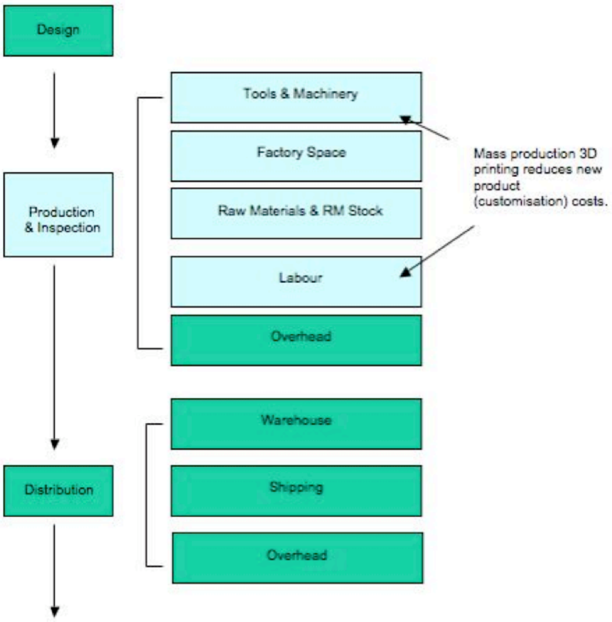
Figure 5 - Traditional process of IC manufacture.



(Image from Epson press release on printing silicon transistors, May 2006)

The potential exists for savings in raw material cost, energy use and also waste production and the resultant environmental impacts. These are all highly dependant upon the object being made and the traditional method used, however they should not be overlooked. Furthermore, as one digital process can be used to create multiple items, often in sequential or integrated runs, the potential exists for further savings in factory space – see figure 6.

Figure 6 - Potential savings from use of 3D printing techniques



So how big is this factor? It depends upon what is being achieved, Steve Jones has estimated that “interconnect manufacture will be 10x cheaper and 10x faster using such techniques”[2], other groups estimate a 20-200x cost saving on RFID.

This benefit is of course on top of the benefits gained from the reduction in capital and retooling costs with new product runs.

However it’s not just about cost and time saving, there are other benefits including geometric and compositional freedom.

All additive processes provide the ability to fabricate with unbounded geometries and therefore to create complex geometries that are not achievable with subtractive techniques. Furthermore additive methods allow for precise control of material composition (when using multiple materials) by geometry. These techniques combined together allow for the creation of novel and new types of objects which were previously not achievable.

In the long term a further benefit comes in the area of distribution. In our current manufacturing process, centralised production or assembly is required for efficiencies of scale to offset the capital investment required to setup and tool the factory to produce a single type of object. Under a printed manufacturing regime these efficiencies are altered as the printers can easily change from printing one object to another. Hence economies of scale become more about creating millions of things rather than millions of this one specific thing. Under such a model distributed manufacture becomes possible.

This is a balancing act, between the needs of customisation, the cost of capital and the cost of distribution. As the technology matures the high street factory or even Epson’s vision of the factory in every home becomes a reality.

This will make further savings in the following area – see figure 7, note that rather than objects being distributed, raw materials in the form of print cartridges will be.

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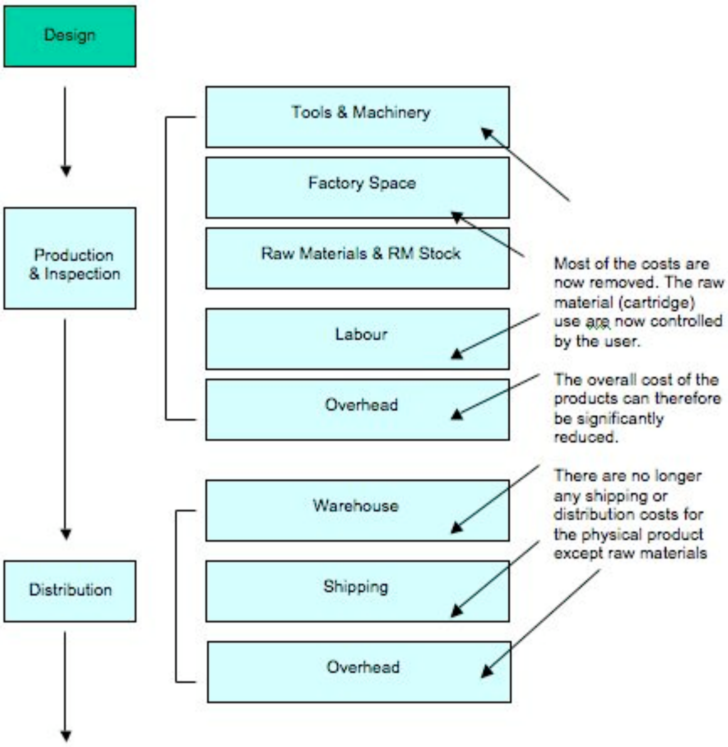
[2] *Steve Jones, Printed Electronics Ltd, report to Printed Electronics Conference, Cambridge 2006.*

Figure 7 - Potential savings from use of 3D printing techniques



The system above is what I have termed **Manufacturing 2.0** it is an environment where manufacture is more distributed closer to the consumer and objects are built on demand and to the requirements of the end consumer in single production runs.

The main product for general distribution are raw material cartridges, the traditional channels (retail etc) even possibly the end consumer become manufacturing units.

Traditional manufacturing companies will tend towards either niche areas using traditional techniques for mass commodity items or more towards design companies. A few of the traditional manufacturing will become printer manufacturers and / or cartridge manufacturers in this new world.

Under this regime there are significant obvious benefits to be achieved, though this does not mean that all products will be manufactured in this way or that end consumers will become designers of their own customised parts. Due to the obvious potential many analysts get carried away with the spirit of this new adventure.

“The world is poised for a **personal fabrication revolution**”[3]

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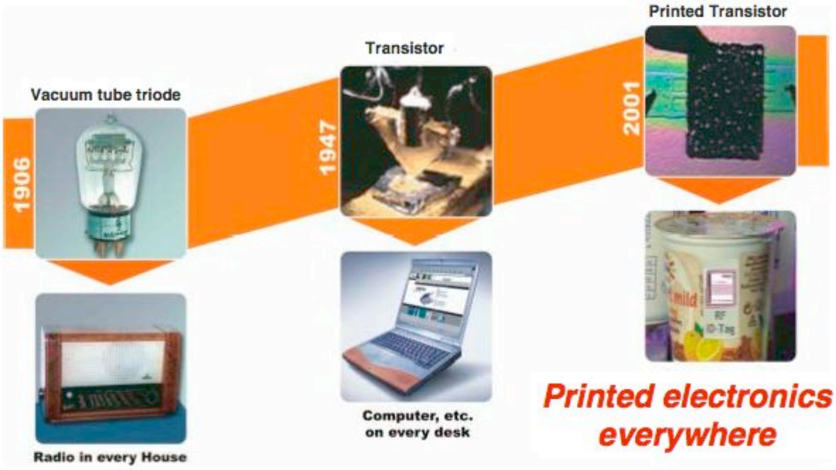
[3] *Reported in Economist, 2005*

PolyIC believes that printing will replace the silicon chip (see figure 8)

Figure 8 – Printing replaces the silicon chip?



(Image from PolyICs presentation at the Printed Electronics Conference, Camb, 2006.)

Where I would agree that long term such things may happen, there are significant engineering and material problems to overcome.

Additive processes do have inherent advantages over subtractive or moulding based processes in terms of reduction of waste and flexibility. If, "Inkjet is a **viable manufacturing tool**"[4]*,* then because of these, it is only a matter of time before printing techniques become dominant manufacturing methods.

"Because the shape of a manufactured product will depend only on its computerised design, the designer's imagination can be given free rein: fuel cells can be microscopic, steering wheels ergonomic. And because the expense of making tools no longer figures in the equation, the economics of mass production will give way to mass customisation. Parts will then be made in production runs not of a million or even of a few thousand, but of one."

Phillip Dickens of De Montfort University

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[4] *Statement from Xennia, at the Printed Electronics Conference, Camb, 2005*

3 The state of the industry

3.1 Market

What is 3D printing used for?
On a macro scale, the majority of three-dimensional printing is used for prototyping or proof of concepts, however the technology is improving to such a degree that mass production with such systems will shortly be viable[5].

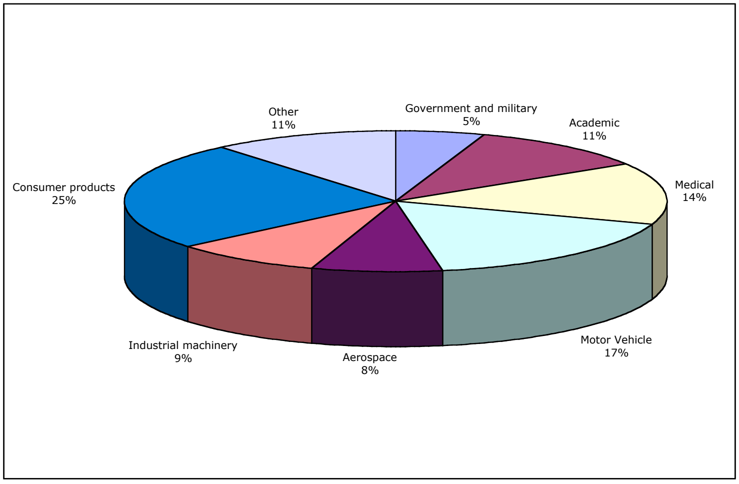
On a micro-electronic scale, it is used sparingly in production systems – most of the work in this area is still proof of concept or prototype stage.

At this moment there is a gulf between 3D printing of macro scale items and micro-electronic. In many cases the same technology is used, this division is more related to the direction by which various groups have approached the area of 3D printing rather than some other inherent difference.

Both groups have a similar focus on resolution, consistency, materials etc and I believe it is only a matter of time before these merge.

Macro scale
On the macro scale - "3D printing" is a major subset of a group of "additive fabrication" systems. It is worth examining this larger group as it gives some indication of the potential market and its growth. The market segment for additive fabrication technologies is shown in figure 9

Figure 9 - 2006, Markets using Macro scale additive fabrication systems.



(Source data from Wohler Report, 2006.)

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[5] *Wohler Associates, 2005 report.*

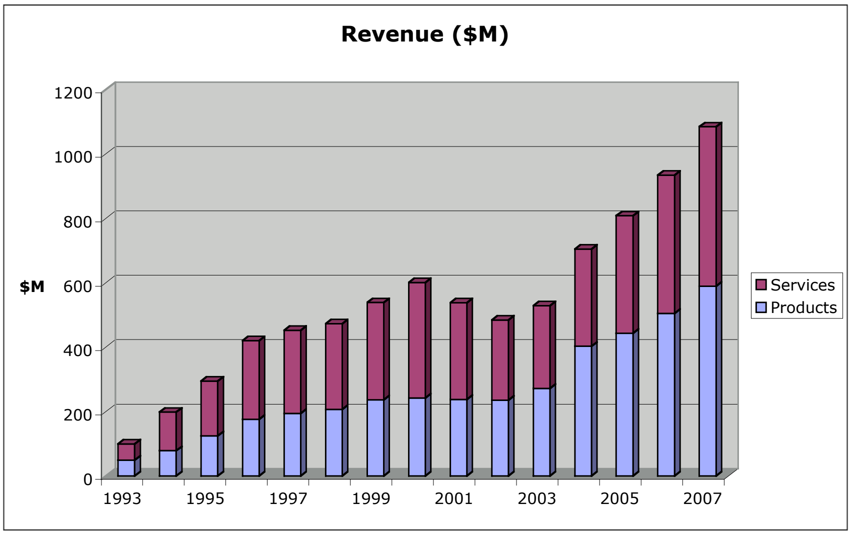
The market in 2005 for all products and services related to additive fabrication grew by over 15%[6] with corresponding new applications discovered and a reduction in the price of such system. As of today the lowest cost desktop 3D printing machines are in the $5,000 to $7,000 range.

Figure 10 – A desktop 3D printing machine

(Image from Desktop Factories web site, 2006)

The sale of additive fabrication systems themselves was up 10%[7] to $443 million, this is provided with trend and forecast in figure 11.

Figure 11 - Service and Product Revenue.



(Source data from Wohler Associates Report, 2006)

Though product revenue is increasing, the average sales price is reducing on additive fabrication machines, down 22% in 2005 – hence it is worth examining the volume of machines sold.

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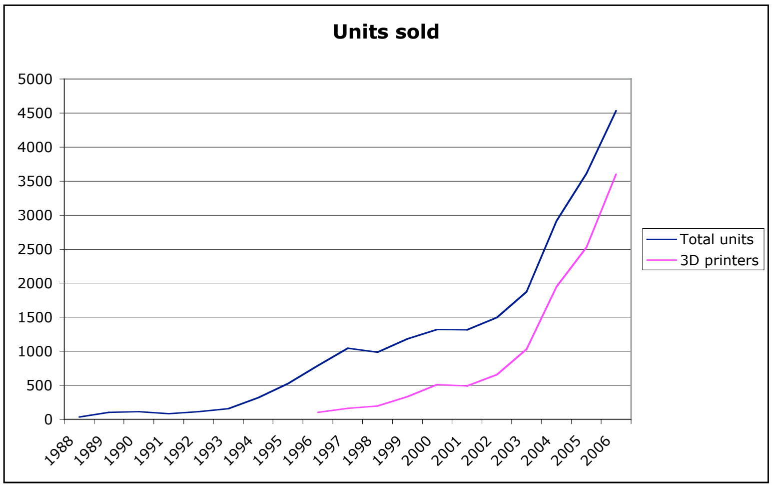
[6] *Wohler Associates, 2006 report.*

[7] *Wohler Associates, 2006 report.*

In 2005, the growth in the volume of additive fabrication machines sold was 23.9% over the previous year (see figure 12), and such double-digit growth has been experienced each year since 2001 with 3D printers taking an increasing share of the market.

Figure 12 - Unit sales of Additive Fabrication Machines



(Source data from Wohler Associates Report, 2006)

Of key interest however is the growth in rapid manufacturing, where the printed object is the final object. True RM systems are not currently available – what generally happens is that RP systems are being used to provide this service.

Wohler highlights that the benefits of RM are several-fold and that several groups are attempting to exploit such benefits: -

- Elimination of mould, dies and other tooling
- Flexibility and reconfigurability of the system
- Design freedom to explore new configurations and shapes
- High volumes are not needed to offset capital investment.
- Customisation of product

Micro – Electronic

Printed electronics is currently where silicon was fifteen years ago, as such it is generally accepted that there is little immediate potential for the replacement of the silicon chip and the incumbent industry.

However, this still leaves a wide area of potential applications from sensors, to RFID, to display to lighting and flexible electronics as well as semi finished products upon which silicon can be placed.

The majority of analysts forecast that printed electronics would be made using organic materials in the most part, however nano-particle (colloid) solutions have been used effectively in printing metallic electronics and this will become a significant market in itself.

The global market for organic electronics is provided in table 1, it must be noted that only a part of the $1 Billion p.a. market will use printing technologies, and though the majority of those are screen printing techniques it is expected that the use of inkjet printing within this market will expand.

Table 1 – Market for Organic Electronics in 2005.

Sector	**Market size**
Logic / Memory	$1 Million
OLED Display	$800 Million
OLED Bill boards	$1 Million
Non Emissive Displays	$50 Million
OLED Lighting	$20 Million
ES / RF Shield	$5 Million
Battery	$40 Million
PV	$4 Million
Sensor	$12 Million
TOTAL	$1.05 Billion

(Source data from idTech X, Printed Electronics Report, 2006)

The above does not paint a full picture for the potential application of printed technology today.

For example, the interconnect market is currently worth $40 billion[8] far outstripping the current OE market, with a number of companies specifically targeting this area (Xaar and Invint).

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[8] *Quote from IDTechX at Printed Electronics Conference, Camb, 2006.*

3.2 Applications

The following table provides an overview of where additive fabrication techniques are used today, with 3D printing being a significant part.

Table 2 – Examples of Additive Fabrication

Macro	**Examples where used**
Presentation Models	Architectural design, new product development
Prototypes & Concept models	Wide range of design, manufacturing and engineering companies.
Functional Models	Wide range of manufacturing companies.
Rapid manufacture	Avionics, Military, Consumer goods etc.
Visual Aids	Research etc.
Micro-Electronic	
Printed Displays	Samsung, Epson, CDT
Printed Chipless Circuits & Memory	Motorola, Thin Film Electronics, Epson
RFID	PolyIC, Philips
Interactive packaging	Cypak, VTT
Batteries and Photovoltaics	Konarka, PowerPaper etc.
Sensors & others	Numerous universities – Tokyo, California.
General	
Medical Applications	UCLH, Hospitals, Drug Trials etc.

