A STUDY OF THE STATE-OF-THE-ART PRINTED PASSIVE ELECTRONIC COMPONENTS THROUGH FULLY ADDITIVE MANUFACTURING METHODS

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ABSTRACT: Additive manufacturing has reached a certain level of maturity that not only allows fabrication of objects used for prototyping purposes but also starts penetrating other industries, e.g., the electronics industry. Numerous simple electronic components can now be fabricated using the "fully additive" method, which refers to those that only involve deposition of materials while more complicated components may require hybrid methods that involve both subtractive and additive processes. In particular, passive components, which consist mostly of resistors, inductors, and capacitors, comprise the bulk of the total number of electronic components in typical circuits. Passive components also can now be printed and embedded within circuits simultaneously. Although there are excellent reviews of printed passive electronic components, there is an urgent need to consolidate recent research activities in this rapidly developing area. In this review, the advantages and disadvantages of each printing technique of the 'fully additive' method for printing electronics will be discussed. Finally, the current challenges of printing electronics using the 'fully additive' method will also be discussed.

KEYWORDS: Printed electronics; passive components; additive manufacturing, 3D printing

INTRODUCTION

Most recent advances in electronic printing technologies have allowed electronic components to be printed using two major approaches, namely the 'fully additive' and the conventional 'mixed subtractive-additive' approaches [1]. The former one refers to the printing techniques that only involve deposition of materials while the latter one comprises a succession of subtractive processes, e.g., photolithography etching, laser ablation, as well as additive processes [1, 2]. In recent years, researchers and engineers have taken great interests in the printing of electronics using the 'fully additive' method as it offers numerous advantages compared to the conventional 'mixed subtractive-additive' method. These advantages include the ability to produce customizable and bendable electronics [3], substantial time reduction for prototyping [4], and a wide range of compatible substrates including flexible ones such as plastic films, papers, and fabrics [4-6]. Moreover, tremendous improvements in the field of additive manufacturing [7] technology have been made in the recent years. In particular, the 'fully additive' approach has been developed to a great extent to be capable of manufacturing PCBs and electrical components. Its objectives are to mitigate the disadvantages of the conventional 'mixed subtractive-additive' methods and eliminate the time bottleneck in the current prototyping process of manufacturing electronic circuits [2, 8]. On the other hand, although the conventional 'mixed subtractive-additive' approach has been widely and commonly used in mass production of printed circuit boards (PCBs), it has several disadvantages such as high manufacturing costs, time bottlenecks in prototyping and development stage, excessive wastage resulted from the subtractive processes, and pollution due to corrosive chemicals usage [1, 2]. Furthermore, the manufacturing processes employed by this approach for multilayer PCBs are inherently complicated as the masking and etching steps are required at every layer using specially designed machinery and framework [2].

The present review, therefore, focuses on the 'fully additive' approach, in particular on how it is used to fabricate passive electronic components. The advantages and disadvantages of each 'fully additive' technique are compared and discussed in details. The present review also discusses the current challenges of printing electronics using the 'fully additive' approach.

FULLY ADDITIVE METHOD

To date, the 'fully additive' method used to print electronics includes various printing techniques, which can be further divided into two different categories, namely, contact printing techniques and non-contact printing techniques [2, 9]. The contact printing techniques are screen-printing, gravure printing, flexographic printing, and offset lithography. These printing techniques are the

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conventional methods that have been used for printing media for the past few decades and generally have high throughputs. [10] The non-contact techniques are inkjet printing and aerosol jet printing.

Table 1 shows the comparisons between technical specifications of all the 'fully additive' printing techniques presented in the previous sections [11-19]. In terms of ink viscosity, screen printing, and offset lithography techniques require high viscosity while the inkjet printing method requires low viscosity. The aerosol jet printing technique accepts a wider range of viscosities from very low to moderate values (1-1000cP). Table 1 also compares the minimum line width, layer thickness, and printing speed for all the printing techniques. Among all the techniques, aerosol jet printing and offset lithography offer the best resolutions: they both are capable of generating minimum line width of approximately 10 μm. The resolution of the printed electrical components is a crucial factor as it affects their electrical performance [20, 21]. Aerosol jet printing also produces the smallest layer thickness (< 0.5 μm) while screen printing gives the largest layer thickness (up to 12 μm). Aerosol jet printing and the screen printing techniques have relatively lower printing speed as compared to the rest. The differences between technical specifications these methods cause various advantages and disadvantages, which are tabulated in Table 2.

