OPTOMEC®

3D Aerosol Jet® Printing - Adding Electronics Functionality to RP/RM

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Abstract

Aerosol Jet printing is a unique CAD driven, Digital Manufacturing technique for creating miniaturised electronic circuits and components. The process works with a wide range of functional materials: conductors, semi-conductors, resistors, dielectrics and encapsulation materials are printed on to virtually any surface material. With no physical contact with the substrate by any portion of the tool other than the deposition stream, conformal writing is easily achieved. Therefore the process can print complex 3D electronic circuits, components and devices. Furthermore, the fine feature sizes produced allow advanced packaging of discrete SMDs such as integrated circuits, MEMS and sensors onto 3D parts. Ongoing research is investigating combining 3D Aerosol Jet printing with traditional RP/RM processes to create parts with novel functionality. For example 3D circuits and devices can be printed on SLS, SLA or other RP/RM produced parts.□ This paper will outline the basics of the Aerosol Jet technology and review the state-of-the-art related to 3D printing. Information will be presented on applications developed with a new 5-axis Aerosol Jet print system. The potential for adding functionality such as sensing and memory will be shown.

1. Introduction

Rapid Prototyping has been commercially available since 3D Systems first introduced Stereo Lithography (SL) systems in 1987. The last 25 years has seen a huge increase in the range of technologies, part quality and materials available. It is now possible to produce functional parts from polymers, metal alloys and even ceramics with exceptional physical and mechanical properties. There is now an increasing interest in adding electronics functionality to RP/RM parts to increase customer value. One way to achieve this is by Aerosol Jet printing the electronic features and devices directly onto the 3D RP/RM part.

2. How the Process Works.

The Aerosol Jet process, **Figure 1**, uses aerodynamic focusing to precisely and accurately deposit functional inks direct from CAD models. The inks can consist of metals, polymers, ceramics and even bio-materials and exhibit diverse functionality.

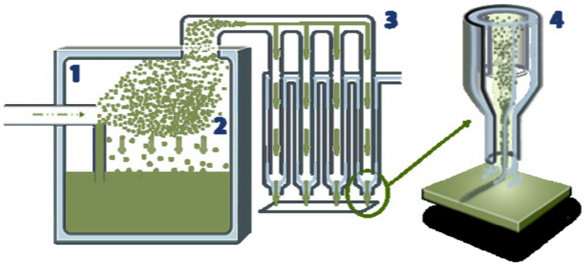

Figure 1. Schematic representation of the Aerosol Jet process

The ink is placed into an atomizer, which creates a dense aerosol of droplets between 1-5 microns diameter (1). Aerosol droplet density can approach 10m drops per cubic mm. Drops larger than ca. 5 microns cannot overcome the force of gravity and drop back into the ink and are recycled (2). The aerosol is carried by a gas flow to the deposition head (3). Within the deposition head (4), the aerosol is focused by a second gas flow (sheath gas), which surrounds the aerosol as an annular ring. When the sheath gas and aerosol pass though the profiled nozzle, the mixture is compressed which focuses the aerosol. The resulting, high velocity converging particle stream is deposited onto the substrate creating the very fine features.

The system uses clean, dry N_2 or compressed air for atomisation of the ink and also for the sheath gas. A mechanical shutter and precision motion control system allow for the creation of complex patterns on the substrate. The system is driven by standard CAD data, which is converted to make a vector based tool path. This tool path allows patterning of the ink by driving the 2D or 3D motion control system and a shuttering system, which interrupts the aerosol stream. During deposition there is no physical contact between: the material being printed and the nozzle, **Figure 2**. This helps to keep the critical area of the print system clean and free of material build up allowing long run times and stable operation. The process has a natural stand off distance of between 1-5mm or more from the substrate and the aerosol beam can stay focussed over a range of several mm (nozzle type & parameter dependent). Therefore conformal writing is easily achieved. This allows for the processing of 3D

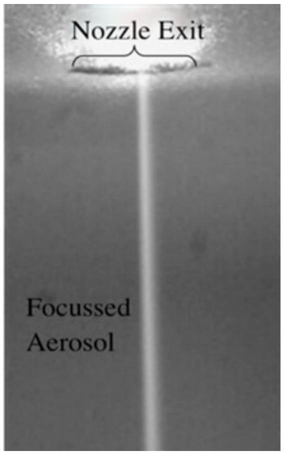

Figure 2. Photograph of the aerosol stream exiting the print nozzle. Aerosol diameter =15 microns in this example.

substrates.

