



# 3D-printing and advanced manufacturing for electronics

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Received: 19 July 2018 / Accepted: 28 January 2019 / Published online: 4 February 2019  
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## Abstract

Printed electronics currently holds a significant share in the electronics fabrication market due to advantages in high-throughput production and customizability in terms of material support and system process. The printing of traces and interconnects, passive and active components such as resistors, capacitors, inductors, and application-specific electronic devices, have been a growing focus of research in the area of additive manufacturing. Adaptation of new 3D-printing technologies and manufacturing methods, specifically for printed electronics, are potentially transformative in flexible electronics, wireless communications, efficient batteries, solid-state display technologies, etc. Other than printing new and reactive functional electronic materials, the functionalization of the printing substrates with unusual geometries apart from the conventional planar circuit boards will be a challenge. Building the substrate, printing the conductive tracks, pick-and-placing or embedding the electronic components, and interconnecting them, are fundamental fabrication protocols new 3D-printing systems should adopt for a more integrated fabrication. Moreover, designers and manufacturers of such systems will play an important role in scaling 3D-printed electronics from prototyping to high-throughput mass production. This review gives a groundwork for such understanding, defining methods and protocols, reviewing various 3D-printing methods, and describing the state-of-the-art in 3D-printed electronics and their future growth.

**Keywords** Additive manufacturing · 3D-printing systems · 3D-printed electronics

## 1 Introduction

Electronic devices are small modular components that are connected together to manipulate the flow of electrical current with the goal to control the processing of information [1]. The miniaturization method in a form of integrated circuits has initiated the modern electronics trend worldwide. With this modern electronics boom, the global electronics components industry has been projected to have a continued growth of 7.7%, reaching 7.86 million US dollars in 2022 from 5.41 million US dollars in 2017 [2]. We see and

use electronics devices and products virtually in all areas of our day to day lives, with increasing levels of complexity in terms of design and applications.

The conventional method of modeling and designing electronics is subtractive in nature wherein selective removal of materials patterned from a master template is a standard process. This includes preprogrammed electronic patterns such as printed circuit boards (PCB), integrated circuits (IC), and chip design. The process is relatively expensive due to the needed equipment and significant amount of material waste—even wasted water (washing–cleaning–disposal requirements). It is deemed not environmentally friendly requiring several chemical-processing stages. It is also time-consuming and iterative to completely design and pattern each layer [3–5]. On the other hand, additive manufacturing (AM) technologies or more popularly called 3D-printing, has paved the way in new areas of electronics fabrication. 2D-printing using inkjet and aerosol [6], which are primarily used for fabricating homogeneous structural electronics in flat surfaces, has given way for multiple layer complex electronics and new substrate geometries. With the need for higher

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throughput, 3D-printing has a great potential to transform the electronics fabrication industry into a more adaptive and smart manufacturing practice [7].

The main concept of 3D-printing can be conveniently described as a replication of the 2D-printing process, i.e., by stacking the 2D patterns as individual layers to produce a tangible three-dimensional output from a digital model created in a computer-aided design (CAD) software [8, 9]. The most common 3D-printing methodologies including binder-inkjet, powder bed-based printing, and extrusion-based printing can be considered as additive adaptations of other 2D-printing and patterning methods. The integration of two or more of these technologies can be a viable tool to fabricate multi-functional electronics. However, each of these machines or methods can be limited to the type of material, the dimension of the build volume and resolution (shape accuracy), and systems integration. Though there is flexibility in design and customization, there are important issues to overcome on build quality and spatial resolution. With the potential advantage of faster manufacturing processes and higher-resolution output of scalable electronic models, 3D-printing can go beyond prototyping and full-scale mass production [10, 11].

In the production of mobile electronic devices, a “3D fabrication mode” has always been used. A good analogy is the integration of flex circuits such as flexible bus cables to connect a motherboard onto other circuit boards. Though not a 3D-printing method, it theoretically follows a 3D electronic modeling and fabrication approach. For now, it is a workable strategy to integrate the more traditional pick-and-place method of building electronics with emerging 3D-printing technologies. For example, reducing the entire volume of a conventionally manufactured device can be done by reducing the space occupied and the materials used to build the electronic architecture. It is a more practical approach to accurately embed electronic components with conductive interconnects within a three-dimensional substrate for a more robust and space-saving model. However, most electronic manufacturing companies are still using the PCB design due to the challenges of integrating new 3D-printing technologies with both machine and material [10–13].

The overall aim of this review paper is to outline the basic methods and challenges of electronics fabrication and update electronics enthusiasts on building electronic component, circuits, and devices through new 3D-printing technologies and materials. This includes understanding the current techniques and processes and the advantages and difficulties of adopting additive manufacturing. More importantly, this review presents an appraisal of the prospective direction and significance of 3D-printing in the field of electronics design both in the aspects of prototyping and future mass fabrication.

## 2 Electronic materials

Knowledge on the range of materials and scalability, i.e., from prototyping to full-scale fabrication are vital considerations in the utilization of various 3D-printing technologies in electronics fabrication [14]. The key to understanding the future role of 3D-printing processes involves mastering the nature and characteristics of the current electronic materials and methods used.

An electronic and logic circuit consists of two main types of functional components: active and passive devices. These basic electronic components are made of functional materials (metal, semi-conductor, dielectric, polymer, etc.) that can be wired, printed or directly placed on various substrates utilizing different printing and patterning techniques. This means the materials can be placed and patterned as solids, pastes, inks, curable thermosets, etc. that can regulate the flow of electrons. An active device has the ability to control the flow of electrons passing through it by way of another electrical signal. Otherwise, it is a passive device. A circuit should at least contain one active component for it to be called “electronic”. Examples of active devices are transistors, rectifiers, light-emitting diodes (LEDs) and thyristors such as silicon-controlled rectifiers (SCRs) and TRIACs (triode-AC). Conversely, passive devices are the actual interconnects or wires, transformers, resistors, inductors, and capacitors. Current flowing through an active device can be controlled either by another voltage or current [15]. Field-effect transistors (FET) are voltage-controlled while bipolar junction transistors are current-controlled devices [15]. There are also components that can do electrical operations by means of mechanically moving parts or by electrical connections, which are called electromechanical devices (e.g., mechanical relay).

Electronic components vary depending on how they are integrated into the entire circuitry. Most of today’s electronic hardware is manufactured using surface mount technologies (SMT). Electronic components built with this technology are called surface mount devices (SMDs). SMT is different from traditional approaches where manual soldering is usually done after inserting the leads of the devices into the holes of the PCB then cutting the excess lead length. The SMT mechanization has helped scale the process of mounting the components on the PCBs by soldering the terminals onto the conductive pads of the SMT-PCBs in a reflow oven without the need for creating holes. The automated soldering process creates electrically and mechanically reliable solder joints [16]. While already considered conventional, such technology has the potential to be adapted for 3D-printing electronics compared to the lengthy through-hole approach.

### 3 Techniques for printing electronics

Printable electronics can be differentiated from traditional fabrication methods in several ways [17]: The freedom to choose materials for the substrate is one factor. But the use of different electric or dielectric “printing ink” gives it a high advantage in design. With the capabilities of 3D-printing and multi-material selection in printable electronics, phases of the conventional method for fabricating electronics can be changed entirely into a more adaptive and inclusive system. This includes material preparation, design, and architectural processes for the structure of both ink and substrate. As an economic perspective, printed electronics should offer better profitability in the long run due to its scalability. Traditional electronics may cut costs in a large-scale production setting. However, the flexibility of producing high performance and more complex designs in a limited production volume can be an advantage for 3D-printed electronics with multi-materials.

In general, modern manufacturing can be divided into two major directions: subtractive and additive manufacturing. Subtractive technology, which is exhibited in computer numerically controlled (CNC) machining, basically removes unwanted parts or material via mechanical tools. Though for electronics, lithography and etching is the most popular method using chemicals to remove unwanted conducting material. On the other hand, additive technologies based on AM technologies [18] adds materials one layer

at a time. Figure 1 shows the main difference between the subtractive and additive approach of manufacturing electronics. In traditional electronics fabrication, lithography involves applying and patterning a material uniformly onto a substrate. Photoprocessing by means of a mask template, etching, and cleaning are performed to eliminate unwanted material from the substrate and reveal the pattern of the design [19]. This concept is demonstrated particularly in wafer fabrication process such as very large-scale integration (VLSI), as illustrated in Fig. 2; whereas, in printed electronics, it becomes a single-layer pass process involving direct and selective printing (direct transfer, embedding, embossing, etc.) of the material on top of the substrate. However, current methods involve single or limited passes and not multilayer or hierarchical material build-up. Also, as previously mentioned, the laborious processes involved in subtractive technology produces high amounts of wastes compared to the additive technology [20].

The advent of 3D-printing technologies can be traced to 2D-printing techniques developed in earlier years. It is important to understand how these 2D-printing techniques have been executed especially in the field of printed electronics.

#### 3.1 2D-printing technologies

The major types of conventional printing that are still used up to this day are flexographic, offset, gravure and screen-printing. These techniques are characterized by the printing

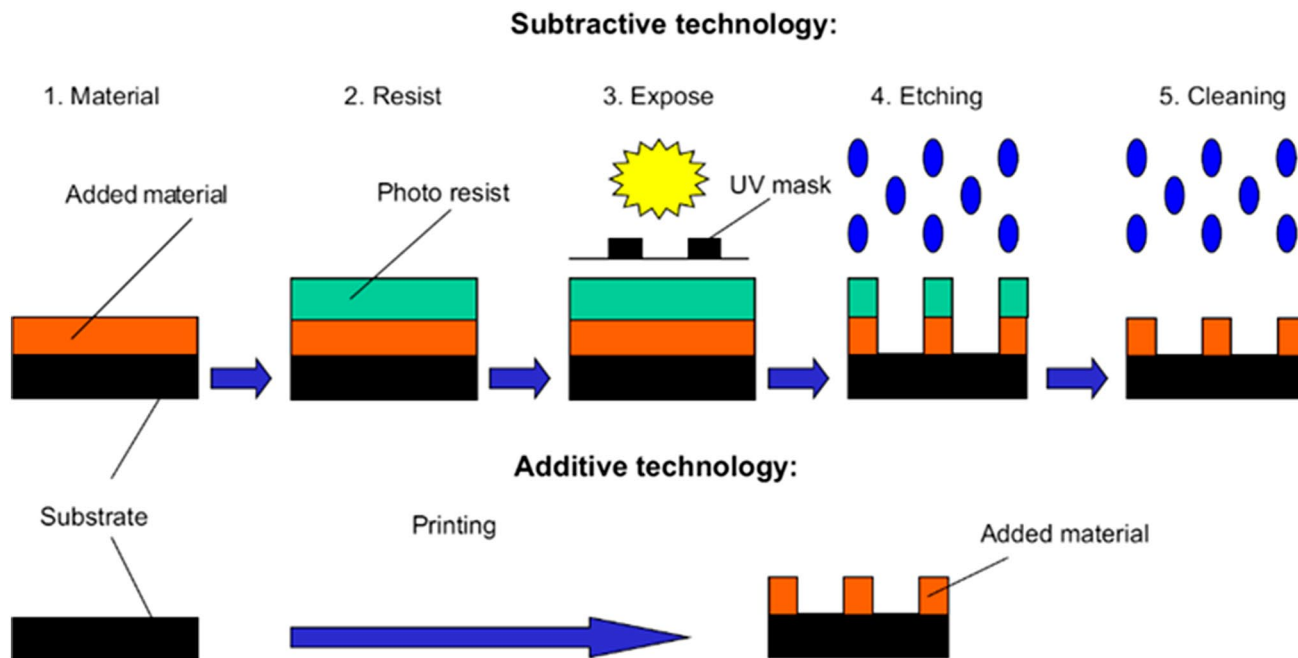
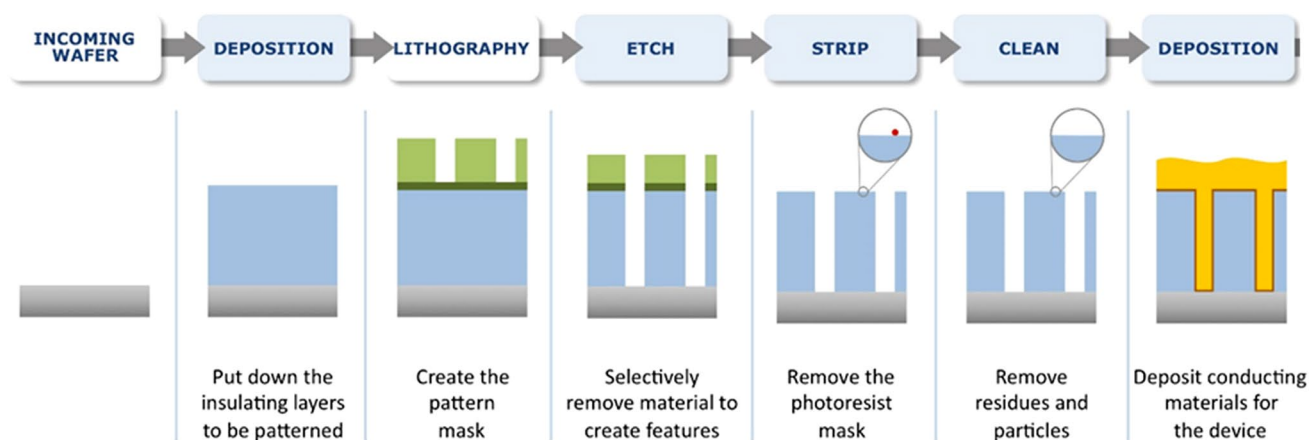