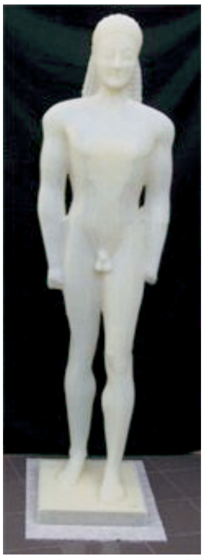
These are just some examples of the use of additive fabrication techniques, as these processes have found significant applications in a wide variety of industries and areas. It should be noted that several of the systems used have combined additive and subtractive techniques or contain multiple additive techniques (hybrid processes).

3.2.1 Macro: Presentation models

A number of companies use additive fabrication techniques for the creation of presentation models – from architecture to designs.

Materialise created a six-foot copy of the Greek Kouros statue using a steliography (SLA) process (see figures 13-14).

Figure 13 - The Materialise Kouros statue.



(Image from the Materialise web site)

Figure 14 - The statue at 24hr and 86hr build times

(Image from the Materialise web site)

A more common use is in architectural models, where many 3D printing systems are used (see figure 15)

Figure 15 - Example architectural models

(Image from the Z-Corp web site)

3.2.2 Macro: Prototype and Concept models

A wide range of companies use additive fabrication techniques (including 3D printing) for the creation of prototypes – from electronics housing to brake pad design and new consumer goods (see figures 16-18)

Figure 16 - Engine Block Housing.

(Image from the Z-Corp web site)

Figure 17 - Brake pad design

(Image from the Z-Corp web site)

Figure 18 - New plate design printed.

(Image from the Z-Corp web site)

3.2.3 Macro: Functional models

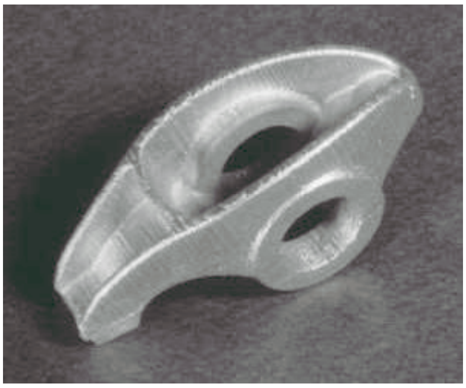
A wide range of companies are using these techniques for creation of functional models prior to some other form of mass production.

Peter Sferro, who introduced these techniques into Ford, provides one of the most dramatic stories of cost savings from the use of such techniques.

Ford was designing a new model of car, which required a particular design of rocker arm. Whilst engineering drawings were sent to four suppliers for quoting, an engineer at ford used the CAD diagrams to create a model through an SLA process.

The engineer discovered a wide range of problems with the design as a result of having the physical model, and was able to significantly improve the design (see figure 19). The new design along with the updated CAD diagrams were sent to the potential suppliers.

Figure 19 - SLA printout of Ford Rocker Arm



(Image from online case study into fabrication techniques)

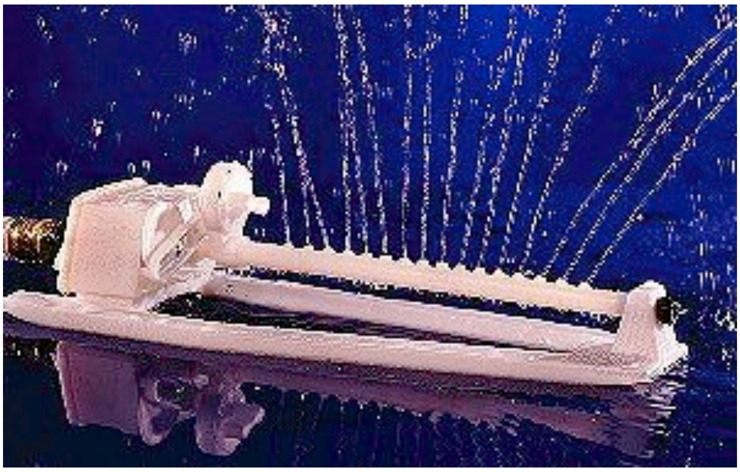
This actually solved another problem that the suppliers were having in understanding the original diagrams. The result was that not only did Ford resolve a number of design issues prior to manufacturing (which would probably not have been discovered) but also the suppliers were able from the physical models to work out more effective ways of manufacture – resulting in an annual $10M saving for this one part alone.

Other examples of the use of functional models are provided in figures 20 – 22

Figure 20 - Liberty Bell test part by Accelerated Technologies Inc

(Image from Castle Island, Case studies into RP & RM).

Figure 21 - Functional testing model of a sprinkler created with FDM



(Image from Castle Island, Case studies into RP & RM).

Figure 22 - Paintball mask created with SLS by Accelerated Technology

(Image from Castle Island, Case studies into RP & RM).

3.2.4 Rapid Manufacture (RM).

Rapid manufacture is where the produced objects are considered fit for use. Most of the areas have developed from using RP (rapid prototyping) techniques rather than specialised RM methods.

Examples include: -

Treviso Tecnologia: produce limited edition designer sunglasses in short runs (eg. 100 frames) – see figure 23

Figure 23 - Designer glasses produced using SLS

(Image from Treviso Tecnologia web site).

Materialise: working with a number of groups, to produce custom manufactured lights – using SLS techniques to produce the object, see figure 24

Figure 24 - Example SLS produced lampshade.

(Image from Materialise web site).

Phonak Hearing Systems (with Siemens): produce custom hearing aids. Using SL techniques.

EOIR technologies: produce battle ready components for the M1 Abrams tank with FDM techniques.

US Military: developed the Mobile Parts Hospital (MPH) that uses RP techniques to replace damaged components on military vehicles. This system has been in battlefield operation since 2003.

From RDECOM

A distressed Soldier entered the US Army Tank Automotive Research, Development and Engineering Center's Mobile Parts Hospital at a military camp in Kuwait, frantic for guidance in getting parts made to retrofit his HMMWV.

The Soldier was faced with a looming mission that was to take place at noon the next day. Having a design in mind, he approached the MPH team with a plan for a modified gun mount to attach a Squad Automatic Weapon to his vehicle. Getting precision parts and getting them quick was essential for the Soldier to complete his mission.

Racing against the clock, the MPH team successfully designed, manufactured and delivered the needed parts in a matter of five hours. The Soldier picked up and installed the parts early the next morning. While executing his mission the Soldier and his crew ran into an insurgent ambush, according to witnesses, the MPH gun mount enabled them to deter and repel enemy attacks safely, allowing for maximum firepower and a successfully completed mission.

Thousands of grateful Soldier testimonials have been sent to the MPH team, headquartered in Warren, Mich. Commenting on the team's speed and effectiveness of their work, 2nd Lt Bruce Neighbor with the 1486th Trans. Company in Iraq, spoke of the hospital as, "necessity in a theater of war." Neighbor, a frequent user of MPH, continues to spread the word on what a fabulous job the team is doing. "Simply put, the parts hospital has saved lives. I continue to bring more and more orders to the MPH, and they have fulfilled my every need."

Nearly 13,000 parts have been produced since MPH's deployment into theater, of which the SAW vehicle mount was awarded one of the Top 10 Greatest Inventions of 2003, by the US Army Materiel Command.

SAAB Avitronics: product the antennas for electronic surveillance devices using additive fabrication techniques.

These are just a few of the countless examples of RM that are starting to occur in all industries.

3.2.5 Macro: Visual Aids.

Additive fabrication techniques have been and are often used to help increase our understanding of complex structures – for example the Black Beetle Virus (see figure 25).

Major scientific breakthroughs on the Black Beetle Virus were discovered only when a university researcher decided to print out an exact copy of the virus (though some 20 millions times larger in actual size) using a LOM technique.

Though the virus had been extensively studied for two decades, was thought to be completely understood and its entire genetic makeup was known, the models revealed previously unseen geometric structures with profound effects for dealing with this virus.

According to the lead researcher "As soon as I saw the model, I was running around like a crazy man, showing everyone how stupid we had been"

Figure 25 - Model of a black beetle virus protein created for Scripps Research Institute

(Image from a "Touch of Science" by Kathy A. Svitil in Discover, June 1998).

3.2.6 Micro-Electronic (M/E)

Printed circuits have now become the end game and it is not just about displays, and thin film transistor circuits but also about power, sensors, actuators etc.

Motorola is targeting multi million dollar markets where the initial applications tend be low cost and low functionality such as interactive displays. Their focus is on printed flexible circuits, printed batteries and interconnects using techniques such as flexographic and jetting.

The following gives an idea of what applications are currently in proof of concept and beyond stages of production.

3.2.7 M/E: Printed Displays

Though printing is only used in part of the range of PLED / OLED displays, this is seen as a technology which can significantly reduce cost and improve yield.

For example, Samsung currently have a 40 Inch single sheet OLED panel which though it is not printed, part of the process includes inkjet printing.

Samsung's OLED technology is licensed from KODAK, and the company is currently investing $500 million in infrastructure for mass production of OLED displays by Q3 2006. Their intention is to ship 20 million units in 2007, this rising to 50 million units per year by 2008. Epson is another company planning to launch large OLED displays in 2007.

Both companies are actively investing in the use of printing technology for electronics. Figure 26 provides an overview of who is actively pursuing OLED (small molecule & polymer) displays and provides an example of where industrial printing techniques maybe used.

Figure 26 - Ramp up for OLED production

Country	Manufacturer	MG Size	Tech.	Material	Equip. Max 000/month	Q1'05	Q2'05	Q3'05	Q4'05	Q1'06	Q2'06	Q3'06	Q4'06	Q1'07	Q2'07	Q3'07	Q4'07
France	Thomson	370x470	AM	SM	2	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Germany	Samsung	200x200	AM	PLED	2	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Japan	Hitachi	370x470	AM	SM	6	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Japan	Pioneer	300x360	AM	SM	10	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Japan	Seiko Epson	400x500	AM	PLED	5	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Japan	TMD	200x200	AM	PLED	5	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Taiwan	CPT	550x670	AM	SM	10	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Taiwan	Chi Jing Optoelectronics Chi Mei)	370x470	AM	SM	10	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Taiwan	DuPont/RiTdisplay	370x470	AM	PLED	5	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Taiwan	Windell	300x420	AM	SM	5	🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
China	Varitronix	550x670	AM	SM	5		🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Korea	Samsung SDI	730x920	AM	SM	10			🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
Taiwan	Toppoly	620x750	AM	PLED	5			🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
Taiwan	Chi Jing Optoelectronics Chi Mei)	370x470	AM	SM	10				🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦	🟦
France	Thomson	300x360	AM	SM	5					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Japan	Seiko Epson	400x500	AM	PLED	10					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Japan	SK Display	550x670	AM	SM	10					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Japan	Toppan	600x720	AM	PLED	10					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Japan	TMD	400x500	AM	PLED	10					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Korea	Daewoo Industries	370x470	AM	SM	5					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Korea	Samsung SEC	730x920	AM	PLED	20					🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦	🟦
Japan	Casio	730x920	AM	PLED	10						🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦
Korea	Samsung SDI	730x920	AM	SM	10						🟥	🟥	🟥🟩	🟩	🟦	🟦	🟦
Japan	TMD	400x500	AM	PLED	10									🟥	🟥	🟥🟩	🟩

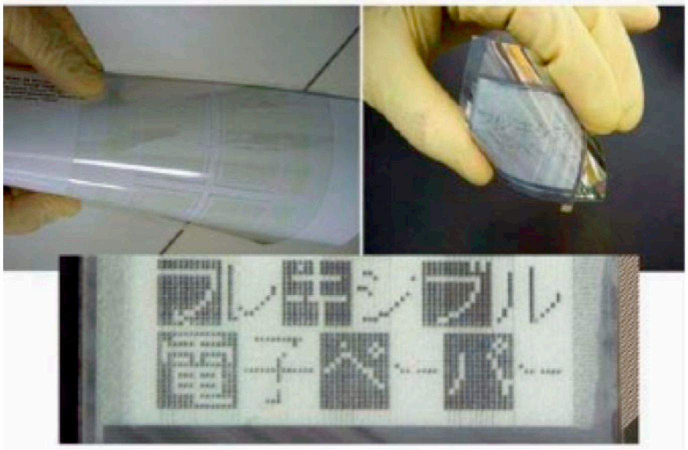
🟨 R&D/Pilot

🟥 Equipment Ordered 🟩 Equipment Installed 🟦 Mass Production

(data from Display Search, 2005)

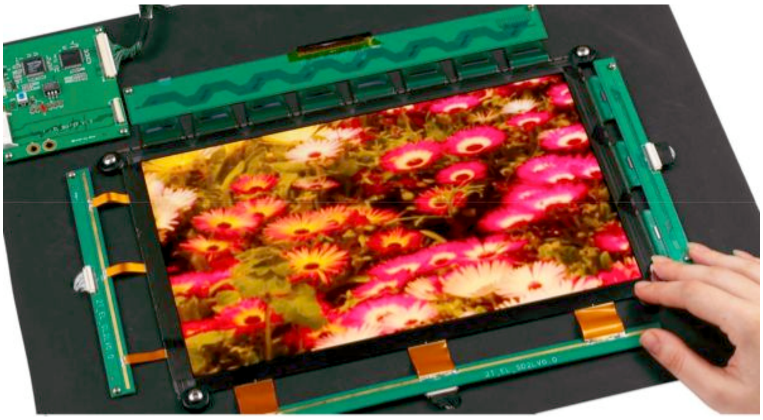
Of particular interest is Toppan Printing Company, who is actively involved in the development of E-Paper and other forms of flexible displays (see Figure 27) as well as the inkjet printing of PLED displays - a technique used by other companies such as Universal Display Corporation and CDT (see Figure 28). A key benefit of printing technologies is the ability to manufacture devices with all forms of substrates including flexible plastics.

Figure 27 - Demonstrators of flexible displays and E-Paper.



(image from IdTechX presentation on Toppan)

Figure 28 - A printed PLED 14" display.



(Image from CDT press release, April 2006)

To give an idea of the pace of speed in this industry, whilst writing this report, UDC have announced

Universal Display Corporation (NASDAQ: PANL), a leading developer of organic light emitting diode (OLED) technologies for flat panel displays, lighting, and other opto-electronic applications, today announced it has been awarded a $100,000 *contract to provide the U.S. Department of Navy with a prototype communications device based on a full-color, active-matrix OLED prototype built on metallic foil.*

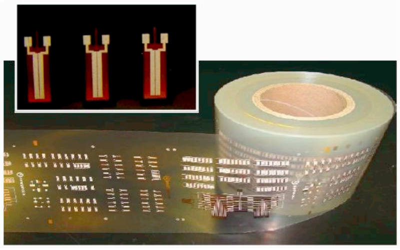
The significance of this is that flexible displays have gone beyond proof of concept.

3.2.8 M/E: Printed Chipless Circuits

Another key area of research and development is that of printed chipless circuits. Though at this moment in time, printed electronics is not seen as a replacement for silicon (basically due to resolution requirements), smaller and less complex circuits are seen as likely to be one of most common areas for printing techniques.

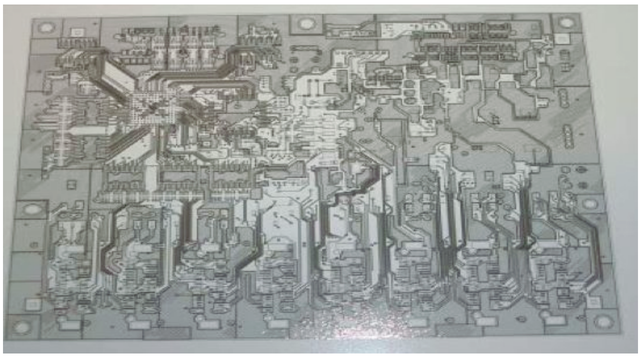
This includes such things as R2R printing of circuits, a process that has been pioneered by Motorola's Printed Electronics Group and others and is expected to be in production by 2007 (see figure 29). Desktop demonstrators of sheet feed printing of electronic circuits are already available (see figures 30 & 31).