The fine aerosol droplet size is the key to being able to create fine features, good edge definition and also accurately control deposit thickness/profile. For the Aerosol Jet process, the 1-5 micron diameter droplets allow features as small as 10 microns to be printed with clean edges, even thicknesses and smooth profiles. Deposit thicknesses have been precisely controlled from a thin as 25 nano-meters to several microns in a single pass (material dependent). In certain applications such as solid oxide fuel cells [1] layers of 50microns or more are deposited.

Once deposited, the inks require post processing (drying, sintering, curing) to achieve their final properties. For metallic inks, thermal sintering is applied to increase electrical conductivity and mechanical stability. The end result is a high-quality thin film deposit with excellent edge definition, smooth surface profile and near-bulk electronic properties. Polymer based inks can be dried and cured using appropriate post-processing methods, for example UV curing for epoxies and acrylic dielectric inks.

3. Materials Compatibilty.

The Aerosol Jet process is capable of handling the entire range of materials classes required for Printed Electronic manufacturing: conductors, resistors, dielectrics/insulators and semiconductors, Table 1, and also combinations of materials printed layer-wise to create differing functionality.

Conductive Metals	Nano-particle Ag, Au, Pt, Pd…
Conductive Polymers	PEDOT, Carbon Nano Tubes (CNT) …
Semi-conductors	P3HT, PQT, CNTs…
Resistors	Carbon, Metal Oxide…
Dielectrics	Epoxy, Acrylic, PMMA, Polyimid, PTFE…

Table 1. Examples of materials for Printed Electronics.

4. 3D Printed Electronics.

The large standoff distance between the print head and substrate and long focal length of the process enables 3D printing. For small variations in height, up to ca. 2mm, 2D tool-paths can be used to create 3D circuits. The aerosol jet is able to focus over the height variations without changing standoff distance of the print head. An example where this capability is in use is in the replacement of wire bonding in microelectronics packaging applications. The combined ability to write fine interconnects/pitches of 25 microns/50microns on 3D profiles is key to enabling next generation memory packages, **Figure 3**. In this device, an insulating layer is deposited on the sides of the die stack. A laser then opens the desired contacts on the chip stack (insert in **Figure 3b**). The interconnect is then written up the die stack connecting the dies on different levels. This method allow finer pitches for the interconnects and reduced size of the final die module compared to current industrial solutions. Furthermore, the interconnects do not suffer from cross talk at GHz frequencies, which is often a problem for wire-bonds, and interconnect distances can be shortened which speeds signal processing times.

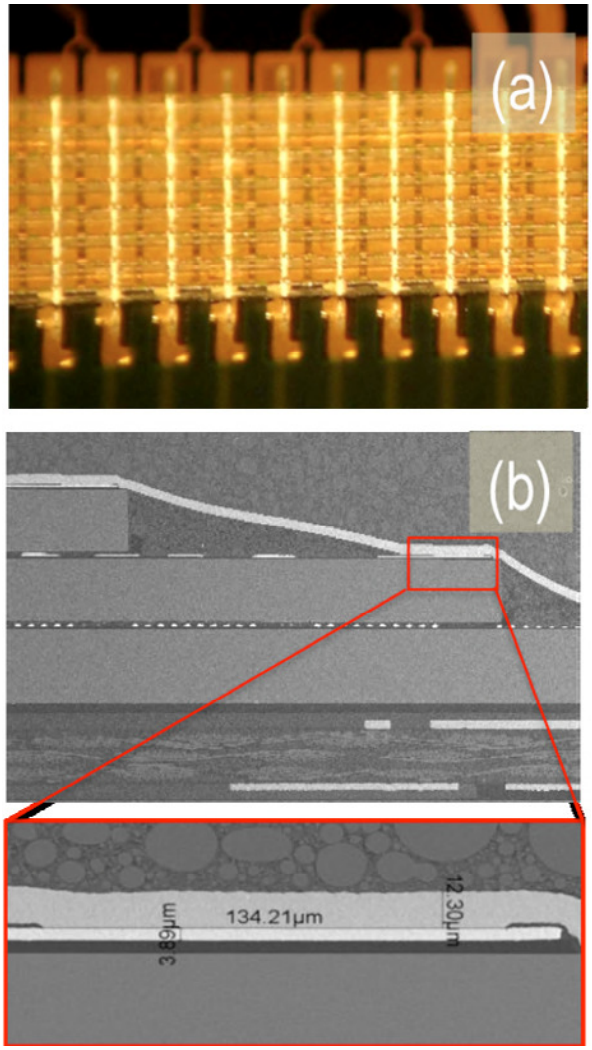

Figure 3. Wire bond replacement.
a) 25micron printed interconnects written up an 8 die stack.
b) Cross section of the interconnect. Insert shows detail of the contact area.