Fig. 1 Subtractive vs additive manufacturing technology [104]



**Fig. 2** Wafer fabrication process for VLSI [105]

pattern, the layer depth and the viscosity range of the various inks used. Basically, information in the form of graphics and texts are first made with printing template, which also requires lengthy preparation and setting up. Table 1 shows the specifications of conventional printing technologies [21].

Digital Printing (DP) came to existence as printing techniques have evolved into combining traditional printing methods and computer-aided design (CAD) technologies. The new DP printing process skips the need to prepare a master template for the required patterns. Since information in a form of digital data is the source of the design, its main mechanism often utilizes a liquid droplet equivalent to the pixel size of the digital design (resolution). The droplet is accurately and selectively deposited either on the substrate (inkjet and thermal transfer printing) or directly on the plate (electrophotography and magnetography). This digital process has also been made readily adaptable to manufacturing lines especially in fabricating electronic components for PCBs [22].

In general, current printed electronics relies on available printing technologies, conventional and/or digital, in manufacturing electronic components, structures, and circuits by

direct ink application on a substrate. In organic electronics, organic materials including electrically conductive polymers are used for imparting pattern and functionality (e.g., variable resistivity or conductivity and dielectrics). Moreover, flexible electronics has become popular as well by distinctively using a flexible plastic substrate such as Poly(ethylene terephthalate) (PET) or polyimides (PI). The ink must maintain a proportional functionality and adhesion to the substrate, which can be bent, rolled, or stretched. Flexible electronics is further discussed in the latter part of this review.

### 3.1.1 Inkjet printing technology (conventional)

Inkjet printing is digital printing that uses a droplet depositing nozzle connected from a fluid channel and reservoir. Its resolution level depends on the volume and area coverage of the droplet being deposited out of the nozzle. It is also dependent on the wetting behavior of the substrate. An inkjet or digital printing facility is a favorite choice among other printing machines in terms of saving floor space, initial investment and commissioning time. A process line can be scalable, from prototyping electronic designs to the actual

**Table 1** Printing technologies and significant characteristics [14, 21, 101–103]

Printing technologies	Characteristic
Flexographic printing	Printed pattern defined by surface relief (raised features) of template Thin layers of about 1 $\mu\text{m}$ possible; high resolution ( $\sim 20 \mu\text{m}$ ) Dynamic viscosity of ink: 0.05–0.5 Pa s
Offset printing	Printed pattern defined by differences in wetting of a plane surface Thin layers down to 0.5 $\mu\text{m}$ possible; high resolution ( $< 20 \mu\text{m}$ ) Dynamic viscosity of ink: 40–100 Pa s
Gravure printing	Printed pattern defined by surface relief (recesses) of template Broad thickness range ( $\sim 1$ to 8 $\mu\text{m}$ ); high-resolution ( $< 20 \mu\text{m}$ ) Dynamic viscosity of ink: 0.05–0.2 Pa s
Screen printing	Printed pattern defined by openings in printing template Thick layers ( $> 10 \mu\text{m}$ ) possible; low resolution ( $\sim 100 \mu\text{m}$ ) Very bad dynamic viscosity range, from gravure inks to offset inks

production by parallel printing with a high number of printers. With inkjet printing, the print head with a nozzle, allows freedom to place the print head in any location in the  $X$ – $Y$ – $Z$  planes of the substrate much like a CNC movement but much closer to the substrate. It is capable of producing patterned thin film devices that complement the fabrication of organic electronics [23]. It offers a good alternative method to etched interconnects (conductive paths) between electronic parts of a traditional PCB by using inks that have dielectric or conductive properties. The most common inks used for inkjet printing are inorganic/metal in nature because they offer better conductivity and durability than organics (several thousands of hours in operation). The functional materials can be made cheaper for disposable applications including radio frequency identification (RFID) [20] antennas that are commonly used as unique tags for inventory monitoring in commercial stores or ease of payment processes.

Inkjet printing can be classified into two major types: continuous inkjet (CIJ) and drop-on-demand (DOD) printing techniques. DOD printing is further classified as thermal, piezo and electrostatic inkjet printing. Table 2 differentiates the characteristics of the individual inkjet printing techniques. CIJ continuously ejects droplets of ink regardless of the pixel information of the image and tends to put a lot of ink to waste. Yet, this technique can be advantageous in printing on an intricately shaped substrate. For these reasons, CIJ is less popular in printed electronics. Among DOD inkjet technologies, piezo inkjet (PIJ) is most popular in printed electronics due to the following reasons: more stable ink materials (thermal inkjet causes functional materials to degrade), a broader selection of inks, and electrostatic technique for controlling resolution [24]. However, thermal inkjet has been proven effective in the fabrication of inorganic quantum dot light-emitting diodes (QD-LED) [25]. The PIJ system uses inverse piezoelectric effect by applying

a voltage across the terminals of the piezoelectric transducer. It produces precisely timed actuation that generates specific frequencies of 1–20 kHz. This, in turn, regulates the ink droplets coming out from the nozzle [26].

### 3.2 3D-printing technologies and classification

3D-printing, additive manufacturing, rapid prototyping (RP) or solid-freeform technology (SFF) are almost synonymous terms in the manufacturing world. Charles Hull (founder of 3D systems) tried to solve the long process of prototyping and the design defects of the final product [27]. He also developed the .STL file format (which is originally referred to as STereoLithography). In some literatures, the acronym may mean “Standard Triangle Language” or “Standard Tessellation Language [28]”. Nowadays, the .STL file format has become the standardized digital file that contains the information of the coordinates of the three-dimensional model of the object and which serves as the electronic language between the CAD software and the 3D-printing hardware [29]. Most 3D printers are designed to understand the coordinates from .STL file via the embedded slicing software. The slicing software creates a G-file that holds the information of the succession of stacks of the 2D layers (cross-sectional slices of 25–100 microns thickness of an object relative to the 3D-printing technology) that are to be added [30]. Efforts in improving output quality addresses the development of efficient algorithms and mechanisms that offer adaptive control systems of the entire 3D-printing process (from CAD model to the final product), as shown in Fig. 3 [31, 32].

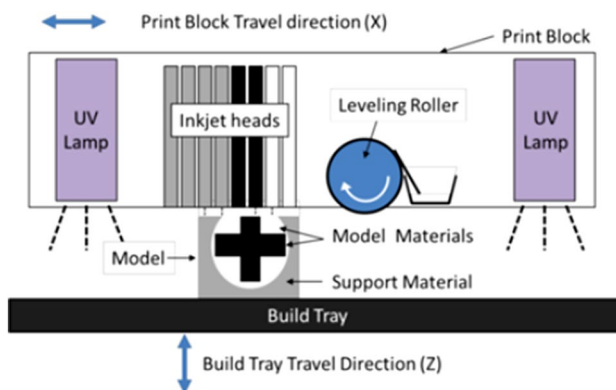
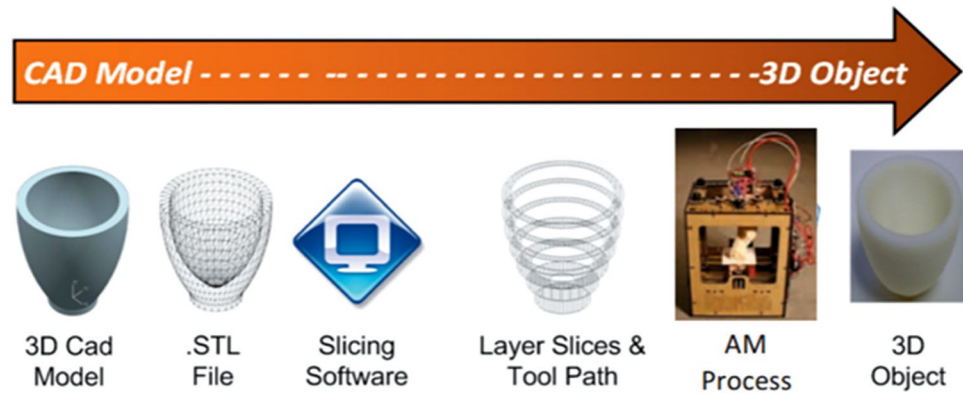
Thus, a 3D model is merely a set of 2D patterns ( $X$ – $Y$  plane) assembled vertically ( $Z$ -axis) during printing. So, a 2D-printing technology such as an inkjet printer that reiteratively prints different patterns on the same page, is

**Table 2** Classification of the most common inkjet printing technologies [21, 24, 101]

Inkjet printing technologies	Characteristics
1. Continuous inkjet	Ink column under pressure A stream of ink droplets continuously ejected by nozzle Charged droplets deflected and positioned using electric field Remaining droplets collected by a gutter and recycled
2. Drop-on-demand inkjet	Droplets ejected on demand Simpler system than continuous inkjet Multiple actuation mechanisms: thermal, piezo and electrostatic
2a. Thermal	Flash heating of the ink by heating element Bubble formation resulting in ejection of ink droplet from nozzle
2b. Piezo	Voltage pulse applied to a piezoelectric transducer (PZT) Acoustic wave propagation in ink channel due to PZT actuation Inkjet droplet ejection nozzle
2c. Electrostatic	Electric field exists between inkjet setup and substrate Droplet formation involves complex interaction of surface tension ratio between ink and nozzle and electric field Signal fed to print head balances forces to create ink droplet



**Fig. 3** Generalized 3D-printing process [33]



**Fig. 4** PolyJet printing process [106]

analogous to accumulated layers of material placed on top of another until a 3D object is formed. This is 3D-printing in its simplest sense [33].

Here we summarized some of the most common 3D-printing methods:

### 3.2.1 PolyJet technology

PolyJet is a photopolymerization printing method, which employs a print carriage containing two or more print/jetting heads (one head for the model and another for the support material), and curing units. The jetting heads spray resin outlining the object in a two-dimensional pattern and layer-by-layer fashion. Print heads with colorants and other additives are commonly used. The resin is photopolymerized or photo-crosslinked by a UV lamp within the printer. The height of the build plate is then adjusted to deposit the next layer. The parts produced using this technique are smooth and precise. The support material can be easily removed by water or a solution bath (Fig. 4). Post-curing is usually not needed [34].