Figure 29 - Examples of Motorola's printed electronics



(Image from Motorola presentation at Printed Electronics, Camb, 2006)

Figure 30 - Examples of sheet feed desktop printed circuits by Konica-Minolta



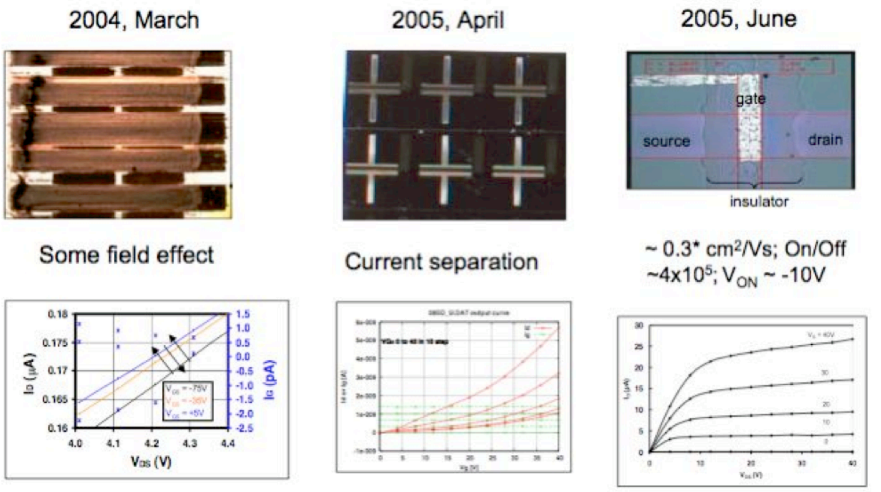
(Image from Konica - Minolta presentation at Printed Electronics, Camb, 2006)

Figure 31 - Demonstration desktop printer by Konica-Minolta

(Image from Konica - Minolta presentation at Printed Electronics, Camb, 2006)

A number of research groups and companies have been working in the area of printed circuits with active and passive components printed into them; of note is HP's work in the US. With thermal impulse inkjets – HP has successfully printed transistors and other components (see Figure 32)

Figure 32 - Inkjet printing of transistors.



(Image from HP presentation at Printed Electronics, Camb, 2006)

Furthermore, Transparent Thin Film Transistors (TTFT) have been printed with novel compounds such as Zinc Tin Oxides[9] and also more complex circuits combining multiple components (e.g. a six-ring oscillator) have been made.

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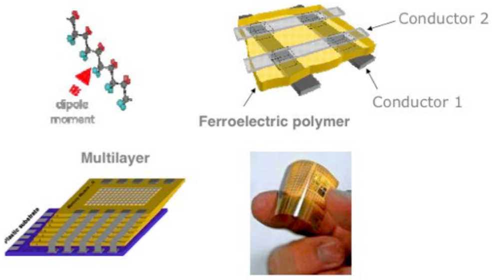
[9] *H.Q.Chiang, Applied Physics, 2005*

Beyond printed circuits and basic printed components, companies such as TFE *(Thin Film Electronics)* have developed printable non-volatile rewritable memory technology. TFE has developed polymeric Ferroelectric RAM (PFRAM) that uses polymers with dipole moments in an electric field to create read / write memory. This technique does not require transistors, it can be easily stacked, has fast read / write speeds and can be printed by inkjet, gravure or flexographic processes on a range of substrate (see figure 33). TFE is further developing this approach to include reader circuits that are printed into the device.

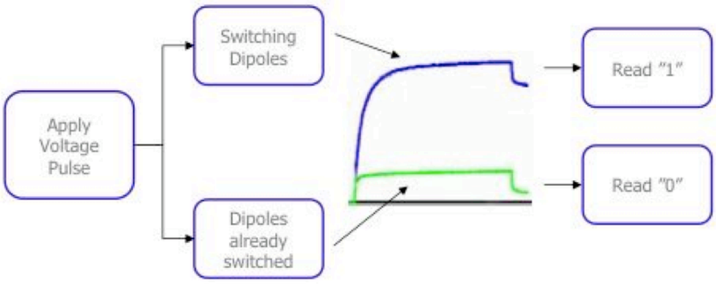
The system works by applying an electric field to the array, causing dipole switching of node points – see figure 34. This orientation can then be read in a destructive manner (e.g. each read requires a write back operation). The cells (or nodes) can withstand $>10^9$ operations and are non-volatile. Target applications for this are RFID, toys, smart packaging, unique ids etc.

Figure 33 - Printed PFRAM.



(Image from TFE presentation at Printed Electronics, Camb, 2006)

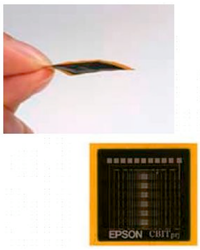
Figure 34 - Operation of PFRAM



(Image from TFE presentation at Printed Electronics, Camb, 2006)

Along with printed circuits, transistors and memory, groups such as Epson have developed techniques for printing with multi-layer circuit boards. Epson's 20 layer board is 200 microns thick, the silver wiring lines placed on each layer measure 50 microns wide and 4 microns thick with metal posts printed into the insulator layers to provide 2,480 interconnects between layers (see figure 35)

Figure 35 - Multi-layer circuit boards.



(Image from Epson Press Release, 2004)

In summary techniques exist today for

- R2R printing of circuits (incl. inkjet)
- Inkjet printing of components (active and passive)
- Printing of memory
- Printing of interconnects

These techniques are expected to find their way into industrial manufacture of electronics over the next few years.

Other examples include: -

- In 2000 Bell Labs researchers constructed an electrically powered organic laser by using FETs with organic tetracene crystals. This techniques has been further developed with companies such as Universal Display Corporation and others working towards printable organic lasers.

- In 2006, Epson announced that it has jointly developed a super bright OLED (which can be printed) in conjunction with Sumitomo Chemical Co. Ltd. This will enable small thin print heads to be created. The technology uses CDT's P-OLEDs.

- A number of research groups have shown success with printed optical sensors.

3.2.9 M/E: Printed RFID

A number of companies and institutions are working on the printed RFID. The use of printing techniques is seen as a way of significantly reducing RFID cost and to allow for item level tagging of objects.

The printing of RFID antennas is relatively straightforward, however the goal has been towards the printing of the entire RFID tag.

Printing RFID Antennas: Using a gravure process with Parmod Silver Ink (flaked silver particles), Parelec has created printed silver antennas with characterstics superior to those of etched copper or aluminium. It should be noted that

- Antennas are 4 microns thick
- The process produces no waste
- The cost of the antenna is $0.005 and 9x cheaper than etched counterparts.
- A single gravure process can create 48,000 Antenna per minute.

Printing entire RFID: over the last six months, a number of significant announcements have been made.

- *IMEC, Belgium*
  Printed organic diodes capable of rectifying signal at 50MHz.

- *Philips, Netherlands*
  Printed a multi-bit, 13.56Mhz plastic RFID chip.

- *PolyIC, Germany*
  Printed an 8 bit, 13.56MHz TFTC RFID tag.

At this moment of time there are no commercially available fully printed RFID tags, however this is expected to change soon with companies such as ACREO using printing techniques in trial for the production of chipless RFIDs.

3.2.10 M/E: Interactive Packaging

Various companies are examining and testing printed electronics in packaging and tape to provide interactive packing and security products.

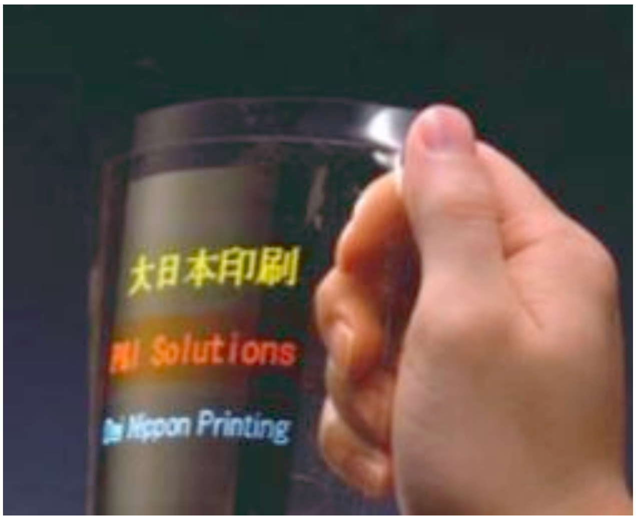
A noted example of this is Cypak who use a mix of printed circuits and non-printed components to produce Secure Cartons. This provide information to the end user on when the carton has been opened, and are primarily focused for the postal industries (see Figure 36)

Figure 36 - Secure Carton

(Image from Cypak Presentation, Printed Electronics, Camb, 2005)

However, the industry expects that novelty and other brand enhancements using simple printed electronics on packaging and products to be developed soon. It should be noted that these innovations are being driving primarily by printing and packaging companies (e.g. Toppan, Dai Nippon) as opposed to electronic manufacturers and are expecting to commercialise these products in 2007 (see figure 37).

Figure 37 - Dai Nippon printed displays



(Image from Dai Nippon web site)

VTT also has a number of demonstrators for such products (see figure 38) combining both traditional packaging printing with electronics printing and display components.

Figure 38 - Demonstrators for interactive packaging.

Hockey and jungle game demonstratos

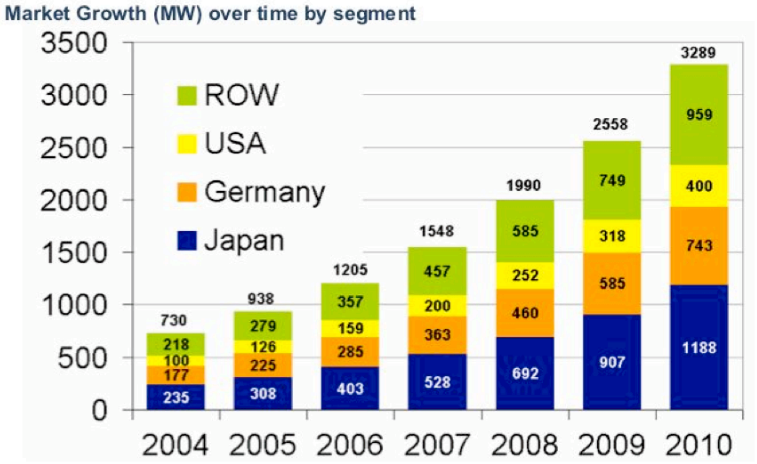
7 printed layers
- conductors
- dielectrics
- heating elements
- thermo chrome ink

(Image from VTT presentation, Printed Electronics, Camb, 2006)

3.2.11 M/E: Batteries and Photo Voltaics

One of the major issues with photovoltaics is its reliance on the silicon industry and the competing interests of the silicon chip manufacturers. PV is a growing market (see figure 39) with strong interest due to the issues of global warming.

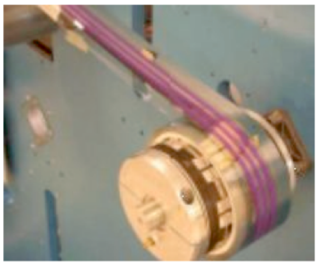
Figure 39 - Estimated Growth of PV Market



(Data from Konarka, 2006)

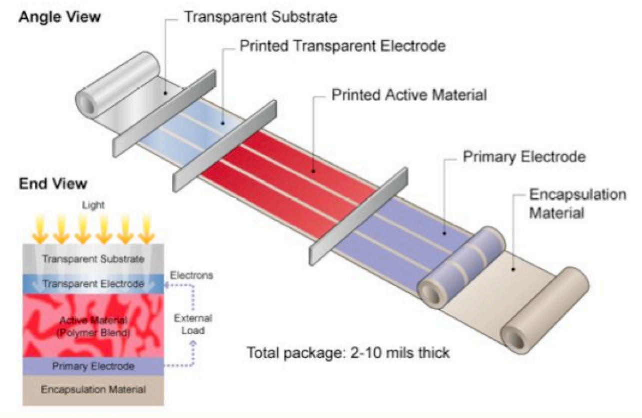
A number of military and industrially sponsored projects exist to examine the possibilities for printed PV's. Of note, Konarka has already begun testing of printed batteries and photo-voltaics in commercial interactive packaging. The company uses a R2R (reel to reel) process of manufacture (see figure 40 and 41) that combines both printing and more traditional methods of encapsulation.

Figure 40 - Example of printed PV's.



(Image from Konarka presentation, Printed Electronics, Camb, 2005)

Figure 41 - Method of OPV production.



(Image from Konarka presentation, Printed Electronics, Camb 2006)

Along with PVs, several groups are currently involved in printing batteries – for example Varta GMBH have a process for printing flexible batteries (see figure 42) and are currently examining methods of integrating this with more traditional techniques.

Figure 42 - Flexible printed battery

(Image from VARTA Gmbh presentation, Printed Electronics, Camb 2006)

Also Toppan have launched audio paper for use in cards and promotional throw away. The paper is made with a printed battery and a flexible actuator.

3.2.12 M/E: Sensors and other areas

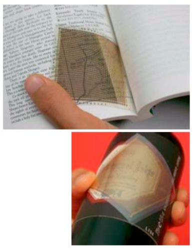
A wide variety of research, proof of concept and demonstrators are available for printed sensors. Of note are: -

University of Rochester
B. Kahn has been using flexographic techniques to print environmental sensors.

University of California
Developed a printed “nose” sensor for organic gases in consumer packaging[10].

University of Tokyo
Has developed an organic flexible image scanner. The scanner has no moving parts but consists of a polymer laminate sheet containing a two dimensional array of organic transistors and organic photo diodes. The sheet uses ambient light to detect an image (see figure 43)

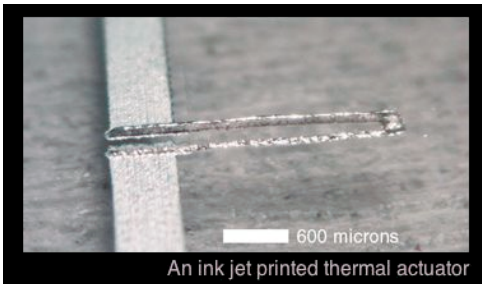
Figure 43 - Organic Flexible Image Scanner



(Image from IDTexchX presentation, Printed Electronics, Camb 2005)

MIT, Centre for Bits and Atoms (CBA)
CBA has developed techniques for printing micro machines, sensors and actuators (see figure 44).

Figure 44 - Inkjet printed thermal actuator



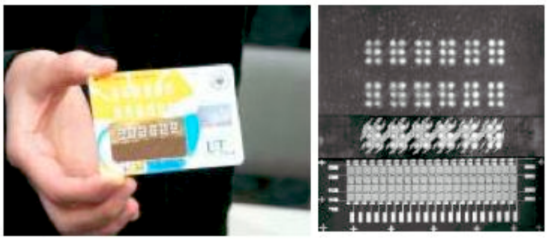
(Image from CBA website)

Kodak
Has developed an organic Braille display using organic transistors and actuators made from polymer materials. Projecting and retrojecting the surface using electricity forms the raised letters (see figure 45).

---

[10] Vivek Subramania, University of California, Low Cost Printed Electronic Nose Gas Sensors, 2005

Figure 45 - Organic Braille display



(Image from IdTechX presentation, 2005)

3.2.13 Macro & M/E: Medical Applications.

Object printing is already used in a number of medical facilities. On a macro scale this varies from visual aids to building of medical devices (see figures 46 & 47)

Figure 46 - UCLH, Visual aid for damaged skull, model produced from X-rays.

(Image from web, 2003)

Figure 47 - Plastic model of skull used to help doctors in planning patient's reconstructive surgery.[11]

(Image from web, 2004)

However micro-electronic printing is also used in smart packaging materials, principally for drug trials and testing. Cypak commercially produce packaging that is capable of recording patient activity – the packaging at this current time uses a mix of printed material (including circuit) and integrated non-printed components (see figure 48).

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[11] Steve Deak, Hasbro, Inc.

Figure 48 - Cypak smart packaging, CEREPAK.

(Image from Cypak Presentation, Printed Electronics, Cam, 2005)

Another use of printing technology is in the creation of smart patches. A number of companies are developing such products, and a few have made commercial releases (e.g. Estee Lauder in Japan) – see figure 49

Figure 49 - Smart patches, Paper Power.

(Image from Power Paper Presentation, Printed Electronics, Cam, 2005)

3.2.14 Summary

The above examples use either 3D printing directly or related additive techniques.

Using these techniques you can create: -

- Large-scale physical objects
- Substrates and supporting structures
- Electronic circuits
- Electronic components
- Display components
- Sensors and Actuators
- Batteries and PVs

No single system exists which is capable of spanning all these areas; though in many cases the technology is common.

The biggest obstacle to applications on both the macro and micro-electronic scale would appear to be education and the need to move away from a more traditional mindset of manufacture. In some cases this is happening in a piecemeal fashion – the use of RP techniques for RM etc.

One company stands out as attempting to address this issue of education. Elumin8 provide screen-printed electroluminescent large displays and through sponsorship of design colleges and design schools they have managed to achieve notable adoption of this new technology.

3.3 Competitors

At first glance, one would suppose that the typical competitors for this new industry would be the traditional manufacturers of electronic components.

However this new industry changes electronic manufacture to a printing technology business and opens the door to a wide range of new competitors (as for example Toppan).

As printing is at the heart of this process, it is questionable as to which group of companies are best placed to take advantage – electronic companies with a heavy investment in traditional electronics manufacture or printing companies with a heavy investment in printing techniques?