Moving beyond this micro-scale 3D the process can use 3 or more axes of motion to create complex 3D circuits on thermoplastics. These devices, known as Moulded Interconnect Devices (3D MIDs), find wide application in the telecommunications and automotive industries where they offer reduced part count, improved reliability and novel design compared to standard electronic systems. Neotech has developed 5-axis Aerosol Jet print systems to enable MIDs to be manufactured.

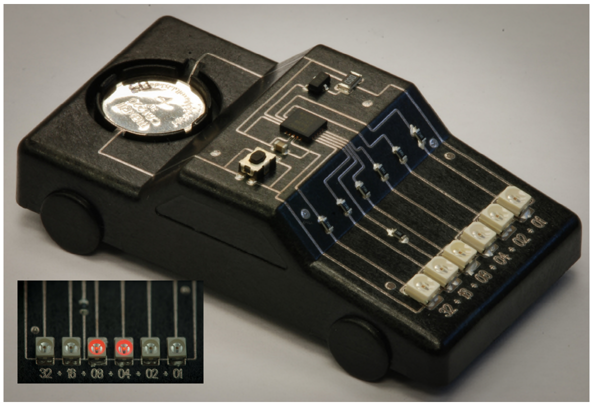

Figure 4. 3D MID Demonstrator. Digital thermometer on PA10 thermoplastic. Source: Neotech/FAPS.

An MID demonstration part is shown in **Figure 4.** The device body is injection moulded from Rapid Tooling in PA10 thermoplastic. Aerosol Jet then deposits the 3D circuit, in this case Ag, which is then sintered to give the desired electrical properties. Finally the SMD components are mounted to complete the functioning device, in this case an electronic thermometer. All the production process are digitally driven resulting in a rapid process chain: Rapid Tooling – Moulding- Aerosol Jet printing – Pick& Place of SMDs.

The same methodology was used in the 3D MID demonstrator developed in the FKIA project ("Functionalisation of Plastics with Ink Jet and Aerosol Jet", funded by the Bavarian Research Foundation), **Figure 5a-c**. In this example, two capacitive sensor structures have been printed on the ends of a moulded PA6 tank. The sensors are connected by a printed Ag circuit and SMD components to complete the sensor device. When water is pumped into the tank the sensors register the water level as it rises, lighting the LEDs to indicate the fill level. When the tank compartment is full the circuit senses the water fill level and reverses the pump direction.

5. Combining Aerosol Jet with RP.

The demonstration parts shown in Figures 4-5. Aerosol Jet is capable of printing complex circuits on 3D structures. However, parts produced by RP systems exhibit some features that complicate the integration of 3D electronic systems. The following challenges have been identified in relation to the RP parts:

i) Rough and porous surfaces
ii) Low thermal stability of the powder materials and
iii) High substrate Coefficient of Thermal Expansion (CTE).

The project "3D Additive Manufacturing of Electrical and Electronic Applications" (3DAMEEA funded by the Federal Ministry of Economics and Technology) is investigating the combination of powder-bed-based manufacturing and Aerosol Jet printing. Fundamentally the rough and porous RP surfaces are not difficult for the Aerosol Jet printing process to work with. It can easily accommodate rough and uneven surfaces. However, such surfaces can adversely affect the behaviour of the deposited ink. Rough and porous surfaces have relatively high surface energy making it difficult for the printed ink to form a clean, even deposit. This is especially true then the surface roughness is much larger than the inks thickness. **Figure 6** shows a printed Ag line on a RP part produced by the powder-bed technique. The extreme surface roughness can be seen to clearly effect the quality of the printed line. In this example, **Figure 6b**, the total surface roughness is 100x the thickness of the printed layer (300 micron peaks marked red to 3 microns printed Ag). One potential solution to this problem is to pre-machine the rough areas where the electrical circuit is to be printed. Neotech is currently in the process of integrating CNC machining capability into the 5-axis Aerosol Jet printer to test this functionality.