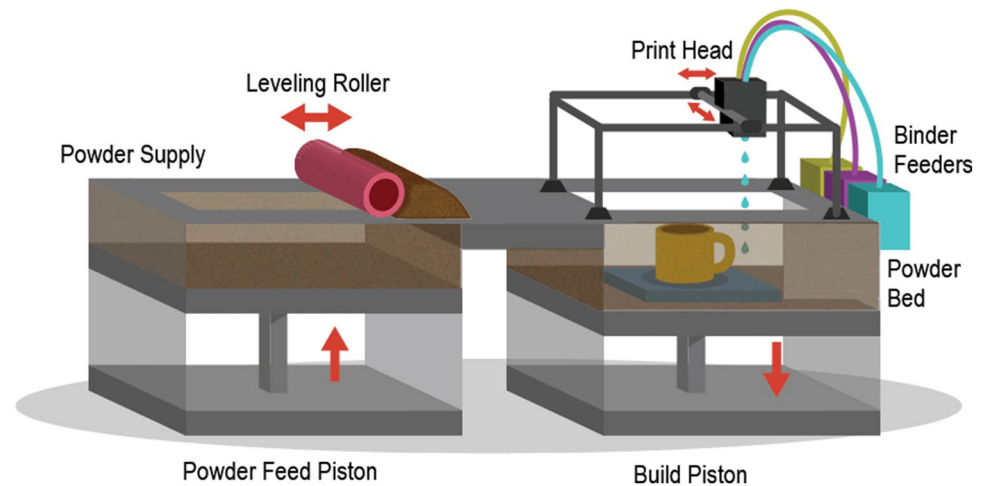
### 3.2.2 Powder bed-based printing

This technique produces solid objects by printing additive two-dimensional layers through fused powders. Each printing starts with a powder layer (atop a powder bed), and then selective application of binder material binds the powder following the drawing coordinates for every layer. The piston supporting the powder bed lowers so that the next layer can be spread and joined. This process is repeated until the object is fully printed. The printed object is heat treated and the nonbound powder is removed. Figure 5 shows the sequence of the operation [35].

### 3.2.3 Paste extrusion printing

A polymeric solution or paste is loaded into a syringe via a syringe pump. The 3D objects are produced with a layer-by-layer process based on the sliced 3D model. Paste extrusion can use a similar machine set-up with the wet-spinning apparatus [36] and the continuous filament writing technique [37]. Fused deposition modeling (FDM) printers are sometimes used to 3D-print pastes and inks using an add-on attachment such as Discov3ry from Structur3D. The difference is that, for FDM, a molten thermoplastic filament is extruded from the nozzle, while in paste extrusion, a highly viscous paste or ink can be extruded at room temperature. A wide range of polymer and viscous materials can be used, which may include gels, monomer resins, functionalized inks with conductive or dielectric properties, etc. [38], a main requirement is a thixotropic viscosity and a latent curing (or hardening) mechanism to prevent sagging. This technique has great potential in the field of flexible electronics where multi-material of elastomers (silicone, a polyurethane material, etc.) and composites of conductive inks can be printed and applied for sensors, transducers, and piezoresistive devices.

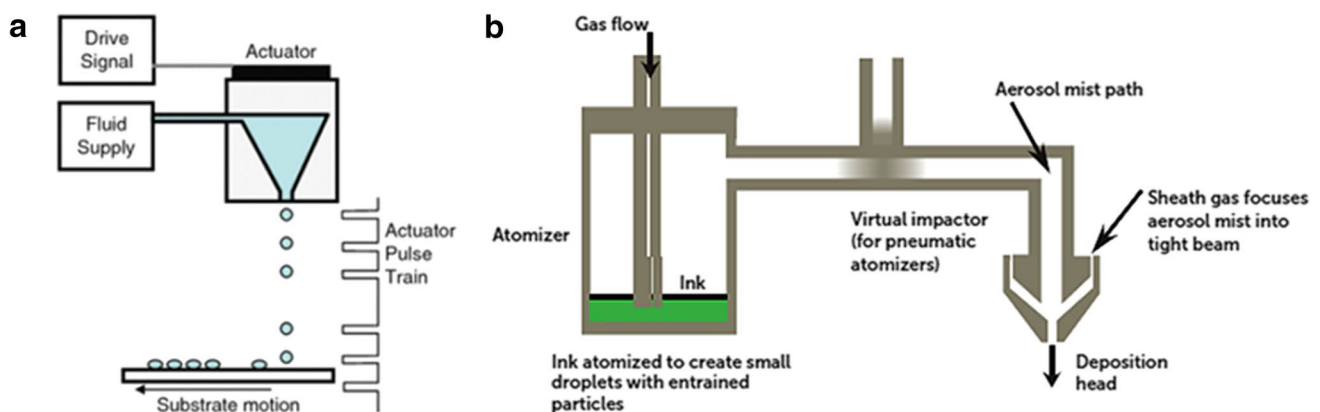
**Fig. 5** Three-dimensional printing schematic [47]



### 3.2.4 Direct write technology

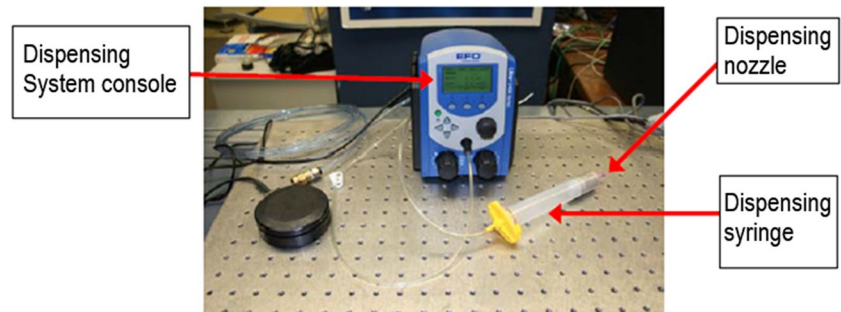
Direct write (DW) is a printing technology that enables selective deposition of a material based on a pattern in a single or multi-layer manner on flat and regular surfaces [39]. DW technology varies based on the design objective. It is capable of printing both passive and active components such as conductive traces, insulators, capacitors, resistors, antennas, etc., from a digital file. Extrusion DW follows the same principle as other extrusion-based printing where a material is continuously extruded by a pressure out of the nozzle and onto the substrate. Droplet DW methods is based on a mechanism which expels droplets of a material on a substrate. Aerosol DW systems spray a material that produces gaseous stream directed and deposited on the substrate as illustrated in Fig. 6b. Directed-energy systems such as a laser-based DW uses laser energy to move a material onto the printing surface. Another deposition technology uses a micro-scale tip connected from a capillary of ink that can readily be ejected on a substrate. This is otherwise known as ink jetting or inkjet printing which is shown in Fig. 6a.

Basically, DW can be hybridized with AM technology and has been employed as an alternative to masking and lithography processes in electronics manufacturing [40]. An advantage is the ease in integrating electronic components as additively manufactured or 3D-printed structures, which addresses the complexity of multi-component manufacturing in the electronics industry [41]. The hybridization of DW and AM should enable unique capabilities in terms of freedom of movement and positioning, control synchronization for deposition and material delivery, and write speeds that can keep up with new 3D-printing technologies used. The DW technologies that have been integrated with AM processes include tip-based deposition, aerosol jetting and extrusion-based printing [40, 42, 43]. An example of a DW system is shown in Fig. 7. A 2405 Ultra Dispensing System is composed of dispensing syringe-nozzle that receives a regulated pressure of 0 to 5 psi from an air pressure control unit. The ink can be controlled using a LabVIEW® software with circuit references. The dispenser can adaptively use a variety of fluid types other than conductive inks. These DW systems can build different kinds of structures, e.g.,



**Fig. 6** Schematic of **a** ink jetting [107] and **b** aerosol jetting [55]

**Fig. 7** DW 2405 Ultra dispensing system [43]



three-dimensional interconnects, given that it can be printed layer-by-layer [44].

### 3.2.5 Ultrasonic consolidation technology

Ultrasonic consolidation (UC) is an AM technique wherein metallic foils are deposited using ultrasonic energy. The process is combined with a milling operation, with a direction normal to the foils, to generate the cross-sectional pattern. It basically produces vibration differences on the subsequent layers with the use of a rotating sonotrode (a tool made of piezoelectric stack that generates ultrasonic vibrations), causing plastic deformation and linking between metal surfaces [45]. The schematic of a UC technology is shown in Fig. 8. The printing process can be abruptly stopped and the printed parts transferred to any process without unfavorable effects. This combines the UC and DW process without the need to integrate both technologies physically. Another advantage of UC is its ability to build solid metal objects at low temperature. This is beneficial for integrating electronic components and interconnects avoiding thermal damage to the components [46].

To date, several familiar 3D-printing techniques have been used in printed electronics especially in building the substrate. Fused Deposition Modeling (FDM) uses a heated extruder to deposit melted thermoplastic filament onto the build plate (some printers have heated plates), layer-by-layer until the object is formed. Directed heat on powder bed-based printing techniques such as Selective Laser Sintering (SLS) and Melting (SLM) are used where laser heating,

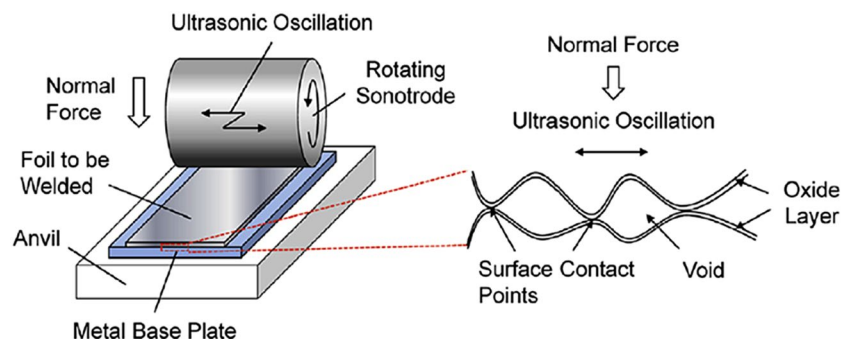
scans a pattern onto a powder bed to create the sintered or fused layers. A roller applies a new coat of powder and the process repeats until the model is fully printed. Selective deposition lamination (SDL) is a lamination technique that selectively applies adhesive to bond layers of papers and a special blade to cut the patterns of each layer to form the object. A photopolymerization approach is utilized in Stereolithographic apparatus (SLA) and Digital Light Projection (DLP) to build a 3D model using a liquid resin with photoinitiators that can be cured by either a scanning UV light or a projected image containing the patterns [47–49].

## 4 Processes in 3D-printing electronics

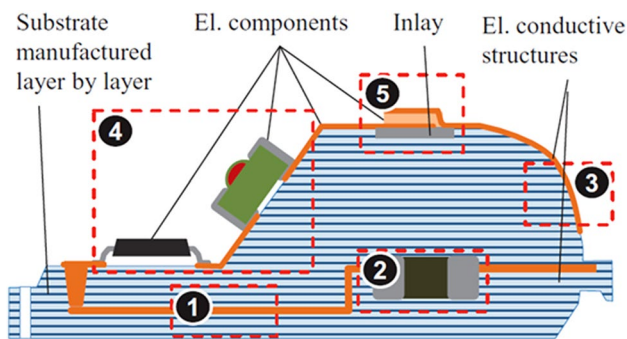
This section presents an exemplar of 3D-printing electronics that demonstrates the meticulous processes involved, the challenges associated with these processes, the materials used, and the utilization of appropriate 3D-printing technologies. Most of the processes involved in electronics production are focused on planar or two-dimensional processes favoring traditional manufacturing. However, a growing interest for 3D molded interconnect devices (3D-MID) demands cost-efficiency through AM technologies for building complex 3D structures and substrate geometries [50–52]. A study conducted by Hoerber et al. focused on improved building processes for 3D devices and functionalization of 3D surfaces for electronics [42].

A cross-section of a typical 3D-printed electronics is illustrated in Fig. 9. To further understand the processes

**Fig. 8** Schematic of ultrasonic AM (UAM) [108]







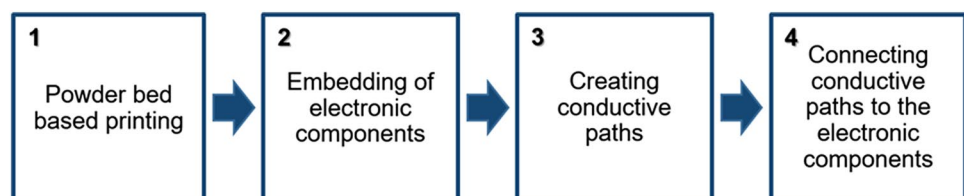
**Fig. 9** 3D-printed electronic device. (1) conductive path; (2) electronic component embedded in the substrate; (3) a three-dimensional circuit track; (4) SMT components; (5) printed electronic component on inlay [42]

and challenges involved in building 3D-printed electronic devices, Hoerber et al. presented a combination of powder bed-based 3D-printing and Aerosol Jet printing as a collective approach to successfully 3D print an electronic device [42].