The following gives a breakdown of their relevant strengths and weaknesses and an examination of organisational types – table 3

Table 3 – Company and Organisational Type

Company Type	**Strengths**	**Weaknesses**
Printing *(P)*	• Printing Experience • Process Capability • Substrate Knowledge • Plate making • Prepress imaging • Access to customers • New business opportunity	• Lack of electrical engineering knowledge • Capitalization
Electronics Manufacture *(E)*	• Large investment capability • Familiar with silicon manufacturing • Ultra clean environments • Strong electronics understanding	• Lack of printing knowledge • Change in direction of existing business with a well established value.
New Entrants *(NE)*	• Clean slate • 1st to learn new design rules • Pioneer in new industry • Closest to market opportunity	• Clean slate • 1st to learn new design rules • Furthest from existing markets.
Material Company (M)		
Specialist Equipment Manufacturer (SEM)		
Organisation Type		
Large Corporate *(L)*	• Resources • Existing market • Technical market	• Inertia • Management • Non-core investment
Startup *(S)*	• Nimble • Result orientated • Investor driven	• Constraints • Burn rate • Critical Mass / Credibility

(Based upon source data from IDTechX, 2006)

This new industry has the potential to change electronic manufacture and object creation in a significant and profound way. It does not hold that the incumbent manufacturers have an automatic right to this new industry, and it may well occur that some traditional electronic manufacturers will find this transition and the resultant change in business direction impossible to achieve.

I have provided a summarised list of potential competitors (table 4), their focus and their type. A more in-depth list of companies working in this area is provided in the index.

Table 4 – Potential Competitors

Company	Type	Organ.	Macro	Micro-Electronic	Hybrid
HP	E	L	🟧	🟧	🟧
Man Roland	E	L	🟧	🟧	🟧
Epson	E	L	🟧	🟧	🟧
Motorola	E	L	🟧	🟧	🟧
Siemens	E	L	🟧	🟧	
Fuji	E	L	🟧	🟧	
Konica – Minolta	E	L	🟧	🟧	
Cabot	M	L	🟧	🟧	
DuPont	M	L		🟧	
Sumitomo	M	L		🟧	
Toppan	P	L		🟧	
Kodak	E	L		🟧	
Agfa	E	L		🟧	
BASF	M	L		🟧	
Nokia	E	L		🟧	
Sony	E	L	🟧		
Plastic Logic	NE	S		🟧	
PolyIC	NE	S		🟧	
Z-Corp	SEM	S	🟧		
3D System	SEM	S	🟧		

(Data collected from found activities of companies)

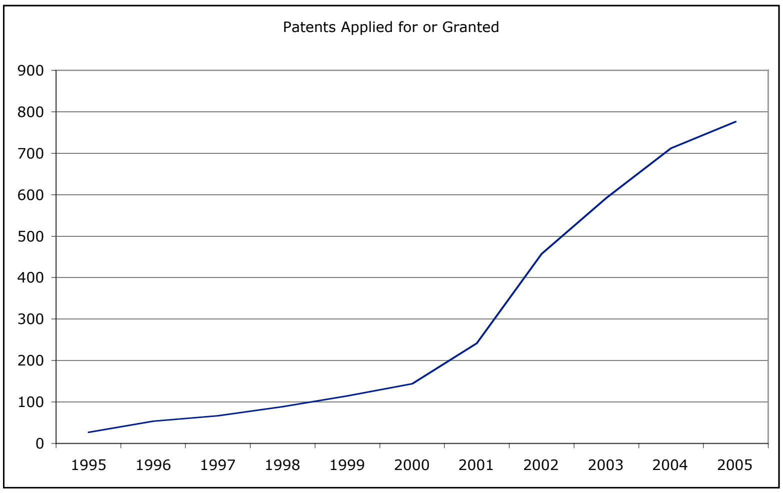
3.4 Technology

Over the last decade there has been a significant growth in the number of techniques and the capabilities of such techniques.

3.4.1 Patents

Though not a true indicator, some idea of the growth of interest can be seen from the patent applications within this field as shown in figure 50.

Figure 50 - Patent growth.



(Source data is Castle Island)

This data is primarily related to rapid prototyping mechanisms (macro), however there exists significant movement in the patent field for Micro-Electronics printing, with key patents already established.

[e.g CN1425204 / US2005026317 in 2003 & 2005 - "A method for forming an integrated circuit including at least two interconnected electronic switching devices, the method comprising forming at least part of the electronic switching devices by ink-jet printing."]

A wide variety of companies are also filing patents in the area of TFTCs (thin film transistor circuits) and printed memory – e.g. HP, Intel etc.

It is notable that a concentrated group of Japanese companies (Matsushita, Ricoh, Dai Nippon Printing) have generated a large number of patents mostly for printed memory and its application to RFID. According to Smart Labels Analyst, March 2006, there is a strong Japanese interest in the printed RFID area.

For the rest of this section, I'll examine the core technologies and materials involved in Macro and Micro-Electronic printing.

3.4.2 Core Processes

According to A.Maier[12] many different processes are employed in the world of rapid prototyping. This list is expanded when you consider the micro-electronic printing world. In table 5, I've summarised the main technologies and their use.

Table 5 – Common technologies used.

Technology	Direct Deposit Process	Macro	Micro - Electronics
Screen	Yes	No	Commercial
Inkjet	Yes	Commercial	Commercial
Flexographic / Gravure	Yes	No	Commercial
SLA	No	Commercial	No
SLM	No	Commercial	No
FDM	Yes	Commercial	No
SLS	No	Commercial	No
LENS	Yes	Commercial	Possible
DLP	No	Commercial	No
LMJP	Yes	Proof of Concept	Proof of Concept
Direct Write Methods	Yes	No	Proof of Concept
Mask patterning	No	Commercial	Proof of Concept
Stamp processes	Yes	No	Production
Mass Production Techniques	Yes	No	Commercial
Surface Treatment	No	No	Prototype

(Data collected from found uses of technology)

Examples of the above are given below, more details are provided in the appendix:

Screen

- Elumin8 is using screen-printing techniques for the production of electroluminescent billboards.
- VTT is currently at prototype stage with techniques for producing thermochromatic displays on paper packaging.
- Sony is using screen-printing for the production of keypads.
- ACREO is using screen-printing techniques for trial production of chipless RFID.

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[12] *A. Maier, Rapid prototyping and Tooling, 2003,*

Inkjet

- Plastic logic is using inkjet techniques in trails for the production of chipless transistor circuits on flexible substrates.
- Objet Geometries and SolidDimension provide a number of inkjet based systems for the production of prototypes.
- ProMetal provides the S15 system, which uses inkjet technology to fuse sand into moulds for final product casting.
- 3D systems provide the Invision system which uses MJM (an inkjet based technique) to direct print polymer based objects.

Flexographic / Gravure

- PolyIC is trialling flexographic techniques for the production of chipless transistor circuits.
- Omron is using in production Gravure technology for the high volume printing of antennas.
- Dai Nippon Printing is at the experimental stage of using Gravure printing for the production of OLED displays.

SLA (Steliography)

- A process that fabricates a part layerwise by hardening a photopolymer with a guided laser beam
- Sony provides a commercial system.

SLM (Selective Laser Melting)

- Similar to SLS but uses metal powders.
- F&S GmbH of Germany provides a commercial system.

FDM (Fused Deposition Modelling)

- Extrusion of plastic material directly onto target.
- Stratsys provides a commercial system.

SLS (Selective Laser Sintering)

- Fabricates through a layering process of powder combined with sintering through a laser.
- 3D systems provide a commercial system.

Laser Engineered Net Shaping (LENS)

- Injecting powdered metal into focus of laser.
- Optomec provide a commercial system.

DLP (Digital Light Processing)

- Texas Instruments method of RP using a photopolymer and digital image.
- Envision Technology provides a commercial system.

LMJP (Liquid Metal Jet Printing)

- Under development at the University of Texas, the LMJP method allows the printing of metals at resolutions of 100 microns using a process similar to inkjet. The work covers metals such as copper, aluminium and has been used for both model manufacture and circuit interconnects.

Direct Write Methods

- This covers
    - Micro and Dip Pen
    - Thermal / Plasma Spray
    - E-Beam
    - Focused Ion Beam
    - Laser Direct Write
- A number of groups, mainly research institutes are working in this area.

Mask patterning

- Shadow mask patterning: material is heating in a vacuum, and evaporated particles are absorbed onto the substrate through a mask. Technique is additive and is used widely in research units. Suffers from low deposition rate.
- Solid Ground Curing (SGC): A UV light and a mask are used to expose an entire surface of powdered material, Cubital provides a commercial system.

Stamping

- Commonly known as soft lithography, use a patterned elastomer or some other material to imprint image onto substrate.
- Also includes pad printing.

Mass production processes

- A number of companies have been working extensively on high volume manufacturing techniques.

- Mass production techniques fall into two distinct bands – R2R (reel to reel) and Sheet Fed *(e.g. Man Roland concept hybrid printer)*

- For both methods, non-contact printing (i.e. inkjet) and contact printing (i.e. Gravure or flexographic) have been used. Both these technologies have distinct characteristics, these are summarised in the table below

Table 6 – Comparison on printing methods.

Method	Advantages	Disadvantages
Inkjet	Digital input Low viscosity inks Strong body of research	Pixilation Slow Accuracy
Gravure / Flexographic	High throughput Good pattern repeatability	New technique High viscosity inks

(Source data from Motorola, 2006)

Surface Treatment

- There are a number of different techniques of which nano-imprinting is of particular interest. HP has used nano-imprinting in order to improve the resolution of its thermal inkjet printed circuits. Most recently NanoIdent has claimed resolutions of 15 nm using this technique. One issue is that nano-imprinting is not amenable to digital production methods.

3.4.3 Hybrid process.

Some work has been undertaken regarding hybrid process – i.e. those that either contains a multiple of printing techniques or a mix of additive and subtractive methods.

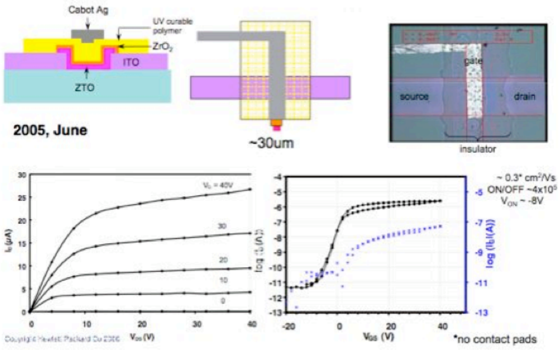
On the macro scale – the Concept laser uses both laser sintering and laser machining.

Whilst on the micro-electronic scale, HP has achieved notable success by combining thermal inkjet methods with laser ablation. The following figure 51 is taken from an HP report on printing electronics and shows how a transistor has been developed using: -

- Thermal inkjet printing of Silver, Zinc Tin Oxide and other layers.
- Thermal inkjet printing and UV curing of an insulating polymer layer.
- Laser ablation for the source drain gap.

It is not clear from the report whether the initial substrate layer (assumed to be some form of flexible polymer) was itself thermal inkjet printed.

Figure 51 - HP’s used of hybrid techniques for transistor manufacture.



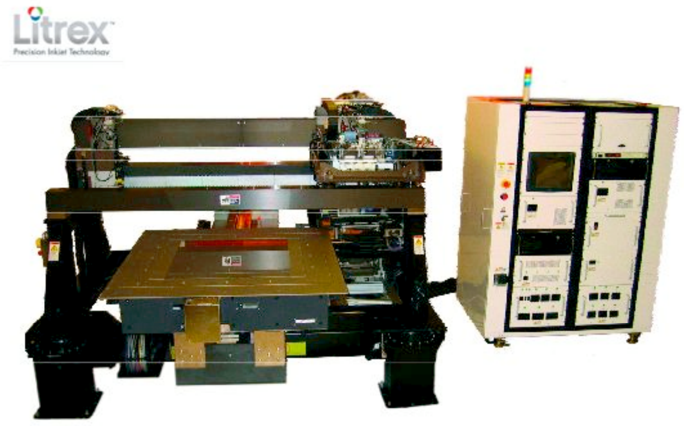
(Image from HP presentation, Printed Electronics, Camb, 2006)

OTB display provides commercial systems for the inline production of OLED displays. Their process uses a number of techniques including: -

- Inkjet printing
- Small molecule deposition
- Plasma enhanced chemical vapour deposition
- Cathode deposition

In March 2006, Litrex shipped its Gen-5 printer for the manufacture of OLED displays (figure 52) that uses inkjets to fabricate panels.

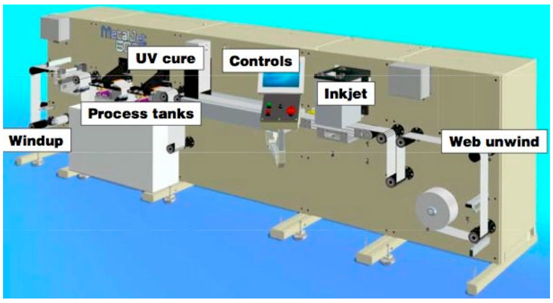
Figure 52 - Gen 5 printer for OLED manufacture



(Image from Litrex site)

In April, 2006, Conductive Inkjet announced the commercial availability of its metal inkjet printing system, which combines inkjet printing and metallisation in a R2T system (see figure 53)

Figure 53 - Conductive Inkjet, Inkjet Metallisation System



(Image from Conductive Inkjet presentation, 2006)

These hybrid process will be key to the future development of this industry, though pure play inkjet systems such as the PixDro 5 micron inkjet material printer (see figure 54) will find a niche market in early materials research and testing.

Figure 54 - PixDro, material inkjet printer.

(Image from PixDro web site)

3.4.4 Merging of technologies?

Of all the techniques so far discussed, only inkjet has been widely used both for macro and micro-electronic manufacture.

The very nature of inkjet (being contact-less) lends itself to large object formation in a manner that contact techniques such as flexographic or gravure printing would not.

Equally, the ability to deal with multiple materials lends inkjet to the micro-electronic world in a manner that SLS, 3DPtm and SLM cannot.

Furthermore though inkjet technology is slower than other techniques, it gains from the ability of digital printing to create varied and different components rather than repetition of the same structure.

Thermal inkjets have also been tested with a wide variety of materials (as per piezo and accoustic).

For these reasons, inkjet is seen as a leading contender for manufacturing – though as per the HP and Concept Laser systems it is likely to form the additive component of hybrid like systems.

This does not mean other techniques will not find their niches – as in mass production or novel mechanisms – however I firmly believe that inkjet will take centre stage.

At the time of writing, there are no commercial systems for hybrid object manufacture, dealing with both Macro and Micro-Electronic scale.

3.4.5 Materials

The properties required vary with the technology used (processability i.e. in the case of inkjets viscosity is critical) as well as the desired result.

For Micro-Electronics the general characteristics most looked at are stability, processability, conductivity and strength. Small molecule organics are of interest in this area because of their suitability to the process and their mobility (which according to IDTechX in some cases exceeds that of amorphous silicon – though I have found no evidence to support this.).

A number of companies are specifically investigating small molecule organics for use in TFTCs. These include Epson, Motorola, IBM, ICM, Hitachi, Sony, Toppan and others. Organic materials are of particular interest over inorganics because they can be deposited at much lower temperatures (the exception to this rule being nanoparticle solutions), they can be deposited by low cost techniques such as printing and spin coating and there exists an abundance of organic material.

Also of interest are nanoscale materials such as colloids and dispersions, powders, nanotubes, nanowires, nanoparticles and engineered ligands.

Nanoparticles show a reduction in melting point relative to bulk counterparts[13]. The particles can be stabilized in solution by encapsulation with organic ligands – such ligands being removed after printing through some form of treatment, eg. UV curing or heat treatment.

Such materials are actively being used in research and trial application, enabling the inkjet printing of metals. The following companies are actively pursuing these lines of research: - Toppan, ACREO, Hitachi, Epson, Sony, Philips and Toshiba.

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[13] Hung et al, Electro Chem Soc, 2003

Mobility is obviously a critical issue, the following table 7 provides some recorded mobility of materials used by the Motorola Printed Electronics Group.

Table 7 – Mobility of materials

Material	**Mobility (cm^2/Vs)**
Carbon Nanotubes	10,000
Gallium Arsenide	5,400
Crystalline Silicon	1,500
Inorganic Nano-enabled inks	**600**
Amorphous Silicon	1 to 10
Organic (small molecule)	0.61
Organic (polymer)	0.1

(Data from Motorola, 2006)

I've summarised the general properties required for different types of components in table 8.

Table 8 – Key requirements of inks for micro-electronic printing.

Use	Characteristics
Conductor	High conductivity Small particle size (high res. Printing) Uniformity
Dielectric	High dielectric strength Moisture resistance Thin film formation High solvent resistance
Semiconductor	High mobility High solvent resistance Stability Thin film formation
Insulating barrier	Moisture, Oxygen and light resistance

3.4.6 Material and printing process

As mentioned, the functional requirements of the ink depend not only on the result required but also the process technology. One of the key issues often raised with thermal inkjets, is their limitation with materials.