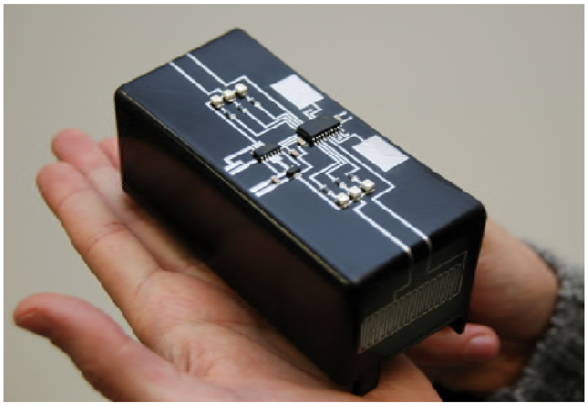

Figure 5a. 3D MID Demonstrator: Tank Filling Sensor on PA6. Source: Neotech/FAPS.

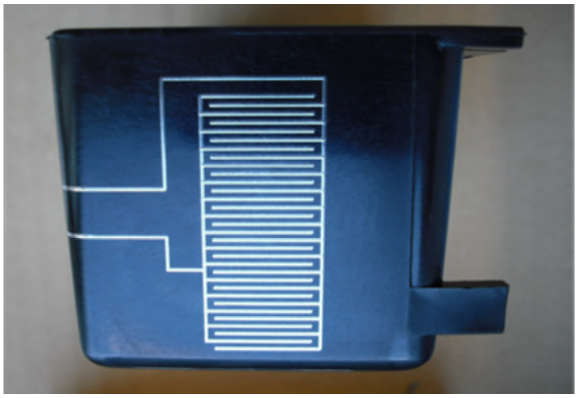

Figure 5b. Detail of capacitive sensor structure. Source: Neotech/FAPS.

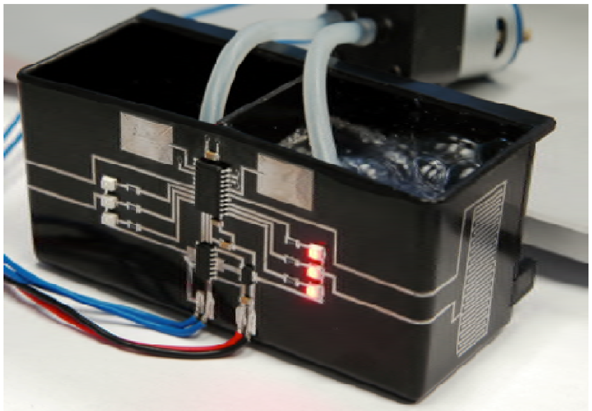

Figure 5c. Tank Filling Sensor in operation. Source: Neotech/FAPS.

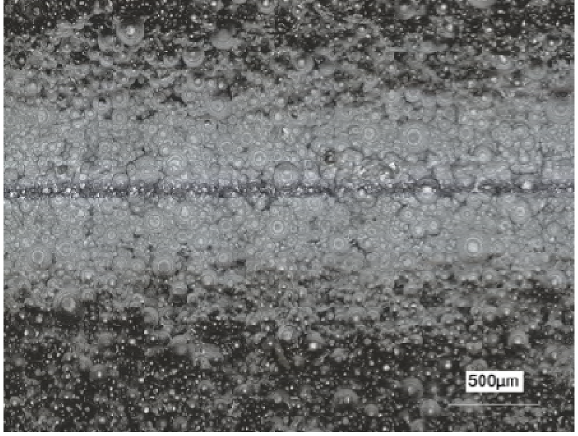

Figure 6a. Ag line printed on a PMMA part produced by powder bed RP (Voxeljet). Source: FAPS.

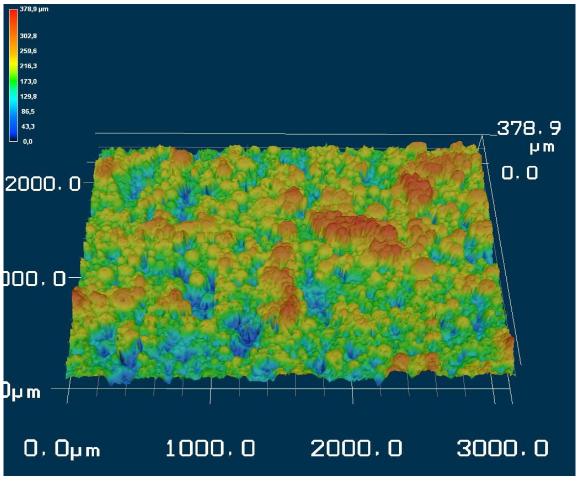

Figure 6b. Profilometry of the printed surface.