#### 4.1 Improved building process for 3D devices

Hoerber et al. demonstrated an improved building process for 3D devices following a voxelization method as shown in Fig. 10. A powder bed-based 3D-printer (Fig. 11a, left) called Voxeljet AG<sup>®</sup> was used. A powder feeder deposited the material that was flattened by a recoater. A Spectra SL128<sup>®</sup> print head from FUJIFILM Dimatix<sup>®</sup> was used to apply the binding material. Figure 11a shows the improved process of 3D-printing by applying powders and connecting the electronic components to form a conductive path. An SMT resistor can be integrated into the part (Fig. 11b, left) that is taller than a one-layer depth (to prevent the recoater from hitting the component). The component was buried into the powder bed by forming cavities. This system had an exhausting needle to accurately create cavities in order to fit the components during the building process. The cavities are usually made wider than the component by 0.7 mm along the perimeter and an increased depth of 0.8 mm. Figure 11b illustrates the procedure of burying the components. Exhaustion was done first at the corners and midpoint (Fig. 11b right, 1a and 1b) and then horizontally or vertically onto the

**Fig. 10** Enhanced building process for 3D devices



entire shape. The component was inserted into the cavity then coated with a powder (Fig. 11b, right, 3).

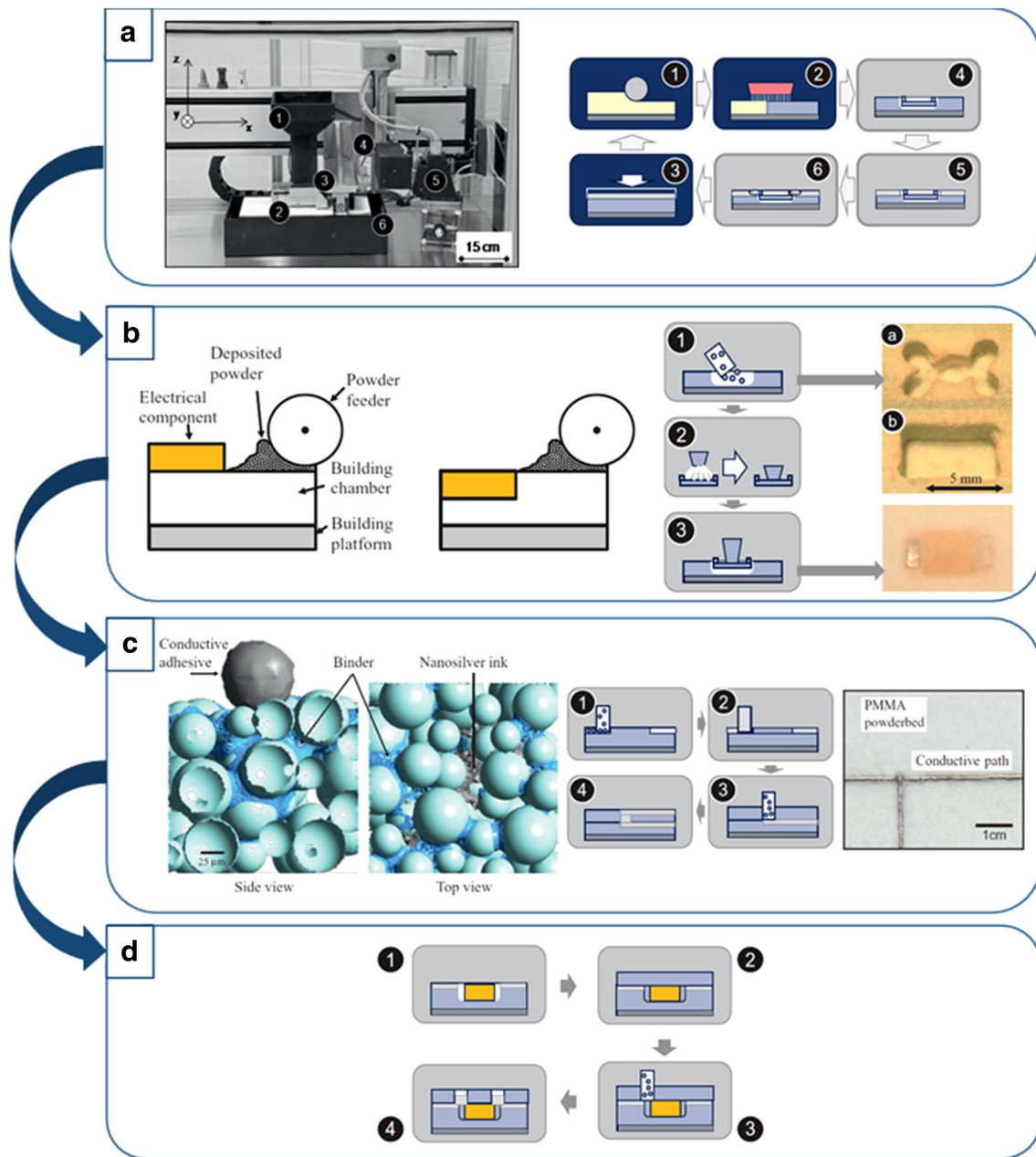
The printing process of conductive paths and channels needs metal conductive elements (copper, silver, etc.), in the form of a conductive ink material. The higher the viscosity of the material, the more difficult it is to print [53]. Inkjet printers can manage conductive materials with less than 20 cP viscosity value. However, higher viscosity can only be handled by specialized dispensing machines (Fig. 11c, left) shows a comparison of an isotropic conductive adhesive (ICA) with  $\eta = 300$  cP and a nano silver ink with a  $\eta = 20$  cP viscosity, respectively. Computational Fluid Dynamics (CFD) simulations enable the selection of the best conductive material and matching of viscosity requirements. It has been observed that high viscosity ICA is retained on the surface of the powder while low viscosity silver nano ink is attracted into the powder bulk media. A compressed air dispenser can be utilized to deposit the ICA and fill in the channels after using the existing exhausting system to create the cavities, as shown (Fig. 11c, right). Channel dimensions depend on the needle size. Through this process, three-dimensional conductive tracks are possible by creating cavities between layers and conductive tracks.

An electrical circuit was created with the closed path of the conductor. Because the cavities were created with a space allowance, the existing gap cuts the track and needed to be filled with conductive material to generate a closed path. Figure 11d illustrates how the gaps were filled to connect electronic components to the conductive path. Filling of powder were done locally until the electronic component and conductive path were visible. ICA was then dispensed into the void to guarantee connectivity between the electronic part and the conductive line.

#### 4.2 Functionalization of 3D surfaces

Hoerber et al. also presented methods for functionalizing 3D surfaces, specifically, 3D-printed substrates and boards, as shown in Fig. 12.

Aerosol Jet printing is a DW technology created by Optomec [40]. It supports a broad range of materials, allowing manufacturing of electronic components from different functionalized inks [54]. Patterns have been printed on 3D substrates using a Neotech Services MTP handling system. A higher degree of precision was achieved by using gravity

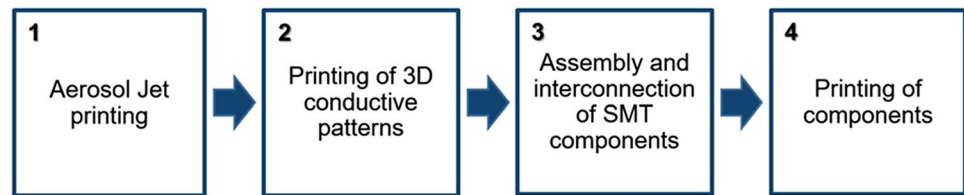


**Fig. 11** **a** Left: 3D-printing test rig; (1) powder reservoir; (2) platform; (3) powder feeder; (4) mechanism for application of suspensions; (5) printing head; (6) powder overflow. **a** Right: enhanced process of 3D-printing; (1–3) powder bed-based printing cycle; (4) embedding electrical components; (5) creating conductive paths; (6) connecting a component to the conductive path. **b** Left: Existing problem when depositing an electronic component on the powder layer, components are placed on the layer then buried the component is buried. **b** Right: burying of components; (1) creating cavities; (2) sucking and placing electronic components; (3) inserting them into the cavity and reapplying with powder. **c** Left: results of CFD-sim-

ulated conductive materials on a powder sample. An isotropic conductive adhesive can be seen on the surface while the silver nano ink seeps into the material. **c** Right: creating conductive paths during the building process; (1) creating channels; (2) filling the channels with ICA; (3) creating a cavity with the exhausting tool; (4) filling the cavity and creating another conductive path. A conductive path is seen on a PMMA powder bed. **d** Connecting the electronic component to the conductive path; (1) inserting an SMD and conductive paths; (2) filling the gaps with PMMA; (3) removing the powder; (4) filling with ICA [42]

to deposit droplets. A concentrated ink path was produced by atomizing the material into a mist through deposition nozzles while enclosed in a gas. This made the flow of the material relatively faster and more focused on the substrate [55].

Conductive patterns can be included in the 3D CAD model to functionalize surfaces of the powder bed. Nexta [56] and MIDCAD [57] are the most common software tools to design sophisticated circuits, especially in molded

**Fig. 12** Enhanced building process for 3D devices

interconnect devices (MID). Powder bed-based substrates suffer from surface roughness, especially when printing very fine circuit patterns. Inks can easily seep through the rough surfaces producing a capillary effect. A solution was presented using silver inks with a viscosity range of 50 to 100 cP to functionalize the surface. In addition, the aerosol jet printer also supports high-viscous inks. Thermal post-processing was required to evaporate the solvent in the ink, and a selective sintering process was performed [58]. The most suitable technique is to use laser sintering (light beam soldering and a diode laser with  $\lambda = 940$  nm wavelength), which can be easily integrated into the printer, rather than oven sintering. Oven sintering could cause warping on other parts of the electronic device [59]. The same postprocessing can be used for curing the ICA stage, enabling interconnection between components.

The pick-and-place mechanism for 3D-printing serves a good integration method for laying down SMT components. MIDs can use multi-axis robots or smart carriers to perform the pick-and-place procedure [60, 61]. An important step is to create interconnects between SMT components within or onto 3D-printed substrates. Soldering poses a significant challenge since most 3D-printed substrates are not suitable for very high temperatures. As a solution, adhesives with low curing temperatures can be used. This method could also be applied with the incorporated sintering system. The use of poly(methyl methacrylate) (PMMA) (Fig. 13b, left) as an adhesive has limitations such as low mechanical interface strength and complex dispensing mechanism for ICA (essential for placing intricate SMT components). This was addressed by creating cavities in the substrate, dispensing the filler material, then placing the SMT component. According to Miettinen et al. [62], interconnects made of conductive ink material could be printed in this manner. A component based on quad flat no-lead (QFN) packaging, having 24 leads (pitch of 800  $\mu\text{m}$ ) was embedded with silver (Ag) tracks (Fig. 13d). Overall, the dispensing or printing of conductive materials can be automated to functionalized and 3D-printed surfaces.

Electronic devices, whether they are active or passive in nature (capacitors, transistors or OLEDs), can be created by 3D-printing functional materials. Printed electronics serve as an alternative to SMDs [63, 64]. However, one potential limitation is dimensional inaccuracy (infill and layer thickness) in 3D-printing. Any system designed should

enable insertion of inlays in the substrate. This has been demonstrated by fabricating a capacitor of up to 100pF with parallel plates (5–50  $\text{mm}^2$  area) and a dielectric material. The layout could be manipulated in the CAD file given the capacitor's parameters: area of plates and the dielectric layer. Through these demonstrated advantages, SMT devices that are currently commercially produced, cannot rival the versatility that 3D-printing systems provide.

