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ADDITIVE MANUFACTURING FOR ACTIVE ELECTRONIC COMPONENTS: A REVIEW

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ABSTRACT: Fabrication of fully functional devices has been one of the ultimate goals of the emerging additive manufacturing technology. In order to achieve this goal, an indispensable step is to fabricate active electronic components using fully additive methods. Although there are still numerous roadblocks that need to be overcome toward this goal, research activities in the field of additive manufacturing for active electronic components are progressing with a considerable pace and have been achieving significant successes. The purpose of this review is therefore to consolidate recent developments in this exciting field. These include the components that currently can be fabricated by fully additive methods such as transistor, LED and battery. We discuss and compare the advantages and disadvantages of these methods in printing such components. We also discuss major challenges that still needed to be addressed in the roadmap towards additive manufacturing of active components.

KEYWORDS: Active electronic components, printed electronics, additive manufacturing, 3D printing

INTRODUCTION

Additive manufacturing (AM), previously known as rapid prototyping, is defined as a process to build 3D objects by means of joining materials layer-by-layer. Recently known as 3D printing, this exciting technology is creating the new chapter of manufacturing industry with the possibility to transform digital information into invaluable-physical components. Its potential has gained many public interests in various fields, for example, automotive, jewelry, aeronautical and biomedical industry (Chua & Leong, 2014).

Active electronic components are described as any electronic components or devices capable of controlling and amplifying the flow of electric charges (Das, 2015). Those are also referred to electrical components that can generate power (Gerke, 2005). Examples of active electronic components include transistors, silicon-controlled rectifiers (SCRs), diodes, light-emitting diodes (LEDs), operational amplifiers, batteries, etc. These components normally require highly elaborate fabrication processes compared to those used for passive components due to their complex functionalities. Conventional fabrication methods for active electronic components have been mostly based on photolithography processes, which are subtractive in nature and showing more and more intolerable disadvantages including complicated and expensive setup, hazardous chemical preparation (Reese et al., 2004), and considerable amount of rare-earth material wastage. As a result, alternative fabrication methods are being explored and developed in order to overcome
these disadvantages. One of the most promising approaches is additive manufacturing, or printing of electronics. Fabrication methods using the additive approach have clear advantages over the conventional methods with respect to reduction in material wastage, time bottleneck for prototyping, and setup cost. Nonetheless, these methods still need much improvement and have numerous roadblocks to clear before they can be used to replace the conventional methods. For example, an organic thin-film transistor (OTFT) consists of four layers: two conductive electrodes, a dielectric layer, and a semi-conductive layer. A crucial requirement in the fabrication process of OTFT is the precise alignment of all layers. This poses a challenge for some printing methods, as micro-scale tolerance of the printed patterns is still difficult to achieve.

This review consolidates recent developments in the area of printed active electronic components. In active electronic components chapter, recent developments of printed active electronic components are presented. These developments are mostly concentrated on components such as transistors, LEDs and batteries. In trends and challenges chapter, trends and challenges for printing of electronics are summarized and discussed.

ACTIVE ELECTRONIC COMPONENTS

Transistors: Transistor is one of the most important electronics components and is used in most of the electronic devices to switch or amplify electrical signals as well as electrical power. In particular, transistors made with organic-electronic materials have been having much attention, as their main advantages are compatibility with flexible substrates and capability to process at low temperature. However, organic materials always have low charge mobility (typically ~ 1 cm² V⁻¹ s⁻¹) which reduces the performance of electronic components. An example of printed organic transistors is organic thin-film transistors (OTFT), whose usage has been demonstrated in applications for sensors (Zhu et al., 2002; Jeong et al., 2010) and memory devices (Baude et al., 2003; Mittal et al., 2011). This type of transistors simply consists of 4 layers: two layers of electrodes (source/drain and gate electrodes), a layer of dielectric material, and a layer of organic semiconductor (Figure 1a).

There are two main key measurements of transistor’s performance: The mobility: The mobility is described as the ability of electron moving across the layer per unit time when influenced by an electric field. The mobility range for the best organic materials is in the range 1-10 cm² V⁻¹ s⁻¹ (Kelley et al., 2003; Sundar et al., 2004). The switching speed of the transistor depends on the mobility and the length-to-width ratio of electrode’s channel. To improve the switching speed, many reports focused on reduction of channel length and contact resistance (Sirringhaus et al., 2000; Noh et al., 2007; Herlogsson et al., 2008). The possibility in extremely reducing the channel length is modification of surface energy. Dewetting of solute-containing inks, which is the physical phenomena when liquid remains shape, is involved. Polymer field-effect transistor with channel length as small as 500 nm using surface-energy-assisted inkjet printing technique has been reported (Wang et al., 2004).