Table 1: Comparison of 'fully additive' printing techniques [11-19]

	Screen Printing	Gravure Printing	Flexographic Printing	Offset Lithography	Inkjet Printing	Aerosol Jet
Printing Form	Stencil, Contact	Roll-to-roll, Contact	Roll-to-roll, Contact	Roll-to-roll, Contact	Digital, Non-contact	Digital, Non-contact
Ink Viscosity (cP)	1000-50,000	50-200	50-500	40,000–100,000	5-20	1-5 (UA) 1-1000 (PA)
Minimum Line Width (μm)	30-50	10-50	45-100	~10	30-50	>10
Layer Thickness (μm)	Up to 12 (mesh dependent)	0.8-1 (solvent) 5-8 (UV curing)	0.8-1 (solvent) Up to 2.5 (UV curing)	0.5-1.5	< 0.5	0.1-2
Printing Speed (m/min)	10-15	100-1000	100-500	200-800	15-500	Up to 12

* UA - Ultrasonic Atomizer, PA - Pneumatic Atomizer

Table 2: Advantages and disadvantages of 'fully additive' printing techniques

Printing Techniques	Advantages	Disadvantages
Screen Printing	• Substrates can be either flexible or rigid • Repeatable and precise printing of electrical components [22] • Suitable for mass production of patterning components on large area substrates [22] • Thick layers are possible (>10 μm) [23]	• Only highly viscous or paste-like inks can be used • High surface roughness [21] • Complex setups and preparations prior to printing; high initial cost [10] • Low resolution [21, 23]
Gravure Printing	• Fewer limiting constraints compared to offset lithography or flexographic printing [24] • Mechanically straightforward process [24] • High speed • Well-suited for the mass production of printed electronics • Capable of printing different ink layer thickness on the substrate in a single print [5]	• Planar printing process, not suitable for printing on non-planar surfaces [25] • Materials with compressible and supple properties are more preferred [5], thick and rigid substrates may not be applicable • Complex setups and preparations prior to printing; high initial cost [10]
Flexographic Printing	• Allows compressible substrates surfaces, pressure sensitive foils and metallized films to be printed [12] • High printing speed [26, 27]	• Planar printing process, not suitable for printing on non-planar surfaces [25] • Flexible and thin substrates are preferred, thick and rigid substrates may not be suitable • Complex setups and preparations prior to printing; high initial cost [10]
Offset Lithography	• High printing speed [28] • Good image resolution [28] • Suitable for mass production [28] • High throughput [23]	• Not practical for small quantities productions as the printing plate cylinder had to be customized for every unique print job • Planar printing process, not suitable for printing on non-planar surfaces [25] • Flexible and thin substrates are preferred, thick and rigid substrates may not be suitable • Complex setups and preparations prior printing; high initial cost [10]
Inkjet Printing	• Contactless, digital and maskless method [8] • Do not require pre-manufactured master printing plates	• Clogging of nozzles are one of the common problems [21]

	[10] • Low possibilities of contamination and damage to printed components [8] • Materials-saving [23] • Substrates used can be either flexible or rigid [23] • Allows multi-materials and multilayer printing designs [15]	• Only low viscosity ink and specific range of surface tensions are allowed [23] • Multiple layers must be printed in order to achieve the desired thickness [29] • Unfavorable to non-planar substrates surfaces [29] • Incapable of operating at extremely high frequencies applications due to inkjet printing's resolutions [20] • Lower throughput as compared to the conventional printing techniques [10] • Coffee-ring effects on the printed droplets, that may cause uneven distribution of material deposition [21]
Aerosol-jet Printing	• Contactless, maskless and digital method [15, 29] • Do not require pre-manufactured master printing plates [10] • Decrease the possibilities of contamination and damage of the printed components [30] • No issues regarding the clogging of nozzles • Wide material options (metal, dielectric materials, graphene, carbon nanotubes) [20] • High-resolution printing [15, 20] • Printing on orthogonal and non-planar surfaces are possible [29, 31] • Substrates used can be either flexible or rigid • Allows multi-materials and multilayer printing designs [15]	• Only a specific range of inks viscosities is preferred, typically in the range of 1 -1000 cP [29] • Sheath gas required in the printing process and this may add to the operating cost [30, 32] • Lower throughput as compared to the conventional printing techniques [10]