## 5 Current trends in 3D-printed electronics

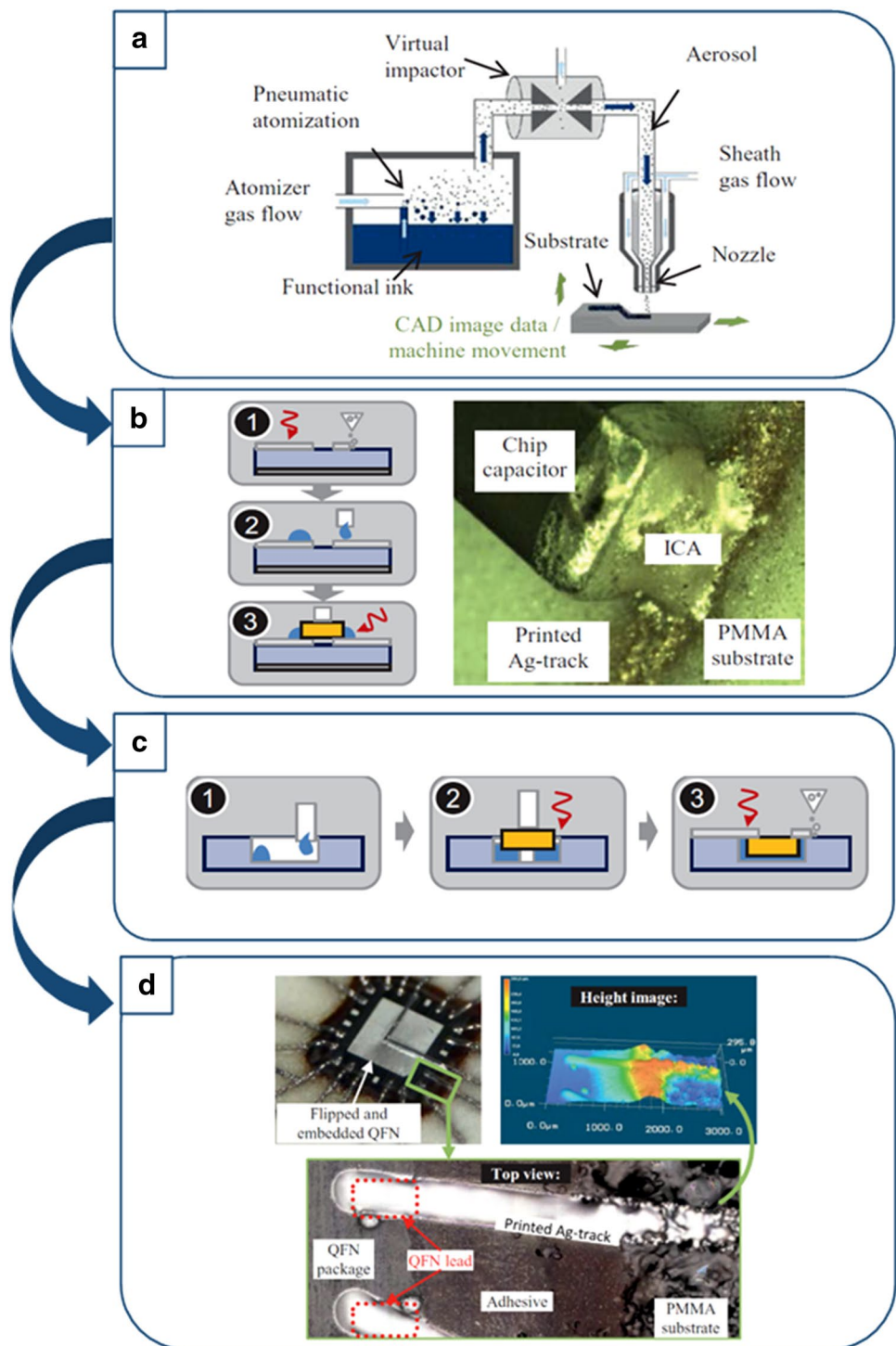
### 5.1 Research

This part of the paper presents an overview of current research areas recently reported in the development of electronic materials and devices through 3D-printing. Researchers have attempted to evaluate and prove whether 3D-printing is indeed more efficient and economical for mass fabrication or just for customizable functional electronic components. In the past decade, AM has been making significant inroads in the design and use of new electronic materials themselves [13, 65, 66]. This includes fabrication of electronic devices such as resistors, capacitors, inductors, antennas and specialized electronic devices using new materials chemistry and polymer composites [67].

#### 5.1.1 Common devices

A group of researchers in Palo Alto Research Center (PARC) in California has developed a printing system capable of integrating functionalized electronic materials and structural objects. The printer design is composed of a UV lamp, extrusion and inkjet heads, and a droplet visualization interface. This could address an important concern in printing both structural material (e.g., the use of a UV curable polyurethane gel with  $-25,000$  cP viscosity) and a conductive material (nano silver ink with 10 cP viscosity) through extrusion and inkjet printing techniques. They have been also successful in printing field-effect transistors (FET) using an inkjet printing technique based on organic semiconductors, nano metals and polymer dielectrics [68, 69], as shown in Fig. 14. They have also reported an inkjet printed bulk heterojunction photodiode as a high-illumination sensor [70, 71].

**Fig. 13** **a** Schematic representation of the aerosol jet printing process. **b** Interconnection of SMT components by ICA. Left: (1) printing of the circuit pattern; (2) dispensing the binder; (3) placement of component and curing of ICA. **b** Right: chip capacitor interconnected by light beam cured ICA. **c** Interconnecting embedded components by aerosol jet printing; (1) dispensing the filler; (2) placement of component and curing of filler; (3) interconnecting by ink printing and curing. **d** Aerosol Jet printed interconnection of a flipped and embedded QFN-component [42]



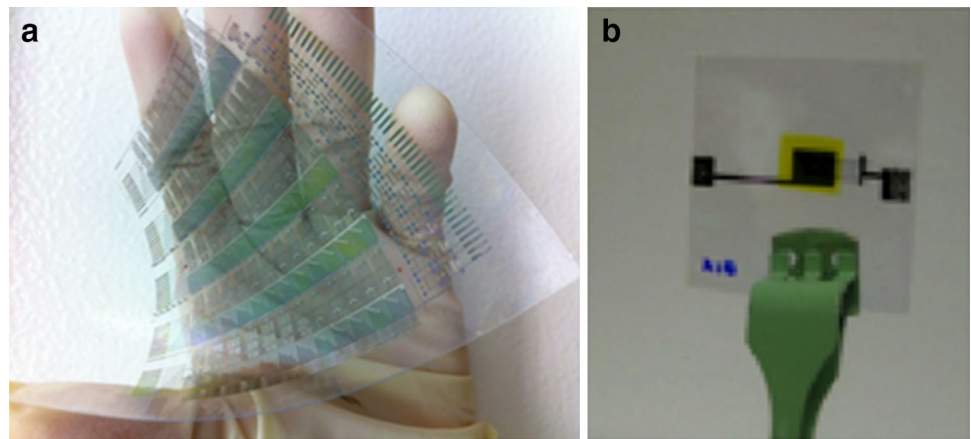
Hybridizing 3D-printing systems has become a trend in the last decade. In combination with printing techniques such as inkjet and extrusion, powder bed-based and aerosol jet printing, has been successfully used for 3D-printing electronic devices. A proposed multifunctional system comprise robots for conveniently placing components and a combination of both subtractive and additive technologies. The

highlight of this concept was to simultaneously 3D print active, passive and electromechanical devices onto multi-material substrates that offer new and multi-functional advantages [72].

As discussed, inkjet and aerosol jet printing AM techniques are widely used in the field of electronics fabrication due to a non-direct contact printing mechanism. In a



**Fig. 14** **a** printed decoder for memory addressing fabricated from inkjet printed complementary organic field-effect transistors [68], **b** a printed sensor [70]



study using these techniques, thin-film transistors have been 3D-printed using silver ink on a polymeric substrate [65]. Jung et al. made it evident that it is possible to 3D-print resistors having a wide range of varying resistances using a conductive polymer on a plastic substrate [73].

A collaborative study from UC Berkeley and NCTU (Taiwan) demonstrated a 3D-printing method to build common passive components such as resistors, inductors, and capacitors (Fig. 15). Hollow tubes were formed by removing the initially printed wax with structural polymers, which were subsequently filled with liquid metal that acted as a functional material exhibiting resistance, capacitance, and inductance elements. As a demonstration application, they used the 3D-printed components as an embedded device in a cap that detects freshness levels of milk products [74, 75].

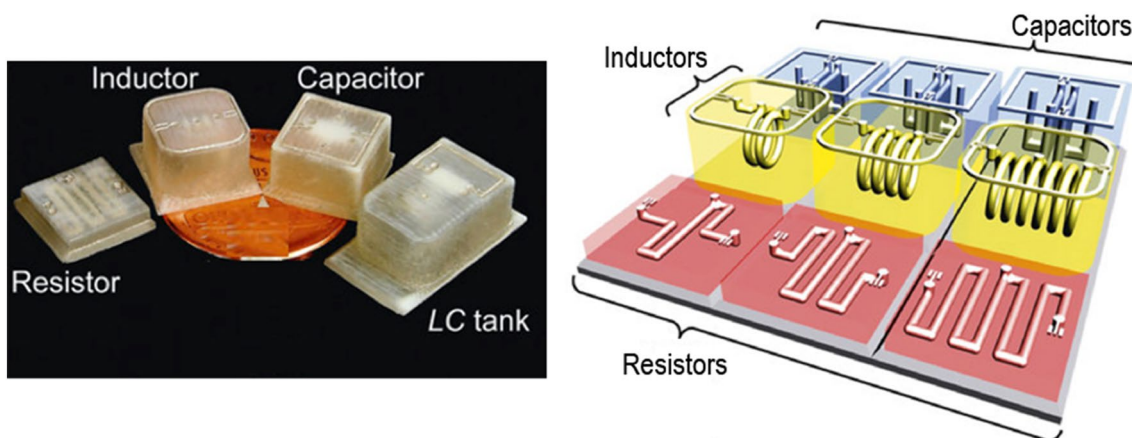
The University of Massachusetts at Lowell group has recently benchmarked an FET operating at 5 GHz constructed with a conductive polymeric gate with carbon nanotubes and printed via Aerosol Jet. The drain-source electrodes were printed with either gold nanoparticle ink or PEDOT: PSS or poly(3,4-ethylenedioxythiophene)

polystyrene sulfonate. Several polymer semiconductors including polythiophenes P3HT, PQT12, and F8T2, SW CNTs were used [55].

A specialized kind of light-emitting diode called quantum dot-based light emitting diodes (QD-LEDs) was 3D-printed and exhibited highly tunable color emissive properties [13]. In this study Kong et al. systematically presented a diverse array of materials that were 3D-printed: quantum dot nanoparticles, conducting polymers, an elastomeric matrix, metallic terminals, and on a UV-adhesive clear substrate. It was demonstrated that 3D scanning technology played an important role in conformal printing on different topologies such as on curvilinear faces (Fig. 16). They were also able to 3D-print LEDs encapsulated in a cube, which would not have been achieved using standard microfabrication technologies [13, 76].