The on/off current ratio: The on/off current ratio is the ratio of the currents in active period to that in inactive period. For OFET and OTFT, their switching performance strongly depends on this ratio. An extremely low off current is required to prevent the current leakage during the inactive period. Typically, the on/off ratio is up to 10⁶ (Reese et al., 2004).

There have been numerous reports on printed transistor that achieved high performance using the printing techniques described above: Jo et al. (2009) used flexographic printing to print electrodes in Organic Field-effect Transistors (OFETs) with 16 μm channels on flexible-plastic substrate. The printed transistors had a field-effect mobility of 0.08 cm² V⁻¹ s⁻¹ and an on/off
current ratio of $1 \times 10^5$. Kang et al. (2013) used gravure printing OFETs using the P3HT/PHEMA/XL-PHEMA/Ag ink. The result showed field-effect mobility of 0.04 cm$^2$ V$^{-1}$ s$^{-1}$ and an on/off current ratio of $1 \times 10^4$. Wu et al. (2005) demonstrated fabrication of thin-film source/drain electrodes by using ink-jet printing. In this work, gold nanoparticles ink was used and resulted in high mobility of 0.15 cm$^2$ V$^{-1}$ s$^{-1}$. Cho et al. (2008) fabricated all-printed FETs by using aerosol-jet printing. In this experiment, it was shown that the fabricated FETs offered high performance with the mobility of 1.8 cm$^2$ V$^{-1}$ s$^{-1}$ and the on/off current ratio of $1 \times 10^5$.

Figure 1. (a) Schematic drawing of top contact OTFT architecture (Reese et al., 2004) (b) Basic structure of battery’s cell (Rahn & Wang, 2013) (c) Basic OLED structure (Geffroy et al., 2006) (d) OLED structure with electron- and hole-transporting layers. (Yersin, 2004).

Light-Emitting Diodes (LEDs): LEDs is one of the most low-cost lighting devices that can emit the light when they are supplied by low voltage. Printed LEDs are particular attractive with the introduction of electroluminescent materials (Hutchings & Martin, 2013). The common LEDs have three layers – two layers of electrodes (anode and cathode) and a single emissive inorganic electroluminescent layer (Figure 1c). This layer is sandwiched between two electrodes, one of which is generally transparent. If the layer is made of organic electroluminescent materials, the device is then called organic light-emitting diodes (OLEDs).

The working principle of OLEDs involves the energy between the gaps of two electrodes. Electrons, at the cathode, are injected into the lowest unoccupied molecular orbitals (LUMO), while holes, at the anode, are injected into highest occupied molecular orbital (HOMO), similarly to valence and conduction bands in inorganic semiconductors (Burroughes et al., 1990). After applying the voltage, electrons and holes are moved toward each other. When these two charges encounter, an exciton is formed. A moment after that, the exciton can decay to generate the light
with the specific color depending on the HOMO-LUMO energy gap. However, typically in common OLEDs, the equal number between the electrons and holes and the transport are unbalanced. This can lead to inefficient emitting function of OLEDs. In order to solve this problem, a few layers are deposited in between the electroluminescent layer and the electrode layers (cathode and/or anode). For example, an electron-transporting layer will be fabricated between the cathode and light-emitting layer, if the lighting layer transports holes principally. On the other hand, then an electron-transporting layer will be placed in between the anode and emissive layer (Figure 1d) (Baldo et al., 1999; Adachi et al., 2001).

There are two major applications of printed LEDs:

**Lighting:** In order to establish this technology, it is essentially in developing the white-light OLED that efficiently performs its function at high current level without operational failure. In addition, it should be stable to withstand environmental degradation. Previously, some OLED devices have operational failure due to organic material properties (Ke et al., 2002). The solution is to avoid using purely organic materials, instead, using inorganic light emitters or hybrid materials, e.g. inorganic quantum dots (QDs). Singh et al. (2009) demonstrated a hybrid organic-inorganic materials using inkjet technology to deposit the emissive layer. The result showed that the device exceeded 10 kcd m\(^{-2}\) for rigid and 9.6 kcd m\(^{-2}\) for flexible substrates, respectively.