PASSIVE ELECTRONIC COMPONENTS

Electronic components can be divided into two main categories, specifically passive and active components. Passive components are those that do not generate power or gain in their operations [33], and the passive components include resistors, capacitors, and inductors.

Resistors

In electronic circuits, resistors are passive electrical components that are used to control current flow. The resistance of the printed resistor is usually measured by the four-point probe method in order to avoid the contact resistance at the connecting points [34-36]. The printing process of a fixed resistor is as follows (see Figure 1a): two separated conductive lines are first printed on the substrate before a resistive layer is printed in between their gap [2, 37]. The ink used to print the resistive layer has much lower electrical conductivity compared to that for the conductive lines.

Capacitors

Capacitors belong to another type of passive electronic components. They are mainly used for temporary storing of charges, or signal filtering in electrical circuits [38, 39]. A printed capacitor [37, 40] typically consists of three main parts, namely the bottom conductive layer, dielectric layer and the top conductive layer, as shown in Figure 1b. After the bottom layer is printed, the bottom layer is to be sintered before printing the next layer of dielectric and the top conductive layer. This is to prevent cracking of the bottom conductive layer and absorption of the dielectric layer into the bottom conductive layer.

Inductors

Inductors are passive electrical components that store electromagnetic energy when electric currents passing through. An inductor can be printed following several steps (see Figure 1c). First, a spiral conductive line that makes up of a few turns is printed and sintered. Next, an insulating layer is printed on top of the spiral conductive line before another conducting line that extends from inductor's outer perimeter to the inductor's center is printed. Finally, a layer of ferrite film is printed over the printed inductor to increase magnetic permeability of the coil and thus increase its inductance [37, 40].

CHALLENGES

There are several challenges to print electronics using the 'fully additive' approach. The most crucial ones are resolution of the printed electronics, manufacturability concerns, maintaining industrial standards, and environmental impacts.

Resolution of the Printed Electronics

The performances of printed electronic components are directly affected by the resolutions of the printing methods. One of the most critical disadvantages of 'fully additive' methods is that they are currently not capable of achieving as high resolutions as the 'mixed subtractive-additive' methods. Thus, electronics components manufactured by the 'fully additive' methods generally have poorer performances than those manufactured by the conventional 'mixed subtractive-additive' methods [21]. Current resolution limitation of the 'fully additive' methods is the main reason preventing wider adoption of these technologies in demanding applications such as high-frequency Radio Frequency (RF) applications [20, 21].

Manufacturability Concerns

Most 'fully additive' printed electronic components have to undergo sintering processes in order to optimize their electrical characteristics. Several sintering processes, e.g. oven sintering, require the substrates to be exposed to the high-temperature environment for a long period of time. This may cause deterioration, deformation, warp, or even damages to the substrates. These sintering processes have become a challenge, or rather, a limiting factor in the field of printed electronics because many substrates are not resistant to high working temperatures. Optimization of the sintering processes also requires not only experience, accumulation of knowledge for different types of working materials, but also physical understanding at the micro level. These so far have not been explored extensively and therefore will need to be studied in details. In addition, future developments of the inks are needed so that the inks will require shorter sintering time, lower sintering temperature, and give better electrical performances [10].