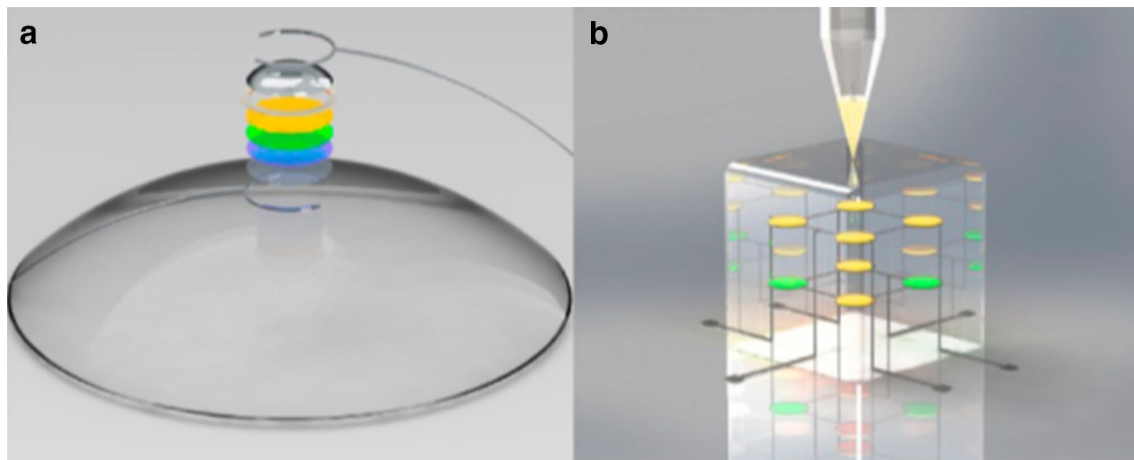
### 5.1.2 Antennas

Antennas are essential devices in wireless communications. They are usually made of a conducting material and



**Fig. 15** 3D-printed passive electronic components [74]





**Fig. 16** **a** Printing on the curvilinear surface. **b** Integrated printing of LEDs and cube structure [13]

are specifically designed for propagating electromagnetic signals with various power rating, frequencies, and directionality depending on the application. The higher the carrier frequency of the antenna, the smaller the antenna structure required. Goh et al. reported the prospect of using 3D-printing to bring down the cost of production. The researchers used ink with silver nanowires to 3D-print patch antennas for low-power wireless applications [77].

Many researches have explored 3D-printing techniques to produce RFID antennas via screen and inkjet printing and microfluidics. Conformal printing has also been used in different designs of 3D-printed antennas, especially in propagating signals of GHz range and above. This opens opportunities for 3D-printing uniquely shaped antennas, given that the shape factor is a design consideration. Adams et al. demonstrated a new protocol to build electrically small antennas (ESA) via conformal printing. The antennas' electrical size is quantified by  $ka$ , “where  $k$  is the wavenumber ( $k = 2\pi/\lambda$ ,  $\lambda =$  wavelength at the operating frequency) and  $a$  is the radius of the smallest sphere that circumscribes the antenna.” For their study, a  $ka$  of  $\leq 0.5$  was used and categorized as ESA. As shown in Fig. 17, the design called for conformal printing of an antenna based on the principle that antennas circumscribing a spherical volume theoretically result in a significant bandwidth improvement in comparison to planar antennas [78, 79].

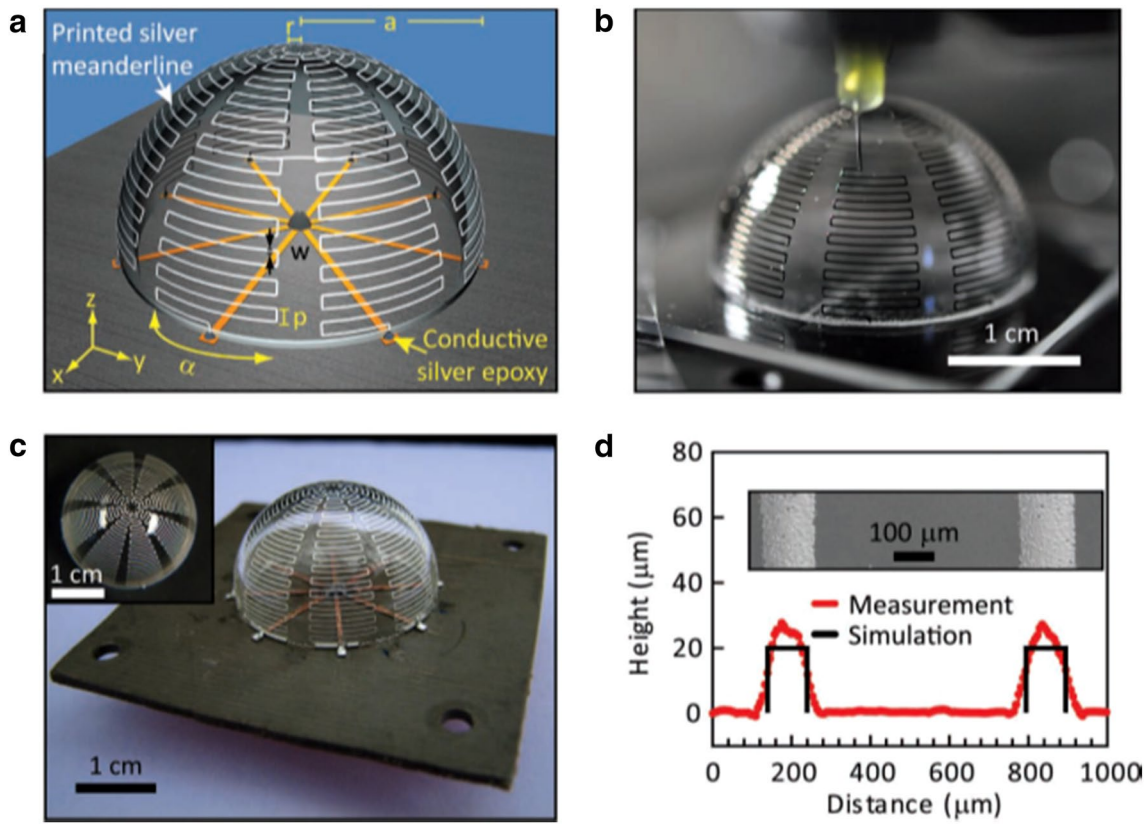
### 5.1.3 Flexible electronics

A broad array of new functionalities has been demonstrated with flexible electronics. This unique type of electronics plays an important role in manufacturing new solar cells [80], displays and LEDs [81, 82], sensors [83] and thin-film transistors [84, 85]. Flexible electronics is used for flexible displays, wearable electronics, etc. Conductive elastic

polymer nanocomposites are commonly used materials for flexible sensors. For example, CNT/graphene–thermoplastic urethane (TPU) composite has been reported for use in highly compressive and recoverable piezoresistive strain sensors [86–88] due to the excellent mechanical response of the thermoplastic polyurethane (TPU). Carbon-based conductive silicone nanocomposites are applicable as triboelectric nanogenerators, strain sensor, etc. [89–91]. Because of freedom of geometric design and the ability to fabricate small-featured structures, 3D-printing is increasingly applied in the field of flexible sensors. FDM printing of TPU has been reported recently [92, 93] and by adding multi-walled carbon nanotubes (MWCNT), conductive TPUs were successfully 3D-printed as a piezoresistivity sensor [94]. The addition of CNT effectively enhances the modulus of TPU improving printability in FDM by increasing the resistance to buckling. The electrical conductivity was not degraded during printing due to the good fusion and adhesion in the layer deposition process.

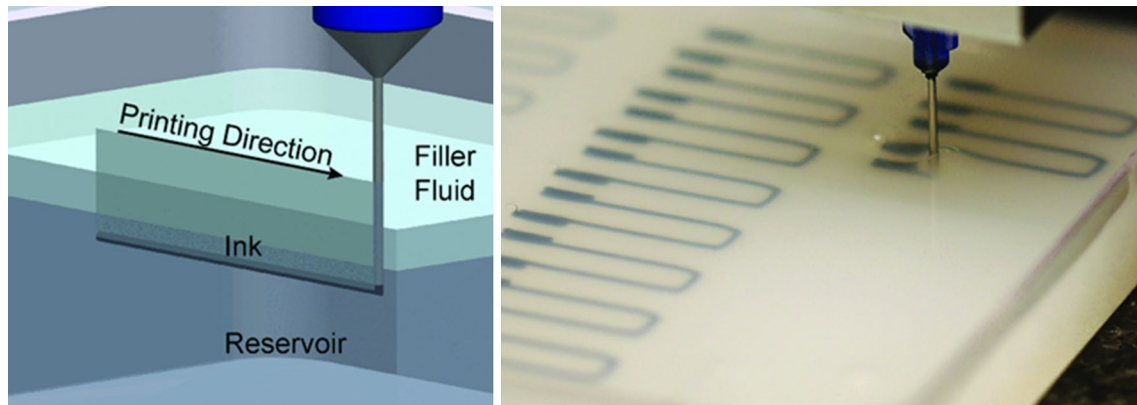
Conductive polydimethylsiloxane (PDMS) has been successfully 3D-printed by using a unique embedded 3D-printing (e-3DP) method, as shown in Fig. 18. A multicomponent materials system composed of an ink, reservoir, and filler fluid was developed. The reservoir was prepared by modifying PDMS resin with a thickener to provide thixotropic property and acted to support conductive silicone grease ink. The filler fluid was prepared by adding thinner with PDMS to heal the defects generated during embedded printing. This unique technology enables the fabrication of conductive components into well-controlled geometry and location in highly elastic PDMS matrix and could be applied as a sensitive and flexible strain sensor to detect multiple hand gestures (Fig. 19) [95].

Kagan et al. developed a way to fabricate electronic devices using nanocrystal containing inks deposited on a



**Fig. 17** **a** Schematic illustration of an electrically small antenna with labeled geometric parameters. **b** Optical image of an antenna during the printing process. **c** Optical images of a completed antenna (ESA1) in side and top (inset) views. **d** Optical profilometry scan of

representative meanderlines on ESA1 with the background surface subtracted and scanning electron microscopy image of these features (inset) [79]

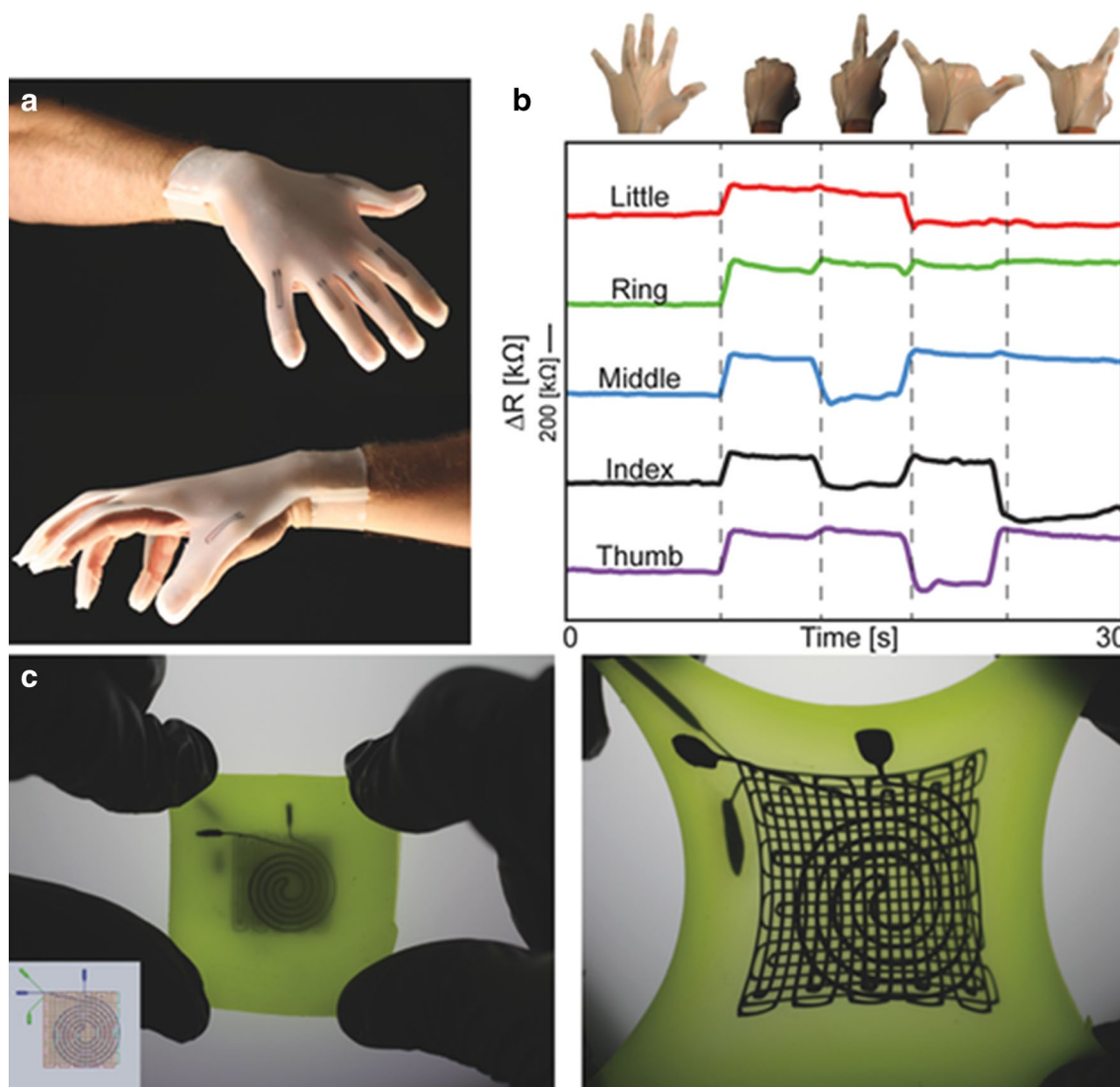


**Fig. 18** Schematic illustration of the embedded 3D-printing (e-3DP) process [95]

stretchable plastic. The inks used were basically colloidal materials, which made up the parts of the FET-printed electronic device. They deposited layers of silver, CdSe semiconductor and Al<sub>2</sub>O<sub>3</sub> insulators onto a polymeric substrate using wet-spinning. This is shown in Fig. 20. This example demonstrates a bright future in the area of

integrating new materials for flexible thin-film integrated circuits [96].