**Displays:** A major reason of using LEDs is for digital displays. They are easily found in television screen, computer screens as well as in portable device screen. OLED has low charges mobility due to poor property of organic materials. Furthermore, it also sensitive to air and water as well as its poorer color purity materials. Consequently, inorganic quantum dots, QDs, have gained more attention as emissive materials because of their air stability and unexpected tunable pure colors which generate fine colors (Hutchings & Martin, 2013). Haavrinen et al. (2010) presented the displays fabricated by using different-sized QDs in quarter video graphics array (QVGA) with full red-green-blue (RGB) driven by direct current (DC). Its brightness was about 100 cd m\(^{-2}\). However, the only disadvantage of inorganic QDs is highly expensive cost due to fabrication process (Middleton et al., 2007). Recently, carbon nanotubes (CNTs), which have higher carrier mobility, have been used in many displays devices. Shigematsu et al. (2008) demonstrated printed electrodes from single-wall carbon nanotubes (SWCNTs) coated with a phosphor as the counter-electrode for emissive displays using electrostatic inkjet technique.

**Batteries:** Electric batteries are devices beside supercapacitors that are capable of both storing energy and supplying power to the circuit (Hutchings & Martin, 2013). In principle, they convert chemical energy to electrical energy and vice versa. Typically, batteries are made of electrochemical substance so that they can charge when connect to electrical sources. Batteries may comprise of a few or many electrochemical cells, which consist of three main components: two electrodes (anode and cathode) and an energy storage medium material (electrolyte) (Figure 1b). The size of these components ranges from micro to macro scales. Printed batteries are normally used in implanted medical devices, which require tiny batteries in order to fit in small cavities of human's body (Oliker, 2015).

Several active materials can be used for printed batteries, mostly solution-based inks. The inks consist of conductive particles, electrochemically active particles, binder, and solvent. They can be deposited on substrates by various printing techniques, e.g. screen printing, contact printing, spray printing, and stencil printing. For each battery, its electrodes’s conductivity depends on the concentration of conductive particles and post-processing techniques. A polymeric or cellulose separator, which is soaked in electrolyte, is used to divide the anode and cathode and to provide an ionically conductive path between two electrodes. The current collectors for both anode and
cathode are fabricated from conductive ink. In order to have high conductivity and reduce ohmic potential drop, silver-based inks is commonly used to print the current collector.

Gaikwad et al. (2013) demonstrated high-potential fully printed batteries. Polyvinyl alcohol/cellulose (PAC) was used as a substrate and separator. The cellulose membrane was resistive to electrolyte (KOH and ZnO solution). The electrodes were made of Zinc and MnO₂, printed using the stencil printing technique. As a result, the dimension of the printed pattern depends on that of stencil’s mesh. In order to increase the conductivity of the electrode, graphite was added to cathode ink. A hydrophobic fluoropolymer solution (Teflon AF) was printed between neighboring electrodes to protect the electrode from electrolyte migration and ionic conduction, which could potentially reduce the battery’s power. The results showed that the initial open circuit potential of the entire battery was 14 V. However, even though the battery could supply high power, it was time-consuming to charge it with an external source. Thus, researches tend to focus more on supercapacitors, which have much shorter charging time, since small circuits do not require high power (Le et al., 2011; Xu et al., 2013).

TRENDS AND CHALLENGES

There are mainly two routes in developing the efficient active electric components: improvement in material’s properties and development of printing processes. In this paper, we mainly focus on the later one. Since printed electronic components in general, and active components in particular, are fabricated with multifunctional layers stacked together, precise positioning and high resolution of the printed patterns are required. We note that aerosol-jet printing offers the best resolution among other printing techniques. However, the high cost of the system and materials is an obstacle preventing wider adoption of the technology.

In term of applications, developments of printing technologies for electronic components tend to focus more on fabric-based devices as they are compatible with multifunctional devices that are easily integrated with human’s life (Chen et al., 2010; Yeo et al., 2014). On the other hand, for industrial applications, the requirements for printing technologies do not only include high resolution and precise positioning, but also high throughput, lower wastage and chemical usage, and lower cost. These are also challenges that need to be overcome for printing processes for electronic components.

In conclusion, the present paper consolidates the most recent developments in printing active electronics components including transistors, light-emitting diodes and batteries. Relevant printing techniques and suitable materials used in both research and industrial scales are discussed and compared. The working principles, key performances and technology roadblocks for printed active electronic components are presented.

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