As a counterpoint to this, I will refer purely to HP's and others' work with thermal inkjets and the materials that they claim they have successfully printed with. These include: -

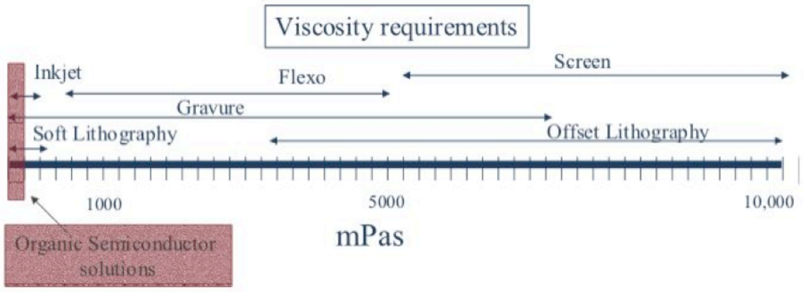
Table 9 – Example materials printed with thermal inkjets.

Ethanol	Diluted Salts	DNA
Methanol	Hexanoic acid	PEDOT
Gasoline	Toluene	Chloroform
Acetonitril	Ammonia in water	Polyaniline
OLED in toluene	Acrylic monomers	Metal nano-particles[14]
Zinc Tin Oxide	Indium Tin Oxide	Silica in water
DNA	Adhesives	UV Curable Acrylate
Quantum dots in water	Carbon nanotubes	Methyl Chloride
Phosphoric acid in water	Ceramics[15]	Silver Metallorganic

(Data taken from multiple sources including HP)

Some materials are obviously more suited for certain types of printing processes than others. A number of factors affect this processability, for example viscosity (see figure 55)

Figure 55 - Viscosity and suitability for printing process, Konarka 2006.



(Image from Konarka Presentation, Printed Electronics, Camb, 2006)

3.4.7 Printing technology

Other than the process and the materials used, what sort of factors affect the choice of printing technology in particular with inkjets?

Inkjets are already a proven and established method that offers the potential to rapidly mature to a manufacturing technology.

The inkjet process itself has the following characteristics: -

- Data driven and direct control of composition
- Additive (and therefore offers material efficiency)
- Operates at ambient atmospheres
- Compatible with a variety of substrates

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[14] A.D. Bernel and D.E. Bugner. Particle size effectsin pigmented inkjet jet inks. Journal of Imaging Science, 1999.

[15] P.F Blazdell, J.R.G Evans, M.J.Edirsinghe – Computer aided manufacture of ceramics using multilayer jet printing. Journal of Material Science, 1995.

- Reduces environmental impact

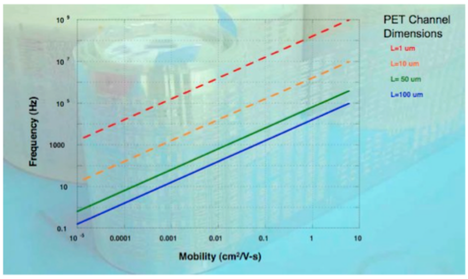
As a general rule the technology in the micro-electronic scale needs to provide

- High precision drop placement, less than 1 micron (accuracy)
- High resolution (width)
- Repeatability (registration)
- High throughput
- Control of line thickness (drop size)

These areas are critical because the performance of printed electronics depends not just upon material properties but also physical properties such as printed resolution and printed thickness.

For example, figure 56 shows some printed electronic transistors (PETs) with different dimensions of channel width (source data Motorola Printed Electronics Group).

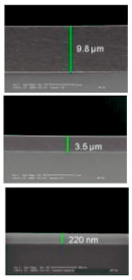
Figure 56 - Variation of properties with channel dimension in PET.



(Image from HP Presentation, Printed Electronics, Camb, 2006)

Some considerable progress has been made in the last two years, in all these areas. HP has also developed techniques for accurately controlling line thickness – these are still proof of concepts (see figure 57)

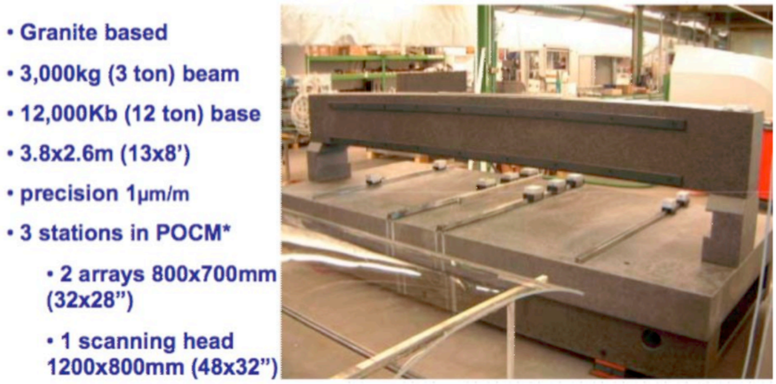
Figure 57 - HP's control of line thickness through inkjets 10 micron – 200 nm.



(Image from HP Presentation, Printed Electronics, Camb, 2005)

Printed Electronics Ltd is working on a large scale proof of concept printer, using Xaar side shooter printheads. The issues being addressed are registration and, critically, accuracy - the system has an accuracy of 1 micron per metre (see Figure 58)

Figure 58 - proof of concept printer.

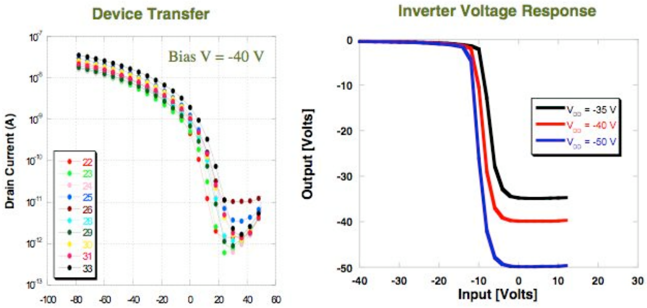


- Granite based
- 3,000kg (3 ton) beam
- 12,000Kb (12 ton) base
- 3.8x2.6m (13x8')
- precision 1μm/m
- 3 stations in POCM*
  - 2 arrays 800x700mm (32x28")
  - 1 scanning head 1200x800mm (48x32")

(Image from PEL Presentation, Printed Electronics, Camb, 2006)

By careful use of process, material and technology some outstanding results have been achieved by various groups around the world. Motorola has been able to consistently and repeatedly print stable circuits and system. Figure 59 shows the results for repeatability and reproducibility of a 10,000 print run of electronic transistors.

Figure 59 - Example data from 10,000 printed transistors production run.



(Image from Motorola P.E.G, 2006)

Equivalent results have been achieved with multi ring oscillators and other simple circuits. In the last year, Motorola has claimed that is has printed over five miles of functional and reliable circuits.

Accuracy and drop size are other key issue. Though a number of groups publicly admit to being able to print at a resolution of 5 microns, privately some groups have had repeatable success at 1 micron resolution.

Furthermore a number of groups are examining self assembly materials, ie alternate drops of repelling material which are overlapped and self assemble to provide resolutions in the nanometre scale – this work is unpublished.

3.4.8 Resolution

As discussed above component properties are significantly affected at the micro-electronic scale by such physical issues as resolution and layer thickness. In general this is not dependant upon the process but how well developed the technology is within that process – for example gravure printing has traditionally never required such high resolutions, and hence development of the process in this manner has only begun recently.

Table 10 provides an overview of the different processes and the best resolutions achievable with those processes.

Table 10 – Process and Technology, current limitations.

Technology	Resolution (microns)	Line Thickness (microns)
Inkjet[16]	10	0.2
Flexographic[17]	15	0.5
SLM[18]	<25	20
SLA[19]	25	25
Screen[20]	100	7
SLS[21]	<100	<100
FDM[22]	100	100

(Source data taken from general review of current published articles).

It is worth noting that in 1970, etched line widths were 250 microns.

3.4.9 Comparison to established technologies

Process, material and technology are just a few of the critical issues in this new industry, other include finishing (surface energy treatment etc) and software.

It is worth however examining how these technologies stand up against more traditional methods.

On a micro-electronic scale, VTT undertook a study to compare the properties of organic semi-conductors manufacturing using spin coating techniques in a clean room and those created using gravure printing, the result is summarised in figure 60.

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[16] Source HP presentation, 2006 and TTP presentation, 2006.

[17] Source data Konarka presentation, 2006, Printed Electronics, Cambridge UK.

[18] MCP Rapid Realiser specification.

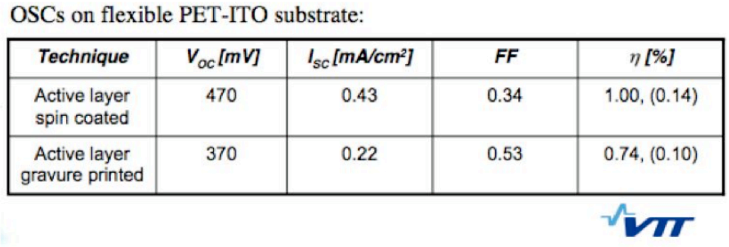
[19] 3D systems, Viper SLA 700.

[20] Source data Konarka presentation, 2006, Printed Electronics, Cambridge UK.

[21] CastleIsland, Guide to Rapid Prototyping.

[22] Stratsys, FDM Titan Specification

Figure 60 - Comparison of properties through different means of manufacture.



OSCs on flexible PET-ITO substrate:

Technique	V_{oc} *[mV]*	I_{sc} *[mA/cm^2]*	*FF*	η *[%]*
Active layer spin coated	470	0.43	0.34	1.00, (0.14)
Active layer gravure printed	370	0.22	0.53	0.74, (0.10)

(Image taken from VTT presentation, Printed Electronics, Camb, 2006)

4 Other’s views on the future.

Printing today is used to manufacture both macro and micro-electronic objects; the progress in the last decade has been remarkable.

This new industry has started to create some shockwaves, and a cursory examination of the popular press paints a picture that 3D printing of electronics and objects is about to revolutionise the world.

“Direct printing **completely changes conventional** electronic manufacturing” *[Nokia, 2005]*

“Inkjet Printed Electronics” & “Desktop Factory” are part of Epson’s **vision for the future**. *[Epson, 2005]*

“Some **seismic opportunities** to replace things such as most lighting, LCD / CRT, simple silicon chips” *[IDTechEx on printing electronics 2005]*

“Printed functionalities have the potential to open **future markets**” *[Agfa, 2005]*

”Rapid manufacturing promises to **transform supply chains**” & “**unleash** an era of personalized **customization**.” *[Business Week, 2005]*

“Inkjet is a **viable manufacturing tool**” *[Xennia, 2005]*

“Businesses and governments all over the world recognize that plastic electronics is going to be an **important new industry** – the race is on” *[PlasticLogic 2005]*

A printed electronics company was named as one of the top ten companies most likely to **transform our world** by Harvard Business School. *[August, 2005]*

“The implications of spray-on electronics could be huge. **Chip-production costs** could — drop by **50 percent**.” *[Newsweek 2005]*

“We are talking about a future with pervasive printed electronics seamlessly integrated into everyday life” *[Motorola 2006]*

In today’s climate, groups such as Intel Venture Capital are heavily investing in companies in this area; over a 100 companies (large and small) are researching and trialling new systems.

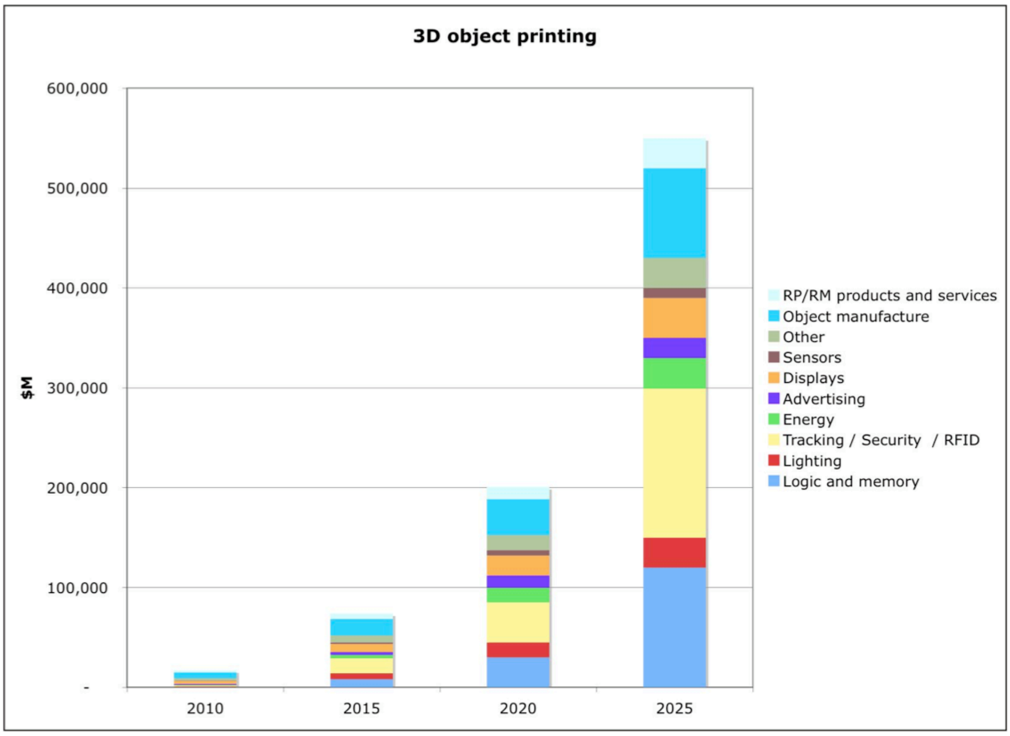
However with all things, how much is fiction?

5 Roadmaps

5.1 Market

Combined Market Predictions
Using source data from various sources – I have provided the following predictions for market development.

Figure 61 - Prediction for future market growth



(Source data extrapolated from Wohler Associates Reports 2006,
IDTechX Printed electronic forecast 2006,
Nano markets forecast 2005,
Motorola forecast 2005)

My prediction is that the combined market will be worth in the order of $500 billion by 2025, with a product and service market worth in the order $100 billion.

The following provides some further background information into the development of each specific sector.

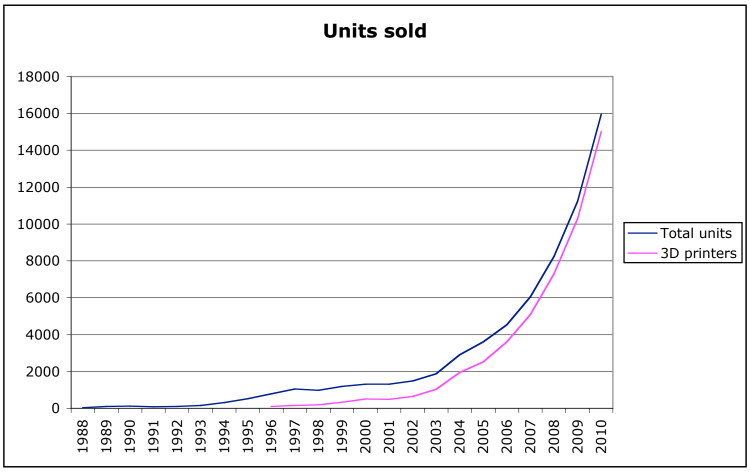
Macro
As noted, the printing of physical objects is already well established and a range of commercial printers is available.

Extrapolating from Wohlers Reports 2006 and the general forecasts for the growth of unit sales of 3D printers in the macro environment, paints a picture of

- Rapidly expand unit sales
- Decreasing sales price
- Dominance of 3D printer units in the market.
- Increase in the use of rapid manufacture.

Wohler estimated that by 2010 – approximately 10,000 3D printer units would be shipped each year. This includes not just large-scale machines but also desktop object printers.

Figure 62 - Prediction for future volume growth of 3D printers.



(Source data extrapolated from Wohler Associates Reports 2006)

However, what is of critical interest is the predicted growth in Rapid Manufacturing and the Market size of the goods produced.

Micro-Electronics

The first wave of industrial electronic printers is expected in 2007 (e.g. Mesoscribe, Agfa, Invint, Litrex), though the use of such techniques has already started. A key factor in the success of the industry is seen as the provision of commercial printers.

There are a wide variety of predictions for the size of the future markets, these predictions are based generally on the end market rather than the print technology and related consumable market.

- Nanomarket, 2005, predicts that worldwide plastic electronics manufacture will reach approx $5.8 billion / year by 2010.

- Motorola, 2005, predicts that printed electronic market is alone worth $350 billion / year by 2025 and $175 billion will be spent in tracking and security.