It has been reported that a soft robot can be fabricated using 3D-printing. The EMB3D technique was introduced to fabricate soft materials that follow microfluidic logic to control and actuate the robot’s movements without the need



**Fig. 19** **a** Photograph of a glove with embedded strain sensors produced by e-3DP. **b** Electrical resistance change at different hand gestures. **c** A three-layer strain and pressure sensor in the unstrained state (left) and stretched state (right) [95]

for conventional electronic components, as shown in Fig. 21. This demonstrates the possibility of creating robots other than traditional robot assembly methods, which is composed of mechanically moving parts (screws, gears, levers, rack, etc. and electronic devices which requires multiple processes to fabricate [97].

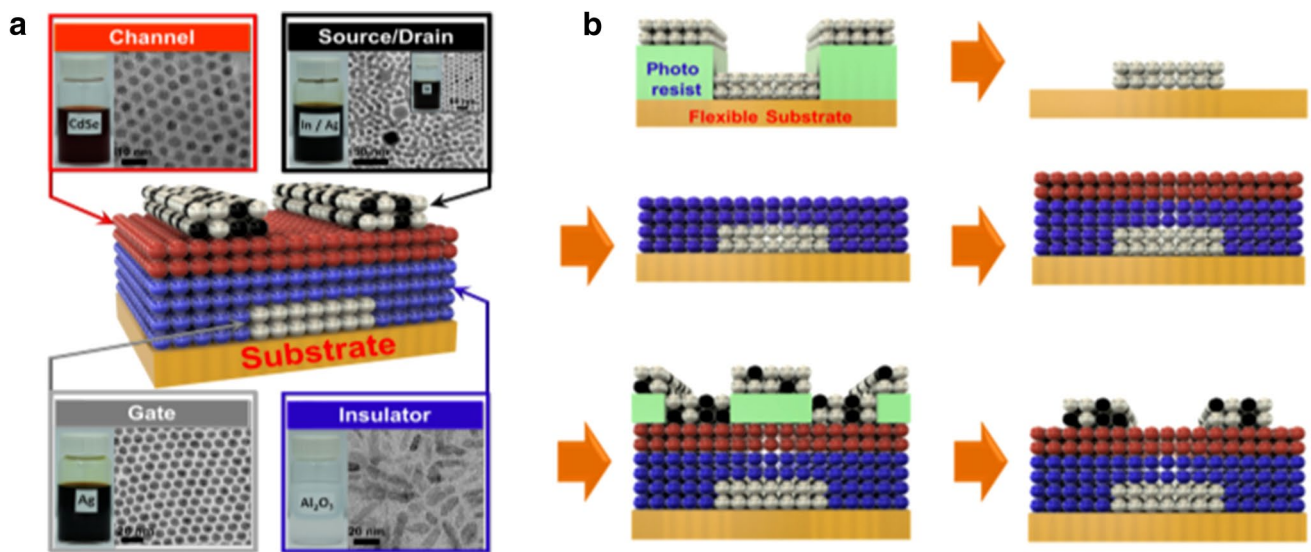
#### 5.1.4 Batteries

Batteries are electrochemical storage devices comprising electrodes (anode and cathode), current collector, and electrolyte. Typical techniques for battery printing can be used such as screen and stencil printing and paste extrusion-based printing. The printing of flexible batteries using stencil printing through direct deposition has been demonstrated

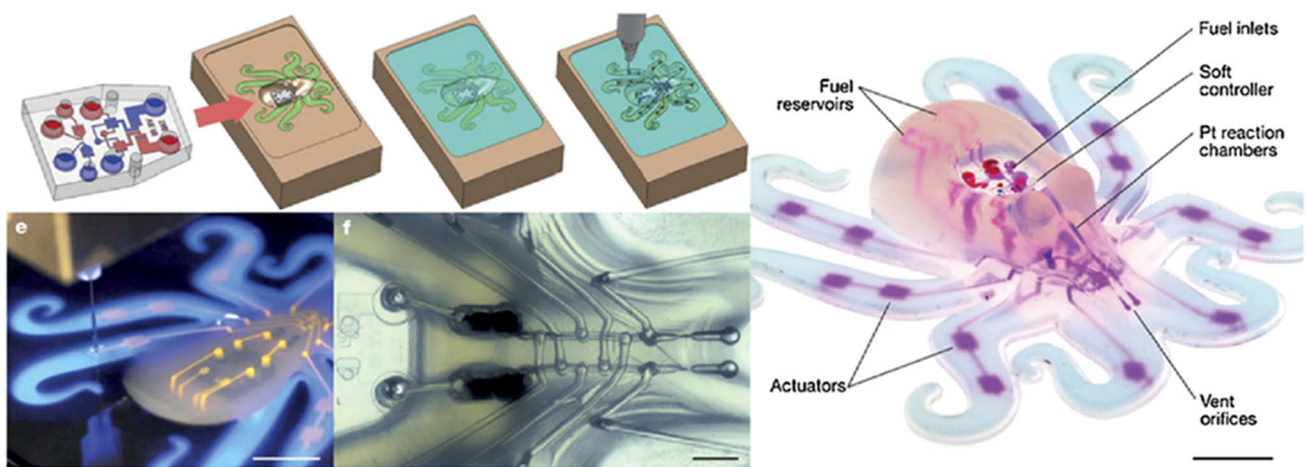
(Fig. 22). The ink composition could be manipulated to adjust the binding factor, which was mixed with a solvent and an electroactive material for printing the electrodes. The battery's flexibility depends on the mechanical nature of its individual parts [85].

A zinc–air battery with a power density of  $1.07 \text{ mW/cm}^2$  was fabricated by Malone et al. using AM techniques. They used extrusion-based printing with a multi-material capability [98]. Moreover, the efficiency of utilizing limited space in batteries is essential for the enhancement of energy density. Thus, 3D-printing has been gaining more attention in the aspect of batteries with well-controlled geometry. Lewis et al. reported a Li-ion 3D interdigitated micro battery architecture (3D-IMA) with a volume of  $6.6 \text{ mm}^3$  and with a power density of  $2.7 \text{ mW/cm}^2$  using extrusion printer.





**Fig. 20** **a** Nanocrystal inks making up a transistor and deposited on flexible backing. **b** Surface chemistry of the inks lets it stay in arrangement without affecting the electrical properties [96]



**Fig. 21** Fully soft and autonomous robot assembly [97, 109]

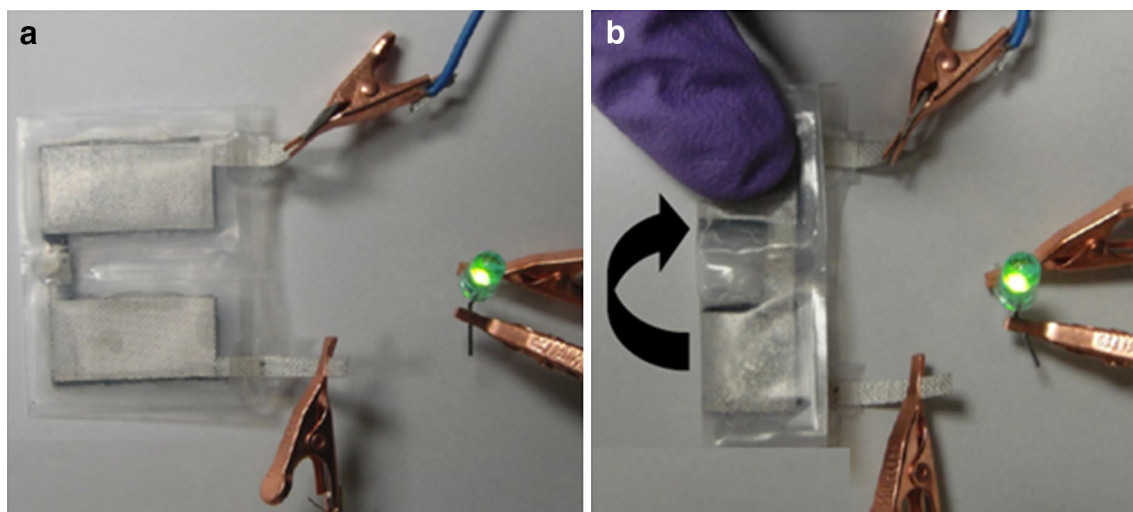
Figure 23 shows chronologically the step-by-step printing process: gold current collector,  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  (Lithium Titanate anode material, mean diameter of 50 nm) and  $\text{LiFePO}_4$  (Lithium Iron Phosphate, cathode material, mean diameter of 180 nm) inks, followed by sintering and packaging. The high loading of powder particles provided functional inks with high viscosity as well as sufficient storage modulus and yield stress that satisfy the rheology requirement in paste extrusion printing. With the help of a well-designed geometry, 3D-printed batteries exhibit high energy density and power density [99].

From these examples, it can be shown that 3D-printing is not limited to familiar techniques in fabricating electronic devices. Moreover, by combining different techniques, it is

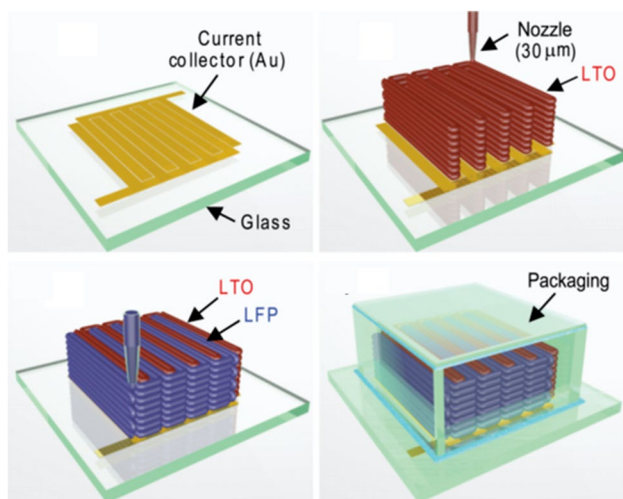
possible to incorporate multiple classes of materials such as polymers, metals, ceramics, and composites with various properties to exhibit the desired functionalities for a specific electronic application.

### 5.2 The market for 3D-printed electronics and integrated machines

According to a 2016 market analysis report, printed electronics, in general, was considered to already have a market value of \$ 3.13 billion with a potential to reach \$ 12.10 billion in the coming decade. For 3D-printed electronics alone, it was valued \$ 20 million as of 2015 [100]. The Asia Pacific market accounts for the largest piece of the market in 2016



**Fig. 22** A stencil-printed alkaline electrochemical cell, shown powering a green LED when **a** flat and **b** folded over a bend radius of 3 mm [71, 85]



**Fig. 23** Schematic of 3D-IMA fabrication process [99]

where the centers of electronics manufacturing are mostly located in China, South Korea, Japan, and India. Europe, on the other hand, holds the majority of research and development activities, and countries such as UK, Netherlands, and Finland are leading printed electronics research in the region [100].