The relatively low temperature capability of many polymer based RP materials can also make it difficult to get good electrical properties from the deposited inks. Commercial silver inks start to sinter at ca. 100^{o}C but for the best electrical conductivity and optimised adhesion higher sinter temperatures are needed. Typical sinter processes for Ag nano-particle inks operate in the range 150-250^{o}C. The majority of polymer RP materials have maximum temperature capabilities in the range 100-150^{o}C, severely limiting the final circuits performance. To overcome this limitation alternative "low temperature" sintering techniques have to be utilised. Possible alternatives include laser, light beam, xenon flash lamp, microwave and electrical sintering. However, not every low temperature sintering technique is easy to use on 3D surfaces. Laser sintering is probably the most promising technique in the near term due to it's ability to input very precise levels of energy into the deposited circuit whist being manipulated/working in 3D space. Ongoing work will integrate a 20W fibre laser with tuneable pulse waveforms into the 5 axis Aerosol Jet printer to test and optimise this method of low temperature sintering. In parallel the 3DAMEEA project has begin to investigate light beam sintering. Using this method, a light for Xenon lamp focused and directed onto the printed circuit. The main body of the part is only marginally influenced by the introduced heat and retains its high dimensional stability. Locally, the uneven surface partly leveled by melting during the sintering process. DC Electrical sintering [1] also offers significant promise for applications where the circuit can be effectively contacted.

For the substrates with high CTE, thermal mismatch can lead to cracking or de-lamination of the printed Ag circuit material. Laser or light sintering may help overcome this by locally softening/melting the underlying surface to reduce the induced stresses. Nevertheless, care should be taken when designing a part to ensure the compatibility of materials properties.

6. Additional Printed Functionality.

Current applications, like those in Figures 4-5 for 3D Aerosol Jet printing are mainly focussed on printing conductive electrical circuits and combining these with SMD components to create the functioning device. There is however great potential in using multiple ink types to give additional functionality especially in the field of sensors. Various researchers are using Aerosol Jet on 2D surfaces to add sensing capability to a system, for examples metallic-biomaterial combinations [2] for sensitive gas sensor applications**, Figure 7**. In this application, Ag ink is used to write a conductive sensor circuit. After sintering, a protein (BSA–Alexa Fluor 350) is printed within the sensor structure to complete the circuit. The proteins electrical conductivity varies with minute changes in gas content. This allows a very sensitive gas sensor to be constructed.

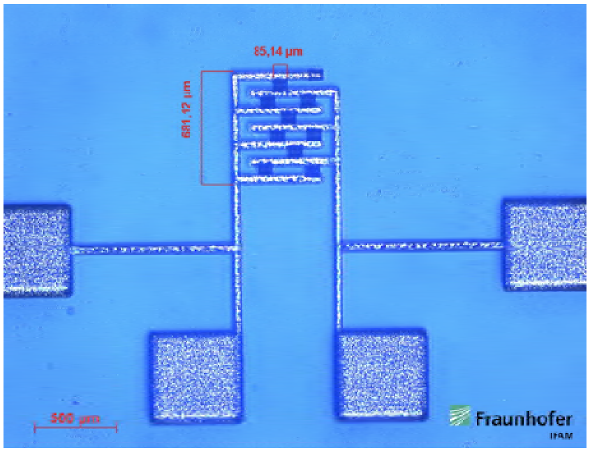

Figure 7. An Aerosol Jet printed gas sensor. The Ag circuit is printed and sintered. A second deposition of biological material (dark blue squares) competes the sensor structure.

Other examples of printed sensors include temperature sensors (Ag-Ni circuits which uses the Seebeck effect to register temperature changes) and strain gauge sensors, **Figure 8**. If the issues with high surface roughness and sintering method can be resolved, these devices can be integrated into RP and RM components.