- IDTechX, 2006, predicts that the organic electronic market is worth $250 billion / year by 2025 and that the printed electronics market (covering both printed organic and printed inorganic) is worth $300 billion / year.

- Printed Electronics, 2006, predicts a $15-$20 billion / year market for industrial packing and printed electronics by 2010.

5.2 Competitors

I see no reason for a fundamental change in the main competitors in this field, who are already well capitalised with extensive research and patent capabilities.

I do however see that some new competitors (such as Intel) will enter the market more aggressively.

Expected market leaders in the field for the next decade.

- HP
- Epson
- Fuji
- Siemens
- Motorola
- Man Roland
- Konica-Minolta
- Intel

Of these HP, Epson and Man-Roland are likely to be the dominant forces in this new manufacturing environment and I'd expect one of these three companies to launch the desktop home factory.

5.2.1 HP

Though HP is heavily involved in this field, few examples can be found of HP's intended direction.

Examples of HP involvement include: -

- Plastic electronic research using thermal inkjet technology at Corvallis[23].

- Funding of various research institutes into novel methods of printing electronics and hybrid processes e.g. Valdmir Bulovic, MIT (Molecular Jet Printers) and Neil Gershenfeld's Media lab, MIT (CBA & Fab Labs).

- On a macro scale, a group of Hewlett-Packard engineers in Corvallis, have built a prototype of a low cost printer designed to allow ordinary consumers to translate their own computer designs into plastic objects.[24]

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[23] Various presentations at Plastic Electronics Conference in both 2005 & 2006.

[24] HP internal research symposium, April 2003.

- Links to specialist equipment manufacturers (e.g. ZCorp).[25]

5.2.2 Epson

Epson has stated that “Inkjet Printed Electronics” & “Desktop Factory” is part of Epson’s vision for the future. The main focus however appears to be directed currently towards printed electronics, displays and memory.

Epson is heavily involved in the field, examples include: -

- Printed electronics, from the funding of university research[26] to its own research in multi-layer circuit production[27] and inkjet printing of electronics[28].
- Uses inkjet technologies in production of displays, E-Paper and has a number of key relationships in this area (e.g Cambridge Display Technology, Sumitomo, NTERA, Litrex)
- Advancement of organic electronics[29] and printing materials (liquid silicon, nano-particle solutions etc)[30].
- Key patents held in inkjet printing of electronics.
- Sponsors and chair of Digital Fabrication Conference and funding of various research projects in Solid Free Form Fabrication.

5.2.3 Man Roland

Man Roland perceives desktop fabrication as a key future direction of the company and it is actively working on concepts for mass production, shop fabrication and personal fabrication[31].

Their vision is described as “transforming your imagination into reality”.

Man Roland examples include: -

- Hybrid process concept electronic printer for mass production of printed electronics[32]

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[25] Z-Corp printers use HP print heads, conversation from 2003.
[26] Cavendish Laboratory, Cambridge.
[27] Epson, Press release on the inkjet fabrication of a twenty layer circuit board, Nov. 2004.
[28] CRLE, Cambridge Research Laboratory of Epson.
[29] CRLE, Cambridge Research Laboratory of Epson.
[30] Press announcement regarding Printing with Liquid Silicon, May, 2006
[31] Man Roland presentation on future product development, April 2003.
[32] Man Roland presentation, printed electronics, Cam, 2005

- Support of various research and other groups including SFF symposium and Fab Labs.

- Concept idea for a hybrid object manufacturing system for production of personalised electronics – known as the “XYZ platform 0”.[33]

- Production of a number of additive and subtractive fabrication systems[34].

---

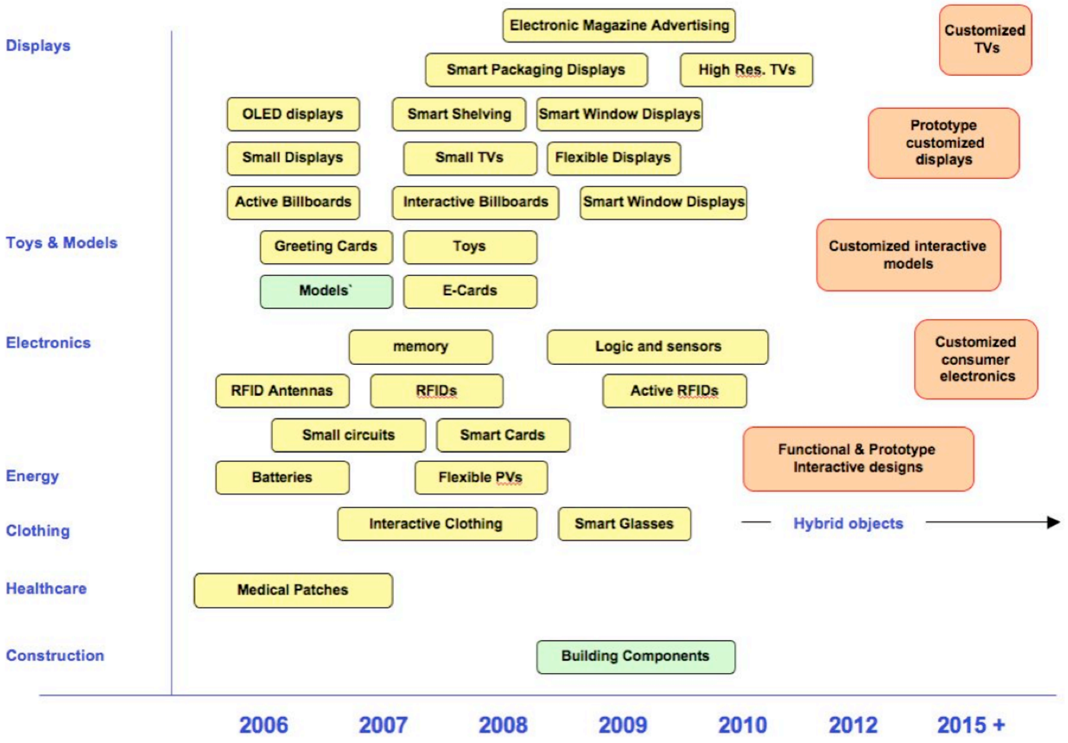
[33] Man Roland presentation on future product development, April 2003.

[34] Examples include CAMM-3 and MDX650-A.

5.3 Applications

The following provides the roadmap for application development in the Macro & Micro-Electronic fields in the short to mid-term.

Figure 63 - Roadmap for applications



(Source data from Nanomarkets, Sept 2005, Printed Electronics, 2005, SFF Symposium 2005, P/E Conference 2006, Wohler Report 2006.)

Beyond the obvious are a number of emerging sectors including: -

- Nano / Molecular Electronics
- Biological Manufacturing Systems
- Smart Materials
- Shape memory alloys
- Electro active coatings
- Bio sensors
- Haptics

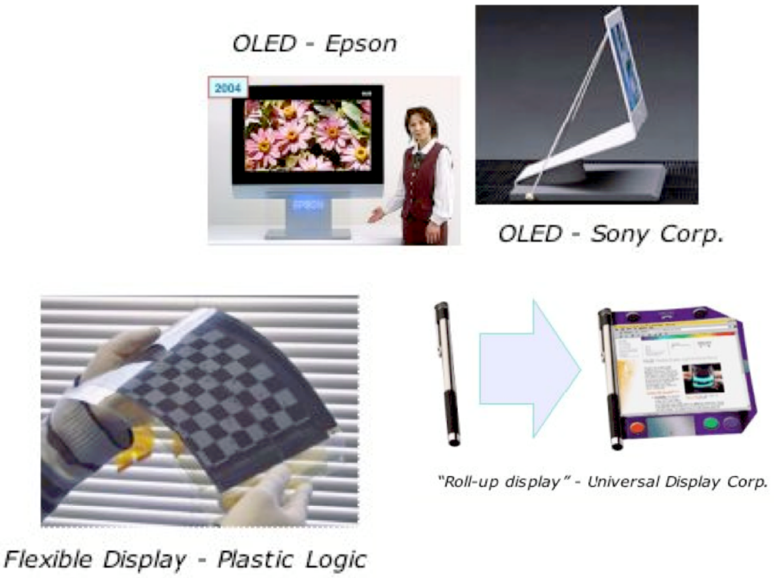
These are not included in the above roadmaps.

To illustrate the development of this roadmap, a few example applications are provided below.

5.3.1 Printed Displays

Though inkjet is currently being trialled in the manufacturing process of OLED (Seiko-Epson, CDT etc), it is expected to make the transition to production in the next year into a display market worth around $2.7 billion p.a. (DisplaySearch) by 2007. Flexible printed PLED TV displays are expected to be commercially available in 2007 – 2008 (PlasticLogic and CDT) and progress is also being made in the area of flexible displays. Universal Display Corp and Ritek have developed a proof of concept roll-up computer display (see figure 64).

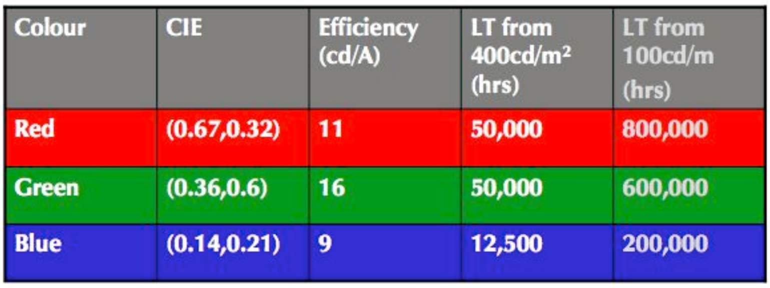
<u>Figure 64 - Example OLED & flexible displays.</u>



(Images sourced from web, 2005)

One of the stumbling blocks, has been the lifetime of blue PLEDs, however significant progress has been made at CDT on this issue in partnership with Sumitomo (see figure 65)

<u>Figure 65 - Published lifetimes for PLED, 2006</u>



Colour	CIE	Efficiency (cd/A)	LT from $400cd/m^2$ (hrs)	LT from 100cd/m (hrs)
Red	(0.67,0.32)	11	50,000	800,000
Green	(0.36,0.6)	16	50,000	600,000
Blue	(0.14,0.21)	9	12,500	200,000

(Data from CDT, 2006)

Flexible displays (and the use of transparent electronic components) opens up new possibilities for applications. One of the major issues with 3D printing technology is breadth of impact, and the need to break away from the mindset of traditional manufacture to see the possibilities.

Examples of new display technologies include smart glass, wearable displays, interactive wallpaper and smart goggles (see figures 66 & 67)

Figure 66 - Smart Goggles

K. William, Brunel University.

(Image from Brunel Site, pre 2005)

Figure 67 - Orgatronics smart goggle (product demonstrator).

(Image from Orgatronics web site)

Furthermore, the use of printed electronics in interactive displays (the advertising display market worth currently $15 billion p.a. in Europe) is expected to increase, following on from the pioneering work of Elumin8 and other companies – see figure 68.

Figure 68 - Use of printed electroluminescent displays in advertising.

(Image from Elumin8 presentation, Printed Electronics, Camb, 2005)

5.3.2 Electronic Cards

Use of printed electronics, power and displays are actively being developed in conjunction with smart cards (Kodak etc) – see figure 69. This is not just limited to novelty or interactive value but also for example security applications such as printed RFIDs in cards and documents (NEC Secure Document System).

Figure 69 - Examples of printed electronics in cards.

Printed batteries by Paper Power

Kodak Corp.

Universal Display Corp.

5.3.3 Printed RFID

By 2015 it is estimated (IDTechX and Nanomarkets) that 99.8% of the expected $24.5 billion / year RFID market will consist of entirely printed RFID's.

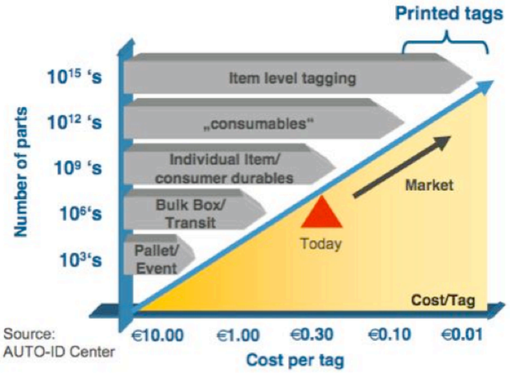
The key driver in the uptake is cost, with printed RFIDs through a R2R process expected to reduce[35] this by between 20x-200x

This reduction is caused principally through: -

- No lithography processes (entire RFID is printed including chip).
- No vacuum processing (CDV, Etch etc)
- Cheap substrate handing and reduced packaging costs

The use of RFIDs is highly dependant upon price. Item level tagging is currently believed only to be achievable for all items through the use of printed manufacture as opposed to traditional silicon – see figure 70.

Figure 70 - Market for RFID



Source: AUTO-ID Center

(Image from PolyIC presentation, Printed Electronics, Camb, 2006)

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[35] *Vivek Subramanian, RFID, University of California, 2006*

The current state of play with printed RFIDs is that printed prototypes are available, but fully printed commercial 13.56 MHz RFIDs are not expected until 2007[36]

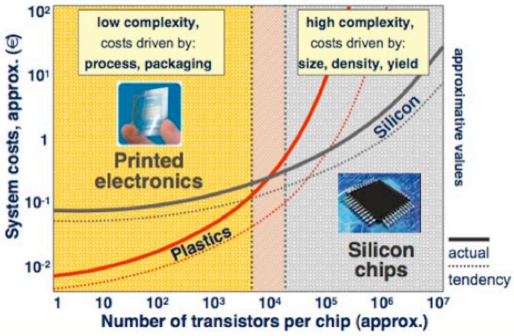
5.3.4 Printed Chips

Though printed electronics is not seen as a replacement for the traditional semi-conductor industry, it is highly questionable as to whether that will remain in the long term.

3D printing has an inherent advantage over photolithographic techniques; in that it is additive and can create objects in the Z dimension. Furthermore though printing techniques cannot currently reach the 65nm resolutions of photolithographic systems, the printing of self-assembly materials can.

However in the short term, printing techniques are not expected to compete but to concentrate on low complexity, cost driven applications – figure 71.

Figure 71 - Printed vs Traditional Silicon Chips



(Image from PolyIC presentation, Printed Electronics, Camb, 2006)

5.3.5 Smart labels

A number of organisations are working on environmental sensors for food label packaging. This is designed to address issues such as

- Food lifespan through environmental condition
- Food preparation.

For example, power paper's cooking timer for ready meals – see figure 72

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[36] *Quote from PolyIC, April 2006*

Figure 72 - Paper timer from PowerPaper.

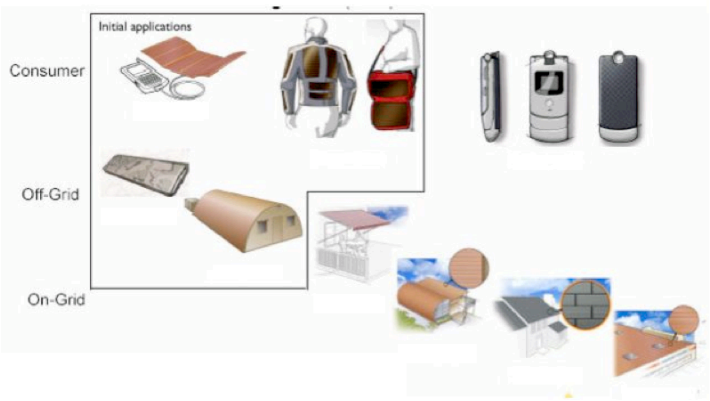
Power Paper Timer.

(Image from PowerPaper presentation, Printed Electronics, Camb, 2005)

5.3.6 Printed Batteries and Voltaics

PV's and in particular flexible PV's have a wide range of future applications. Figure 73 – provides Konarka's overview of this and their focus on new forms of wearable and shape fitted PV's.

Figure 73 - Konarka's target applications for flexible PVs



(Image from Konarka presentation, Printed Electronics, Camb, 2006)

5.3.7 Other areas.

Printed electronics and the use of organic and transparent semi-conductors opens up areas not previously considered before.

Figure 74 shows a plastic sheet containing 56 printed thin film organic transistors within a red box[37].This is used to simply illustrate that future electronics may be transparent, pervasive, embedded and all around us – the potential for new things is extremely broad.