In addition to the geographical classification of the report, individual companies have been mentioned: “the key players in the printed electronics market are Thin Film Electronics ASA (Norway), GSI Technologies, LLC (U.S.), PARC, Inc. (U.S.), BASF SE (Germany), E.I. DuPont de Nemours & Co. (U.S.), Nova Centrix (U.S.), Enfucell OY (Finland), Molex, Inc. (U.S.), E-Ink Holdings Inc. (China), YD Ynvisible, S.A. (Portugal), and T-ink, Inc. (U.S.) among others”. Despite the

number of key players, obscurities in trends arise due to lack of transparent data from some of these companies [100].

The market for 3D-printed electronics today is relatively small. However, the traditional circuit design (consisting of electronic components, wires, and boards) will eventually be outpaced by printed electronics, especially with increase in demand for personalized and customizable electronics. Light-weighting and reduction of electrical wires in the automotive and aerospace industries will be an important driver. The story is all too familiar and similar to the computer industries. The market was first targeted by hobbyists and enthusiasts who tinkered even with do-it-yourself (DIY) projects. It eventually opened to fabrication of prototypes based on desktop 3D-printing machines (e.g., inkjet printers) by using materials such as specialized conductive inks for the traces and interconnects, dielectric materials and plastic flexible substrates. It has now become a viable and efficient solution for fabricating wearables, flexible and structural electronics. Stratasys and 3D Systems are leading companies in multi-material 3D-printing. However, no directed effort has been demonstrated towards the 3D-printed electronics market. Hewlett–Packard (HP) offers the Multi Jet Fusion Technology that can 3D-print both insulating and conducting materials, which may provide a pathway for the printed electronics industry because of its open materials platform. Kickstarter funded companies such as AgIC, Voltera, Cartesian Co. and BotFactory have been slowly emerging to be innovators of PCB based prototyping and fabrication. Besides these companies, Optomec and Nano Dimension are putting efforts on integrating PCB-making coupled with multi-component printing of electronics on 3D surfaces with multiple layers. The hybridization of printing machines will address several manufacturing concerns. The



pick-and-place mechanism can be performed using Squink by BotFactory, and a combined capability of multilayer and full 3D-printing by Nano Dimension and Voxel8 has been demonstrated. These innovative machines are quite promising for the 3D-printed electronics market [55].

### 5.2.1 Demonstrated integrated printing systems for 3D-printed electronics

Printing systems that are specialized for printing electronics are eventually going to become an established category of printers. As an overview, Table 3 presents some of the current popular platforms for 3D-printing electronics.

PCB substrates are typically categorized as FR4, a standard material that is flame resistant in nature and is composed of woven fiberglass cloth bound by epoxy resin. The AM of PCBs have been an interest for a number of Kickstarter systems. One common feature is the support for convertible design files (e.g., Gerber files for PCB layouting). PCBs have been printed using inkjet that is compatible with readily available print heads for the particular technology. The deposited ink can be cured (reactive inks) by the heated printer bed. These machines can work on coated paper substrates, making the heat-curing requirement relatively low compared to other polymer substrates. It is still limited to overall production time, e.g., actual printing of traces and curing the board can last up to 2 h. Voltera V-One<sup>®</sup>, as an example of this type of printer, which uses high precision paste deposition rather than inkjets. It can deposit 0.2-mm tracks with a pitch of 0.8 mm between pins on a 12 × 10 cm print area on boards made of polyamide (PA) and PET. Cartridges for dispensing different functional materials can be swapped in real time since V-One has only one print head. The software automatically understands vias and convert them to conductive traces over insulated jumpers. Solder paste can also be deposited onto patterns to isolate to-be-soldered parts followed by actual reflow soldering via its 550-W

heater. It is capable of printing wider tracks for higher current applications, given that 0.2 mm deposited tracks have 1 to 2 ohms of resistance only [55].

BotFactory's Squink (Fig. 24) is a specialized circuit board printer that fabricates PCBs and does the pick-and-place process for SMDs (through-holes not supported). The traces are printed in a conventional manner, which is followed by depositing solder paste using a solder mask template on the pattern where components are placed. Centroid and rotation algorithm is used in the software to work out the pick-and-place procedure. With the help of a vacuum tool and computer vision, components are placed accurately. As a test, Squink is able to print a specialized 400 MHz antenna without any signal attenuation. Printing waveguides is not yet feasible since swelling in the traces occurs at very high frequencies [55].

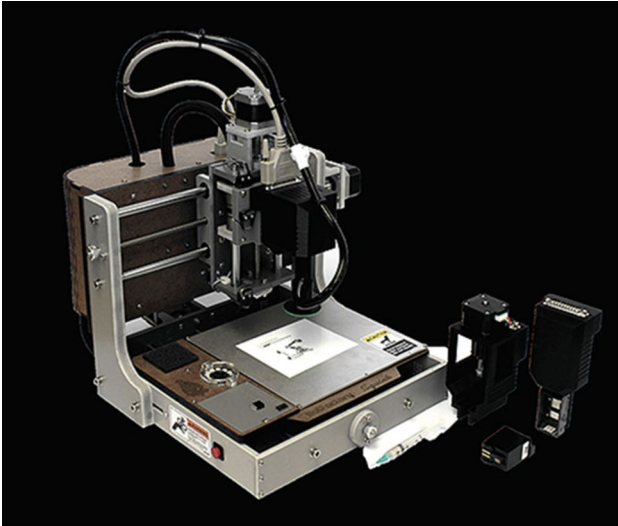
NanoDimension's Dragonfly 2020<sup>®</sup> is designed to fabricate multiple layer PCBs (12 or more layers). It has a big print bed area of 20 × 20 cm, supporting 0.089 mm traces (using commercial high-resolution print heads) and can print vias leaning at a 45-degree angle, allowing geometric freedom between layers. Through the layered PCB design, issues in high-frequency operations can be addressed since the roughness of the edges of an etched trace (conventional fabrication) would be avoided. The material properties used for the substrate can be matched with the standard FR4 properties for commercial PCBs and is stable when exposed up to 300 °C without deformation. This stability should support reflow ovens for soldering. Nano Dimension is taking the lead towards incorporating printing of passive components with a specific design for each type of print head.

### 5.2.2 Printed electronics towards mass production

It is certain that printed electronics will be geared for mass production in the near future and not just for prototyping. Optomec, a company that pioneered aerosol jet printing,

**Table 3** Major 3D-printed electronics platform [55]

Manufacturer	Significant features
AgIC, agic.cc	Special conductive ink cartridges work in home inkjet printers. Can also make traces with a special conductive pen. Prints on special paper
BotFactory, botfactory.co	Squink prints 0.25-mm traces, picks-and-places parts using swappable print and vacuum heads. Prints on paper and coated film
Cartesian Co., cartesianco.com	Argentum printer does footprints as fine as 0.65-mm pitch on treated G10 substrate, 0.8 mm pitch on materials including PA, linen paper, and stone paper
Nano Dimension, nano-di.com	Dragonfly 2020 printer handles complex multilayer boards on FR4, prints 80 to 100 μm traces, 150 μm interconnections, and minimum of 3 μm layer thickness
Optomec, optomec.com	Aerosol jet printer can deliver conductive and semiconductor materials on 3D surfaces features down to 10 μm thicknesses of nanometers
Voltera, voltera.io	V-One extrudes paste to print two-layer FR4 boards, 0.2 mm traces, reflow solders on the printer bed
Voxel8, voxel8.co	2.5 mm traces on PLA using pneumatic DW fabrication, kinematically coupled print head bed

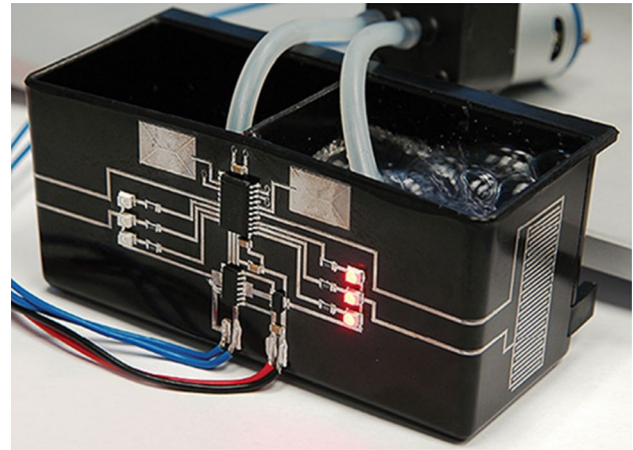


**Fig. 24** The Squink uses two X–Y stages for positioning, one for the print head, the other for moving the PCB platform. A single tool head handles both circuit printing and SMD placement. The first head deposits the conductive ink on the PCB. The user then swaps the conductive ink cartridge for a conductive glue dispenser. Once the glue is in place, a vacuum pick-up assembly gets swapped to pick-and-place components [55]

has envisioned high throughput production. The company designs and manufactures their own components using open systems for compatibility. The print heads are made compatible with most CNC machines, making it adaptable to any integrated 3D-printing systems for various production settings. The machines can readily utilize commercial inks rather than proprietary formulations. Their primary design considerations are focused on printing specialized antennas and sensors. They have printed 3D sensors for detecting expansion or shrinkage of a turbine and interconnects on ICs that serve as an alternative to wire bonding processes. Aerosol Jet has unique merits in 3D-printing electronics. For instance, it is capable of printing antennas directly on any given surface geometry, without the need to use injection molding and laser-based directed printing. Nickel and copper plating are not necessary for constructing the traces and active elements. A three-faced printed traces and sensing circuit has been demonstrated (Fig. 25). With the abovementioned features, Optomec’s Aerosol Jet system is viewed as a key player in the realization of mass production of 3D-printed electronics [55].

## 6 Conclusion and prospects

There are many opportunities and challenges for 3D-printing electronics. New material advances, digital designs, and printing mechanisms and protocols have the potential



**Fig. 25** The circuitry on surfaces of the plastic tank was printed by Optomec Aerosol Jet, while the plastic tank itself was printed by Optomec OEM Neotech Services [55]

to transform the industry. There are many challenges. Conventional electronics design and fabrication process (schematic layout, simulation, and actual implementation) poses a substantial challenge in incorporating its processes (vice-versa) with newer AM technologies (ink jetting, paste extrusion, powder bed-based, and aerosol technologies). In the aspects of software support, PCB layout and design has long been used for creating two-dimensional patterns to place electronic components. However, when a three-dimensional structure is necessary for designing electronics, newer software (such as SolidWorks) needs be used. Current 3D-printing technologies should display compatibility with conventional technologies intended for component placement and insertion (prefabricated and commercial electronic devices). The optimized printing of new reactive or functionalized ink materials (for conductive tracks and 3D interconnects) will help. Difficulties will still arise since the majority of original equipment manufacturers (OEMs) do not easily allow access and modification of the settings and programming for new materials, establishing limits to its entry in current fabrication processes and adaptation to 3D-printing [10]. A definite 3D-printed electronics design tool integrating new materials systems with additive manufacturing methods is going to be a major development leap to bridge this gap. 3D-printed electronics should not only be for prototyping design processes but for scalability and adaptability of the system for mass production. An ideal system is a one-stop electronics fabrication protocol where everything is built and manufactured using an all-around equipment featuring tunable functionalization of materials, support for complex trace patterning on irregularly shaped substrates, automated placements of prefabricated parts, and with web connectivity feature for Internet of Things (IoT). Along with this vision, research in this area should be of high interest for academia,

research laboratories, and manufacturing companies in order to realize full-scale 3D-printing of electronics.

**Acknowledgements** We would like to thank the Case Western Reserve University through PETRO Case, Honeywell—Kansas City National Security Campus (KCNSC) and the Department of Science and Technology—Philippine Council for Industry, Energy, and Emerging Technology Research and Development (DOST-PCIEERD) for resources and funding in the area of additive manufacturing.

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