By further increasing the number of materials it is possible to print complete electronic circuits that contain active components, such as Thin Film Transistors, and passive components, such as resistors and capacitors. TFTs are one the fundamental building blocks for many electronic devices. Complete TFTs have been printed [3] using gold (source & drain), PEDOT (gate), P3HT or CNTs (semiconductor) and dielectrics. The printed TFTs operate at very low voltages, <2V, exhibit low hysteresis and are relatively fast by printed electronics standards, working in the range 1-10kHz for P3HT and several GHz

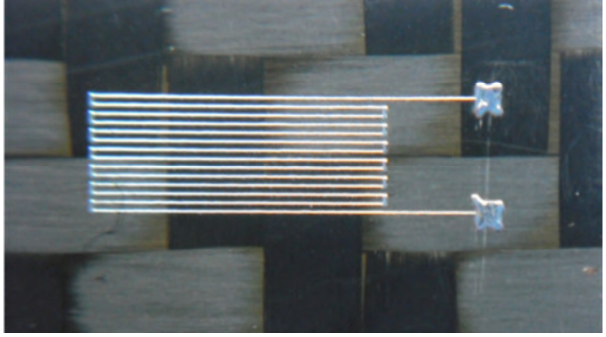

Figure 8. An Aerosol Jet printed Ag strain gauge on Carbon Fibre Composite.

[4] for CNT based transistors.

An example of a complex TFT circuit is shown in **Figure. 9**. This consists of printed NAND gates (each NAND gate is made from 2 TFTs plus a resistor), inverters (one TFT plus a resistor) and circuit crossovers (an insulating bridge with a conductive contact printed over it). As these applications mature it will be possible to transfer them to 3D parts, opening the way for completely printed electronic functionality on RP and RM parts.

Summary

Aerosol Jet printing is a unique Digital Manufacturing technique for creating miniaturised electronic circuits and components on many different substrate materials. The process works with a wide range of functional materials and can print the main building blocks of electronic systems on both 2D and 3D surfaces.

Current work has centred on printing 3D MIDs circuits and systems as well as printing novel functionality for sensors and even complete printed electronic systems using organic electronic materials. Studies are now underway in combining the 3D printing capability with RP parts to create novel components that combine the benefits of digitally driven manufacturing processes with electronics and sensing functionality.

References

[1] Sukeshini1 A. M. , Gardner P., Meisenkothen F., T. Jenkins T., "Aerosol Jet Printing and Microstructure of SOFC Electrolyte and Cathode Layers" ECS Transactions, 35 (1) 2151-2160 (2011)

[2] Werner C.; Behrens G.: Hellbernd K-H.; Godlinski D.; Zöllmer V.; Busse M; "Electrical sintering of printed metal structures for mechanical sensors" , Proceedings: LOPE-C 2011.

[3] Grunwald et. al. "Surface biofunctionalization and production of miniaturized sensor structures using aerosol printing technologies", Biofabrication 2 (2010) 014106 (11pp).

[4] H. Cho et. al.; "Printable ion-gel gate dielectrics for low-voltage polymer thin-film transistors on plastic.", Nature Materials VOL7 NOVEMBER 2008, 900-906

[5] Vaillancourt, J.; Zhang, H.; Vasinajindakaw, P.; Xia, H.; Lu, X.; "All printed carbon nanotube thin-film transistor on a polyimide substrate with an ultrahigh operating frequency of over 5 GHz". Applied Physics Letters 93, 243301 20

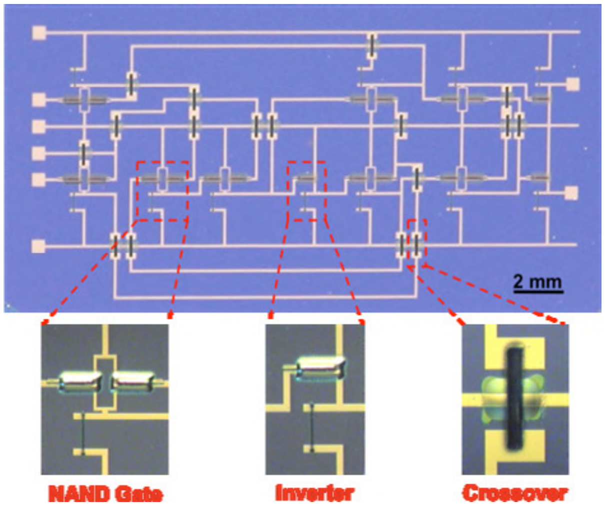

Figure 9. A fully printed Organic D flip-flop circuit with Reset. The device consists of 8 NAND gates + 3 Inverters. Courtesy: University of Minnesota/Optomec