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[37] *B.J.Norris J.Phys. 2003.*

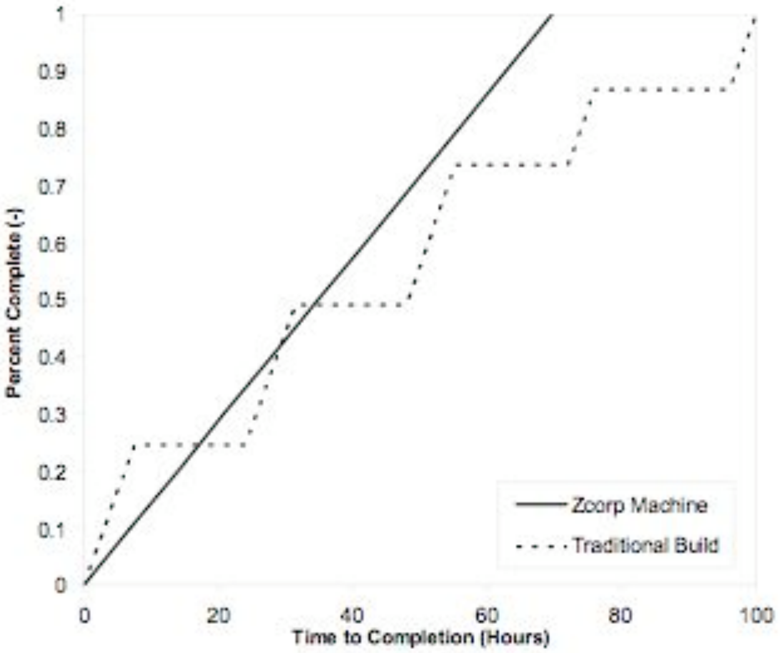
Figure 74 - Printed transparent circuits.

One final area of interest and a long-term future application for printing, is the printing of printing systems. This area of research (known as replication printers) is actively being investigated at Bath University. The potential of this technology is to distribute the means of manufacture, not just manufacturing.

Other areas of research include

Freeform construction process[38] - using 3D printing processes for the construction of components for a building. Figure 75 shows the comparison times between 3D printing of a wall vs traditional means of building.

Figure 75 - Build time for a wall, Boswell et al, Loughborogh University.



(Image from Boswell presentation at SFF Symposium, 2005)

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[38] Buswell, Soar, Gibb, Thopre, Loughborough University, 2005.

5.3.8 Long term.

One question that is often asked is “what are the target applications” for such technology?

To understand the long term potential, it is important to realise that much of today’s manufacturing depends on economies of scale, and an inherent assumption in this is that a manufacturing process produces one type of good.

The real threat exposed by 3D printing is to negate this assumption, moving to an environment where the volume of all goods produced is the key factor compared to the volume of one type of good produced.

This is analogous to printing.

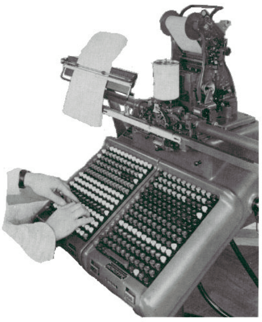
Economies of scale are obtained by printing large numbers of exactly the same thing (as in newspapers etc) however printing has evolved from a centralised operation to a retail and even home environment.

The retail environment works on producing large numbers of different printed material (from company brochures etc) and is able to exist as digital printers can produce different outputs of printed works.

The home environment exists because the cost of printers have reduced to a point that the benefits of personalised printing outweigh this, and further the benefits of personalised printing outweigh the additional cost compared to the retail channel.

It is worth noting, that in 1968 (a mere forty years ago) the printing industry was reliant on “hot metal” letterpresses (see Figure 76) and the concepts of home printers were considered fanciful whilst home photo printers must have appeared ridiculous.

Figure 76 - Example of “Hot Metal” Letter Press.



Source image from http://www.harthouse.u-net.com/printing.html

Even photocopiers, a decade earlier, had been described as a niche market with little value.

"The world potential market for copying machines is 5000 at most." -- IBM, saying the photocopier had no market large enough to justify production, 1959.

Hence, though prediction is a foolish business, I'll make a prediction to emphasise the point of potential applications.

By 2030, most objects with both macro features and micro-electronic features will be printed.

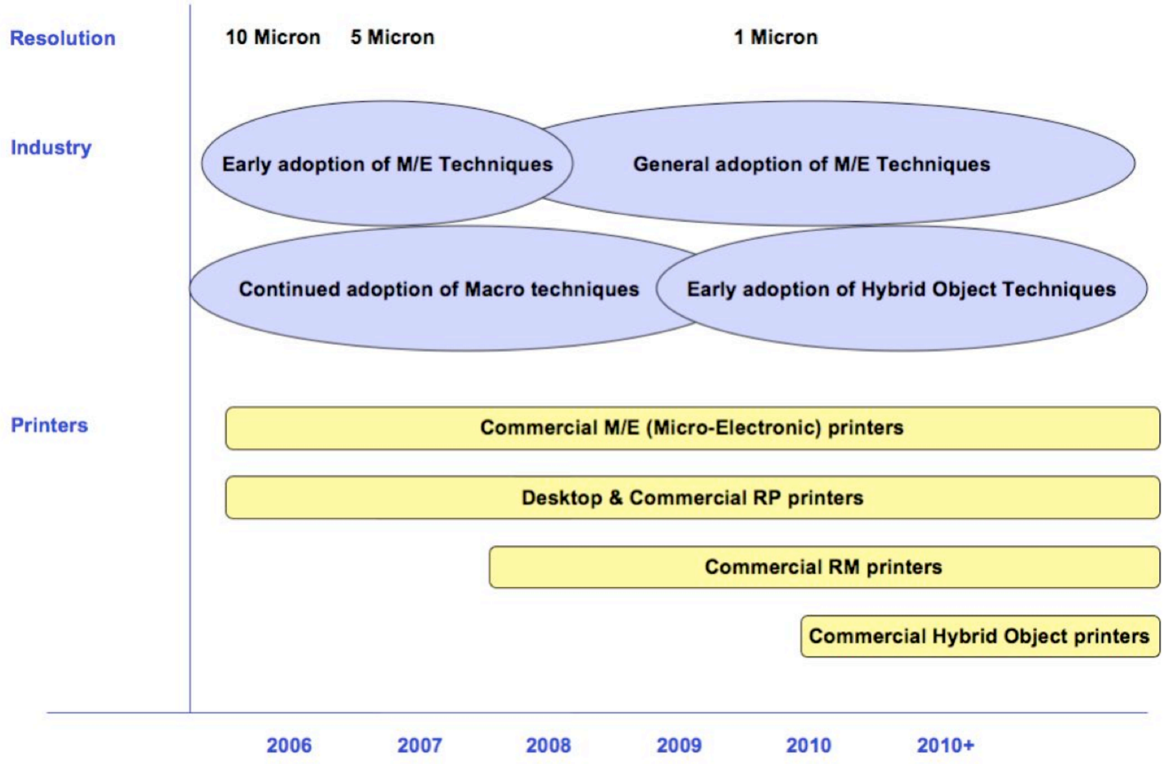
To bring this prediction into sharper focus: if the reader examines all the consumer electronic products demonstrated on the Canon.co.uk website, then all of these or their equivalents should be considered as printable by 2030.

The question to the author is more one of where they will be printed and who will provide the printers and raw materials.

5.4 Technology

New processes and systems are currently under investigation; for the purposes of the roadmap, Figure 77 provides a general overview of what is happening.

Figure 77 - Technology Roadmap.

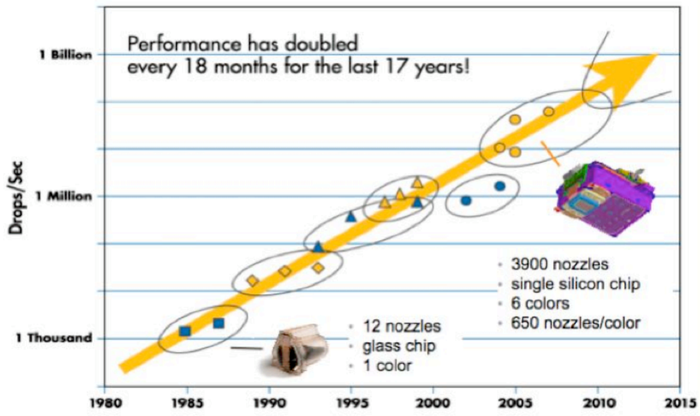


(Source data from general review of industry)

It should be noted that new processes, material and technology are being discovered and as such the roadmap is likely to change rapidly. Notwithstanding any new process discoveries, it is expected that significant improvements will be make in inkjet technology and its application to the micro-electronic scale.

According to HP, thermal inkjet performance has approximately doubled every 18 months for the last 17 years, I see no reason why this trend would not continue – see figure 78.

Figure 78 - Inkjet performance improvements



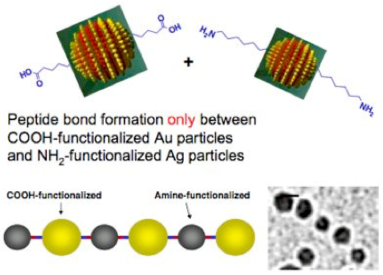
(Image from HP presentation, Printed Electronics, Camb, 2005)

Some key issues still need to be resolved with inkjets, such as the ability to print pinhole free materials.

Another area of interest is use of self-assembly structures. Though initially aimed at the photolithographic processes, because of the "point one" barrier i.e the inability to use UV for structure beyond 0.1 microns due to the wavelength of UV light [39] it has value in printing.

George Whitesides (Harvard University) and Steven Chou (University of Minnesota) have printed nanostructures using self-assembly molecular monolayers. Furthermore Francesco Stellaci, MIT in conjunction with HP have developed thiolated ligands around cores of gold and silver, which form ordered structure when printed – see figure 79.

Figure 79 – Self-assembly materials.



(Image from HP presentation, Printed Electronics, Camb, 2006)

The key area of interest behind this type of work is that the issues of resolution and placement may also be solved with materials as well as through process and print technology.

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[39] Gary Stix, Scientific American, February 1995, pp. 90-95

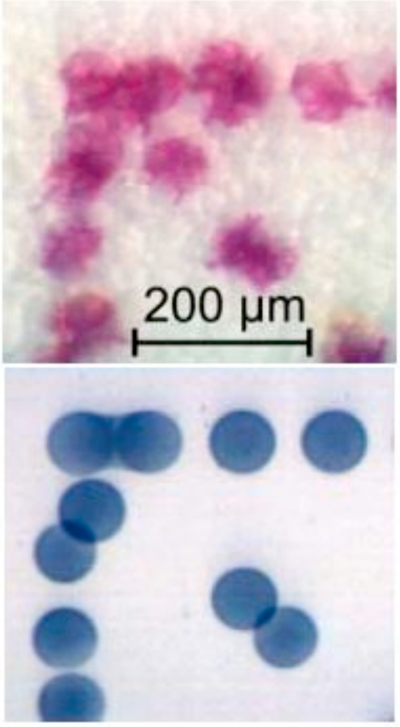
Examples of such work already exist – NTERA uses self-assembly molecules in the inkjet printing of their novel display screens (see figure 80)

Figure 80 – NTERA inkjet printed display

(Image from NTERA brochure, 2006)

The effect of the approach can be seen when comparing inkjet printing of a standard ink on a substrate in comparison to the inkjet printing of the nanochromic ink which they use (see figure 81) to a prepared substrate.[40]

Figure 81 –Comparison of standard ink to Self Assembly



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[40] *Moller, Asaftei, Corr, Ryan, Walder, Adv.Mat. Vol 16, 2004*

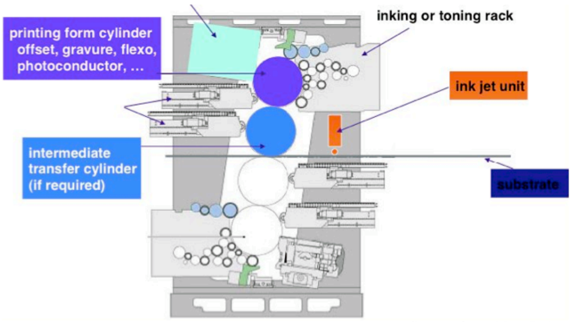
Other research of note includes Steve Yang's work on self-assembly materials[41], Shuguang Zhang's group at MIT and Professor Richard Friend at the Cavendish Laboratory, Cambridge.

5.4.1 Hybrid processes

On both the macro and micro-electronic scale, a number of groups are investigating and using hybrid processes. This enables the strengths of different techniques to be matched to the desired output.

- Concept laser using SLS and laser ablation at the macro scale.
- HP uses inkjet printing with laser ablation at the micro-electronic scale.
- MIT is combining inkjet printing with evaporation at the micro-electronic scale.
- Conductive Inkjet is releasing new systems combining metalization and inkjet printing for the production of micro-electronics.
- Printed electronics and 3D systems (multi-jet) are using inkjet printing and UV curing at the micro-electronic and macro scale respectively.
- Man Roland is examining combinations of flexographic or gravure techniques with inkjet printing for mass production of micro-electronic – see figure 82

Figure 82 – Combined techniques, modular proposal for printed electronics manufacture.



(Image from Man Roland Presentation, Printed Electronics, Camb, 2005)

This combined approach to object fabrication, is shown in the following CENAMPS review. They argue that the subtractive and additive like techniques will combine into hybrid manufacturing processes around the 100nm scale.

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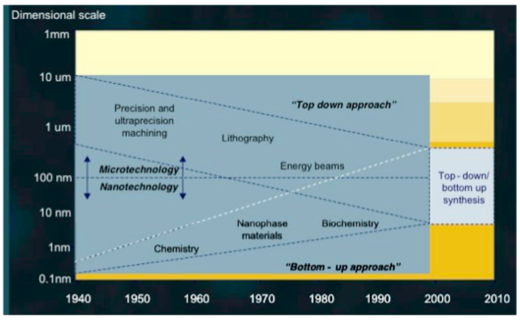
[41] Self-Assembly of Surfactant-like Amphiphilic Peptides made of Natural Amino Acids, Steve Yang, Ph.D. thesis, MIT (2004)

Figure 83 –CENAMPS Review



(Image from CENAMPS presentation, 2006)

However these techniques are focused either on the macro or the micro-electronic scale.

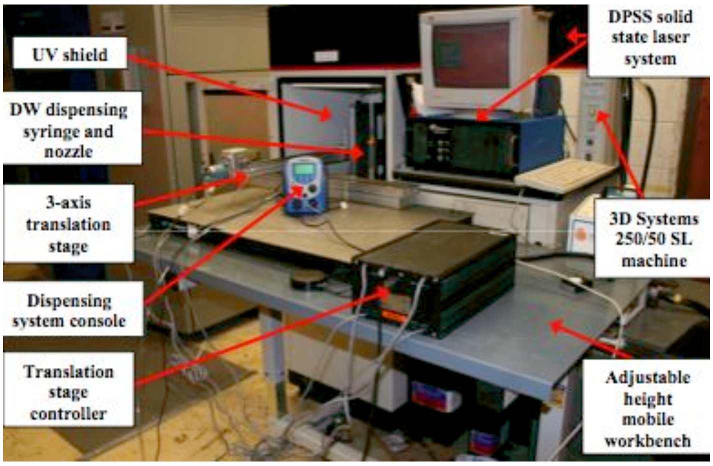
5.4.2 Hybrid Manufacture

A number of proofs of concept or research activities have been undertaken which combine both areas of Macro and Micro-Electronic printing.

Sandia National Laboratories (SNL)[42].

Integration of direct-write (DW) technology and SLA, to provide a hybrid manufacturing environment capable of building multi-layered, high density, integrated and fully functional electromechanical systems. This approach is known as Functional Integrated Layered Manufacturing (FILM) – figure 84.

Figure 84 – Setup of Hybrid manufacturing system



(Image from SNL, SFF symposium, 2005)

The system uses

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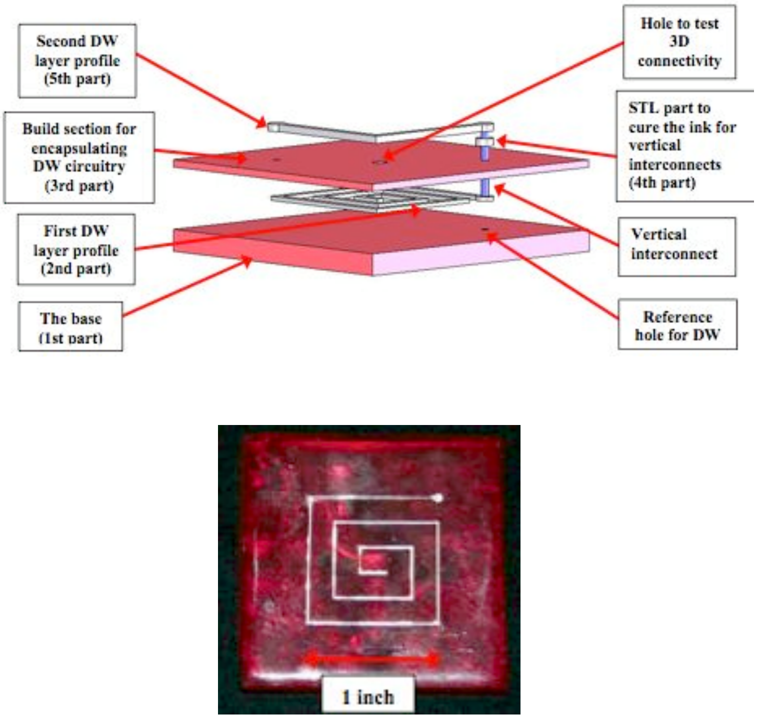
[42] Medina et al, Hydrid Manufacturing: Integrating Direct Write and SL, Sandia National Laboratories, abstract SFF symposium, August 2005.