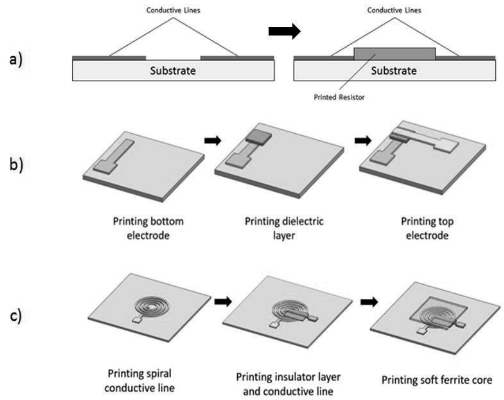

Figure 1: Schematic diagram of the printing process of a) resistor, b) capacitor and c) inductor [37].

Maintaining Industrial Standards

Standardization of manufacturing processes and materials of printed electronic components is a critical step to have better quality control and assurance of products. Industrial standards ensure that manufactured components adhered to the reliability, environmental, and safety guidelines. They also minimize incompatibility issues between different equipment, thus help to build strong industrial infrastructures to further develop and improve current practices and technologies [41, 42]. To date, there are a few international associations that have generated industrial standards and guidelines for printed electronics. The Institute of Electrical and Electronics Engineers (IEEE) published several standards for test methods for printed electronics:

- IEEE Standard 1620.1-2006 - IEEE Standard for Test Methods for the Characterization of Organic Transistor-Based Ring Oscillators [43]
- IEEE Standard 1620-2008 - IEEE Standard for Test Methods for the Characterization of Organic Transistors and Materials [44]

In addition, IPC — Association Connecting Electronics Industries® and Japan Electronics Packaging and Circuits Association (JPCA) have collaborated to develop the following guidelines and standards [45, 46]:

- IPC/JPCA-2291 - Design Guidelines for Printed Electronics (2013)
- IPC/JPCA-4591 - Requirements for Printed Electronics Functional Conductive Materials (2012)
- IPC/JPCA-4921 - Requirements for Printed Electronics Base Materials (2012)
- IPC/JPCA-6901 - Application Categories for Printed Electronics
- IPC-6903 - Terms and Definitions for the Design and Manufacture of Printed Electronics (Additive Circuitry)

The IPC Printed Electronics Committee is also working with major international associations to develop more guidelines for printed electronics. The major international associations are International Electrotechnical Commission (IEC), FlexTech Alliance, Japan Printed Circuit

Association (JPCA), and NPES—The Association for Suppliers of Printing, Publishing, and Converting Technologies [46].

These standards and guidelines will provide a framework for manufacturing repeatable and consistent electrical components and circuits. Changes and developments of such standards and guidelines are expected to continue taking place in the near future along with advancements in electronic printing technologies [45].

Environmental Impacts

'Fully-additive' methods for electronics manufacturing do not use corrosive chemicals and are more environmental-friendly than the conventional 'mixed subtractive-additive' methods. However, they still face several environmental challenges, especially at the end-of-life phase of the printed products. Many printed electronic components are designed to be low cost. Disposing, other than reuse or recycling, of these components may be more preferred for cost effectiveness. The disposing process is usually through landfill, which may cause leaching, or incineration, which may produce hazardous gases [47]. Therefore, more elaborate solutions should be created to address such problems.

CONCLUSION

The advantages and disadvantages of all the 'fully additive' printing techniques, as well as the most notable challenges pertaining to printed electronics, have been discussed. The most promising techniques are inkjet printing and aerosol jet printing. Both techniques are digital and non-contact printing techniques. Inkjet printing is a matured technology, whereby, aerosol jet printing is more capable and versatile. As inkjet printing is a matured technology, much understanding and insights have been acquired over the years in optimizing the printing of electronics through inkjet printing. Many research and studies also have been conducted, on the development of the inks for inkjet printers, specifically for printed electronics applications. On the other hand, aerosol jet printing is an emerging new technology and has the most potential to further improve its printing resolution among all the 'fully additive' printing techniques. Therefore, aerosol jet printing is likely possible to be used as a tool for creating high quality and high performance printed electrical components in near future. More research and development works are needed to look into and overcome the challenges of the printed electronics, so as to reap the full benefits of printed electronics through the 'fully additive' method. Nevertheless, hybrids of some of the fully additive' printing techniques can be also be explored into, so as to improve and optimize the way electronics are printed.

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