- SL for construction of structure and supports
- Automated Curing
- DW for circuit creation

Using this approach, the group was able to build a simple SL part (see figure 85) with embedded circuitry.

Note: This approach is suitable for use with inkjet technology as the DW component (currently a mechanical syringe is used to deposit the ink) and also potentially for construction of the support structure.

Figure 85 – Example of object created,



(Images from SNL, SFF symposium, 2005)

University of Texas as El Paso[43]
In conjunction with SNL, J.A Palmers group have been developing hybrid techniques combining SL and DW technologies for the creation of macro / micro-electronic objects (see figure 86)

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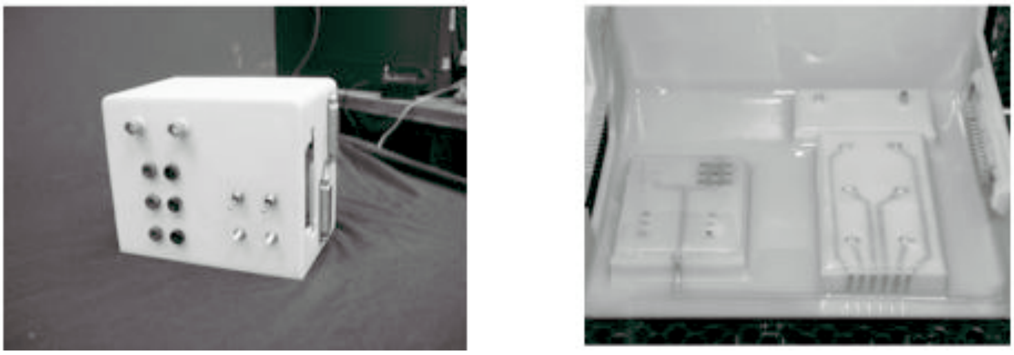
[43] J.A. Palmer, University of Texas at El Paso, A basis for integrated meso-manufacturing, abstract 2005.

Figure 86 – Electrical Junction box fabricated with SL / DW technology.



(Images from University of Texas, SFF symposium, 2005)

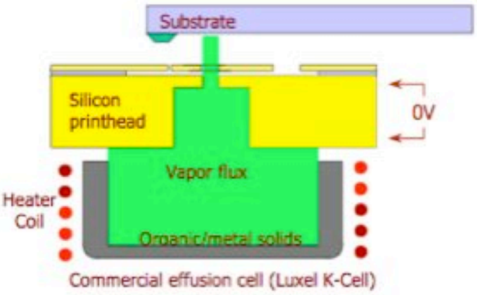
University of Missouri[44][45]
Development of a process known as LAMP (Laser Aided Manufacturing Process) that combines laser deposition and laser machining. Though focused on a macro scale, these techniques are also applicable to a micro-electronic scale.

5.4.3 Novel process and key areas of interest

The following projects are also of particular interest, potentially providing either future techniques or processes that are applicable to hybrid object manufacture.

MIT - Molecular Jet Printer
HP and Valdmir Bulovic, MIT have developed a system which merges MEMS with Thermal Evaporation. This novel micro-machined print head is capable of expanding inkjet printing to metals and molecules that are suitable for evaporative deposition. Hence this “molecular jet printer” has the capability of direct patterning of material with a high resolution – see figure 87

Figure 87 – Overview of molecular jet printer



(Image from MIT, 2006)

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[44] A.P. Padathu, PHD Thesis.

[45] K. Eiamsa-ard, Dept Mechanical and Aerospace Engineering, University of Missouri, 2005.

The system is capable of printing both metals and small molecule organic compounds, and has achieved outstanding resolutions of close to 1 micron. The molecular Jet printer is designed to cope with metals and small molecule organics whereas inkjet deals with solution based. By combining both technologies together, HP & MIT intend to provide a wide spectrum of material capabilities with full patterning control enabling the printing devices such as OLED, OFET (organic field effect transistors) and many more.[46]

University of Texas at Arlington
Dr John Priest's is developing the LMJP method that allows the printing of metals at resolutions of 100 microns using a process similar to inkjet. The work covers metals such as copper, aluminium and has been used for both model manufacture and circuit interconnects.

Cambridge University - Cold gas dynamic manufacturing (CGDM)
Under development at the Centre of Industrial Photonics, Cambridge. Cold gas dynamic manufacturing CGDM) is a new production process that enables novel combinations of materials and metals in a single 3D component. Using this technique, materials with previously unimaginable characteristics can be produced with relative ease. By using a supersonic converging/diverging nozzle, powder entrained in a high speed gas jet is accelerated to velocities in excess of 500-1000m/s. As the particles hit the target surface they impact under large plastic deformations, consolidating to producing localised forge bonding.

Successfully deposited aluminium, copper and titanium metal onto a variety of substrates of metal, ceramic, glass and plastic (including carbon reinforced composites). The deposits range in thickness from microns to several tens of millimetres.

3D mintegration project
This multi-disciplinary project combines the talents of six universities (Cranfield, Nottingham, Loughborough, Cambridge, Heriot-Watt, Greenwich) and 23 companies, with a vision to revolutionise the way that complex and small devices are manufactured.

The scope of the project is from material to products (as highlighted in figure 88) and it intends to develop the new design and manufacturing techniques needed to produce highly integrated and complex 3D miniaturised devices and assemblies as opposed to the current planar and single material methods.

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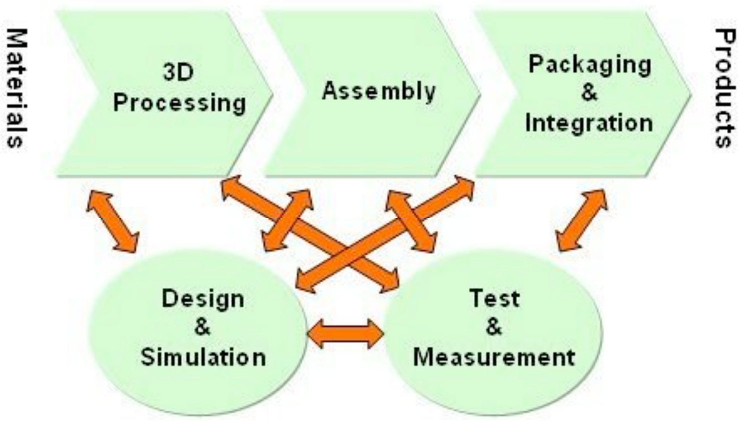
[46] Sun Hoon Kang, Evaporative printing of organic materials, MIT, 2004.

Figure 88 –Scope of 3D mintegration.



(Image from 3D mintegation web site, 2006)

The proposed methods include: -

- Lamination methods, whereby products are built up from sheets of components and interconnects in a reel-to-reel process,
- Modular approach where structures are built by joining together 3D blocks.
- Folding, origami-like, technique where 2D layers are folded together to occupy a 3D space.

The approach is more traditional in nature, however the techniques are applicable to printing.

6 Far Future (15yrs +)

This report is based primarily on near future technology. However it is worth highlighting some key areas and potential long-term futures.

6.1 Replicating Machines.

Mathematician John von Neumann first suggested the idea of a non-biological self-replicating system in the late 1940s.

In order to achieve this a self-replicating machine would need to have the capacity to gather energy and raw materials, process the raw materials into finished components, and then assemble them into a copy of itself.

At the core of this is a process to manufacture a copy of the process itself, for example to be able to print out a printer.

It should be noted that such a machine

- Violates no physical laws
- We already possess the basic technologies necessary

If this is achieved, then in the long term manufacturing becomes viral and hence ubiquitous and commonplace.

In 2004, General Dynamics completed a study for NASA's Institute for Advanced Concepts. It concluded that complexity of the development of such a system was equal to that of a Pentium 4, and promoted a design based on cellular automata.

Since then, a number of groups have been actively pursuing this research[47], the following references are of interest.

- Zykov V., Mytilinaios E., Adams B., Lipson H. (2005) "Self-reproducing machines", Nature Vol. 435 No. 7038, pp. 163-164

- Efstathios Mytilinaios, David Marcus, Mark Desnoyer and Hod Lipson, (2004) “Designed and Evolved Blueprints For Physical Self-Replicating Machines”, Ninth Int. Conference on Artificial Life (ALIFE IX), pp. 15-20

- Studer G, Lipson H., (2005) "Spontaneous emergence of self-replicating, competing cube species in physical cube automata", GECCO Late Breaking Paper, to appear.

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[47] *RepRap project at Bath University and the Cornell University Self Reproducing Robo – specifically Hod Lipson’s work on the universal fabricator.*

- White P. J., Kopanski K., Lipson H. (2004), “Stochastic Self-Reconfigurable Cellular Robotics”, IEEE International Conference on Robotics and Automation (ICRA04), pp. 2888-2893

6.2 Biological Manufacture.

New techniques for creating programmable organisms have been developed over the last four years (Drew Endy, MIT et al) with surprising results.

Furthering on such work, a number of groups are examining the use of biological assembly lines for manufacture.

Of note are: -

- The Design of a Molecular Assembly Line Based on Biological Molecules, Brian Chow, M.S., Media Arts and Sciences, June 2003

- A Fast Flexible Ink-Jet Printing Method for Patterning Networks of Neurons in Culture, Sawyer B. Fuller, M.S. thesis, MIT (2003)

- Growing Machines, Saul Griffith, Ph.D,, Media Arts and Sciences, 2004

8.1 Key technologies summary

The following areas of research and technology are of interest to this proposal.

NB **Doping** is mentioned, as though 3D printing allows geometric & compositional freedom, there does not appear to be any research in the area of varying composition – either through collision mixing or some other method.

Table 11 – Areas of interest.

Area	Technology	3D	2D	Who
Hybrid Manufacture	Hybrid manufacture with SL / DW	Y		J.A. Palmer, University of Texas as El Paso Frank Medina, Sandia National Laboratories (SNL).
	Universal Fabricators.	Y		Hod Lipson, Cornell University. Man Roland.
	Concept Hybrid printer for micro-electronics	Y		Man Roland
	Plastic Electronics Manufacture	Y		CENAMPS, CRLE, HP Corvallis.
Existing Techniques	Multi-Jet modelling for support structure.	Y		Commercial systems available e.g. 3D Systems
	Laser Ablation	Y		Commercial systems available e.g. 3D Systems
	UV curing for photopolymer insulators.	Y		Commercial systems (Objet Geometries, Sony) for macro, TTP has an example system for micro-electronic.
	Thermal inkjet printing of solvent suspended materials.	Y		HP Corvallis, CRLE.
Materials	Use of SAM	Y	Y	NTERA
	Self Assembly Materials	Y	Y	George Whitesides, Harvard University Steven Chou, University of Minnesota Prof. Richard Friend, CDT. Shuguang Zhang, MIT Steve Yang, MIT
Novel Technology	Molecular Jet Printer	Y		Valdmir Bulovic, MIT
	LMJP			Dr John Priest, University of Texas at Arlington
	CGDM	Y		Bill O'Neil, Cambridge
	Doping	Y	Y	None found.

9 Appendix

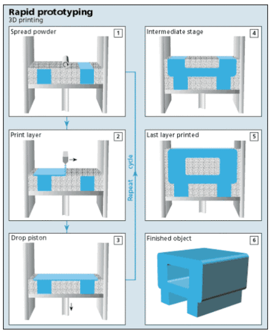
9.1 Processes and Technology

MJM (Multi-jet Modelling)
An acrylic photopolymer material, deposited by an inkjet "like" head. Although not as accurate as other processes listed here, MJM is used for inexpensive and smaller designs, extremely detailed parts or assemblies. The material has a polypropylene "like", feel & finish with a slight wax residue.

Applications: Rapid prototyping
Manufacturers: 3D Systems

3DPtm
The technique developed by MIT is based upon bonding layers of powdered material, the bond being inkjet printing onto the powdered surface (see figure 90 below).

Figure 90 – 3DPtm process.



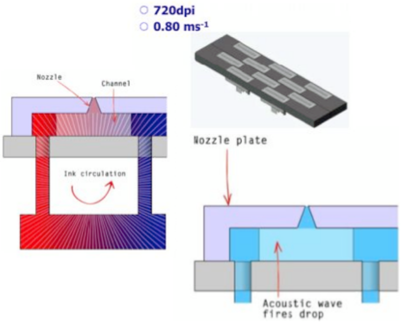
(Image from MIT web site, 2006)

Applications: Rapid prototypes, design concepts and models.
Manufacturers: ZCorp.

Acoustic Inkjets
In 2005, Xaar released a new form of print head technology known as an acoustic inkjet *(the product is known as The Side Shooter).* The new print head is specifically at inkjet printing electronics, and is claimed to be capable of printing difficult materials with consistent high quality and accuracy.

The technique differs from Piezo and Thermal inkjets by providing a chamber of continuously circulating ink, with a mechanism of using acoustic waves to cause ejection – see figure 91. Generation II is expected for release in 2006.

Figure 91 – Overview of Xaar, Side Shooter



(Image from Xaar product presentation, 2005)

Applications: Micro-Electronics printing
Manufacturers: Xaar

Piezo
Piezoelectric inkjets have been used by Epson and others to construct electronic components in a wide variety of materials and also in the production stage of OLED. Epson successfully inkjet printed a multi-layer circuit board and expects to commercialise the technology in 2007.

Applications: Micro-Electronics & Macro printing
Manufacturers: Epson

Thermal Impulse Inkjets
Proof of concept use of thermal impulse inkjets in Micro-Electronic manufacture has been achieved at HP and Xerox. This has been achieved with both organic materials and traditional materials (silicon, copper, gold, silver etc) by use of nano-particle solutions to produce both working electronic components and also displays (through use of OLED).

Furthermore high resolutions have been obtained by combining with other systems such as surface treatment through nano-imprinting or laser ablation.

Thermal impulse inkjets are also widely used throughout a number of rapid prototyping systems.

Applications: Micro-Electronics & Macro printing
Manufacturers: HP & Xerox

Flexographic
Proof of concept and trial versions for the mass production of electronics have been achieved using flexographic techniques

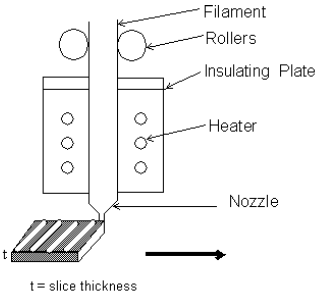
Applications: Micro-Electronics printing.

FDM (Fused Deposition Modelling)

FDM (Fused Deposition Modelling) uses a thermoplastic material with a heated nozzle. It uses a layering approach to create the model, the materials tending to be ABS or Polycarbonate plastic – see figure 92.

The process of manufacturing are relatively slow – though major improvements have been made and the entry-level type systems are now below the $30K mark (originally the systems were in the $500K range).

Figure 92 – Process of manufacturing using FDM



Applications: Rapid prototyping and functional prototypes.
Manufacturers: Stratasys

EBM - Electron Beam Melting

Uses an electron beam to melt powdered metal, to form objects.

Applications: Target markets are medical implants and titanium components for the aerospace industry.
Manufacturers: Arcam AB
Noted Researchers: Dr Ola Harrysson.

DLP – Digital Light Processing

Technique developed by Texas Instruments using photopolymers and a projected light display. System images an entire layer at once, and can have resolutions in order of 13 microns and thickness layers of an equivalent size.

Applications: Rapid prototyping.
Manufacturers: Envisiontec

SLM – Selective Laser Melting

Technique developed by the Fraunhofer Institute for laser Technology. Resolution is good with thickness layers of less than 30 microns.

Applications: Rapid manufacturing of metal parts.

SLA (Selective laser ablation aka SL and Steliography)

A laser based process that solidifies a photopolymer epoxy resin. Due to the softer material surface properties, SLA has a high resolution and is most commonly used as patterns for rubber tooling. Often sanded, painted, & plated.

Polyjet

PolyJet is "SLA like" in output and deposits layers at 16 micron vertical slice. The PolyJet materials are stronger than most commonly used SLA resins and can be primed, painted, plated & used as patterns. Resolution of 50 microns achievable.

Applications: Rapid prototyping
Manufacturers: Objet Geometries.

SLS (Selective laser sintering)

This process is similar to SLA except that a laser beam is traced over the surface of a tightly compacted powder of thermoplastic material.

Applications: Rapid prototyping / Rapid manufacturing
Manufacturers: 3D Systems