Technological Capabilities of Printed Electronics: Features, Elements and Potentials for Smart Interactive Packaging

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Abstract*—Printed Electronics is a fast-developing enabling technology that employs electrically functional inks and traditional printing techniques to revolutionize the fabrication of various electronic devices to add intelligent and interactive features to physical items, as products packaging. Like every emerging technology, Printed Electronics has been developed for a few decades and moved from the research-oriented to commercially-available production. The technology has taken one more step further into innovation by enabling printing on various substrates, such as flexible plastics, thin films, paper and cardboard. As a result, the traditional passive consumer packaging is facing alternatives and more advanced forms of packaging are being introduced to the market. The entire communication system of the enhanced packaging can be enabled by low-cost, light-weight and flexible electronics as NFC tags, batteries, displays, antennas, and other. Therefore this paper aims to explore the characteristics of printing electronics and its potential for smart interactive packaging innovation including available printing techniques, conductive materials and substrates. Paper encompasses an extensive literature review and a set of empirical observations from the industry. The key findings provide a list of potential electronics that can be applied onto smart interactive packaging, as well as a value chain of operational activities related to the manufacture of PE-enabled consumer packaging.

I. Introduction

In general, the traditional packaging has been primarily designed to contain, protect, and preserve the packed goods, as well as to communicate messages about the product [1] [2]. Packaging has always served its practical function to hold products together and secure them in the entire logistic infrastructure until the goods reach the end user. However, the importance of the packaging has gradually increased due to improved packaging functionalities. Since packaging has evolved from its primary role of containing products to actively merchandising and communicating with the surrounding environment of the package, the complexity of packaging's role has grown [3]. The development of enabling technologies has influenced the enhancement of the main packaging functions [4]. The recent advances in augmented reality, Internet of Things (IoT), conductive inks, and printed electronics (PE) have led to the refinement of the primary communication function, and in tandem to the emergence of smart interactive packaging [5]. The latter is able to go beyond the traditional concept of communication aspects and create two-way interaction between the consumer and the brand [6]. IoT is able to provide an interactive dimension between the two agents with the help of standardized communication protocols, smart sensors and incorporated smart Near Field Communication (NFC) or Radio Frequency and Identification (RFID) tags that highly increase the design freedom for new packaging applications, especially in the Consumer Packaged Goods (CPG) industry. As a result, traditional consumer packaging has been challenged, and more advanced forms of packaging are being introduced to the market [6].

Businesses are trying to do their best at gaining favorable margins derived from cost-effective packaging. As a result, the incorporation of advanced technologies into CPG packaging design depends on the economic prospect of the manufacturing process. Therefore a viable option for manufacturing low-end products at high volumes is offered by Printed Electronics technology [7]. PE is an increasingly expanding technology that enables the fabrication of low-cost and large-area electronics due to efficient and effective roll-to-roll (R2R) manufacturing [8]. Consequently, PE is considered as a potential enabler to produce and incorporate sophisticated, but low-cost, light-weight and flexible electronics devices into packaging design to enhance consumers' experience or functionality of the packed products.

The integration of PE technology into core technical capabilities of the company not only facilitates the technology change, but also changes or creates new activities in the manufacturing process. Therefore this paper aims to explore the recent characteristics of PE technology in relation to feasible printing techniques, conductive materials and printing substrates, and its potential for smart interactive packaging innovation including the investigation of potential electronic devices and components that can be applied to smart packaging applications. As a result, the research question of this work is: what is the current state-of-the-art status of printed electronics applied to smart interactive packaging? This investigation will also help to identify where packaging manufacturers, printing houses or CPG brand owners may need to develop new technological capabilities besides their core competencies to apply printed technologies onto product's packaging.

II. Methodology

The main aim of this research is to explore the potential of printed electronics to be applied for smart interactive packaging from both engineering and technology management (TM) perspectives. The independent extensive literature review together with empirical research were performed to (1) develop

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an overview of the main enablers of PE technology including conductive inks, printing substrates and printing methods, and (2) investigate the manufacturing characteristics of potential electronic elements that can be printed or incorporated into smart packaging applications. Finally, based on the results, the value chain of activities for manufacturing process is presented in the context of the application and integration of printed electronics in smart interactive packaging.

III. Theory

Connected physical and digital approaches, i.e. physical passive packaging and sophisticated communication technologies, contribute to new value creation for enterprises, therefore companies are in need to innovate their business processes in regards to the technology change. Since the technology has already been admitted as a central role in the economic growth [9], CEOs and senior managers are increasingly taking technological decisions to shape the future of their businesses [10]. According to authors, technological competitiveness as the ground for sustained competitive advantage becomes essential at different levels of the corporation. Reference [11] concurs and states that technological changes contribute to a new product, service, process and organizational development. As a result, the technology effort has to be consistent and aligned with the corporate strategy [10] [12], and thereby management of technology combines all the factors, including R&D, finance, economics, marketing, organization, engineering, and other, and make them work together in an efficient way to make sound investment decisions and produce long-term profit [9] [12].

Every organization can be conceived as a collection of activities that are carried out to design, create, produce, deliver and support its products and services [11]. All these individual activities reflect upon an organization's history, resources, strategy and economics. Reference [13] consents and states that every company must have some specific capabilities in order to exist and thrive. Such capabilities are named under different labels, such as human resources, invisible assets, repertoire of routines, core competencies, technological capabilities, to name a few [13]. Overall, firms attempt to create such specific capabilities and exploit them strategically to identify market gaps and offer new value [13]. Consequently, TM can be considered as the development and exploitation of these capabilities, specifically to those that are related to technology [11]. Reference [14] adds that TM as capability itself makes effective use of technical knowledge and skills not only to develop and improve products and processes but also to improve existing technology and create new knowledge and skills regarding the competitive business environment. Thus this research investigates the technological knowledge related to PE technology to form a technology base that later could be turned into new products and processes in terms of smart interactive packaging. Furthermore, this investigation will help to identify where packaging manufacturers, printing houses or CPG brand owners may need to develop new technological capabilities besides their core competencies in order to apply printed communication technologies onto their product's packaging. The following section will investigate the PE technology in depth concerning key characteristics, potentials and technological feasibility to be applied onto smart interactive packaging.

A. *Printed Electronics Technology*

Printed Electronics is a fast-developing enabling technology that employs electrically functional inks and traditional printing techniques to revolutionize the fabrication of various electronic devices and to add intelligent and interactive features to physical items, as products packaging. Like every emerging technology, PE has been developed for a few decades that has influenced a significant shift from the research-oriented to commercially-available production [16]. Due to increasing technological demands, PE has demonstrated a substantial potential to produce novel and commercially viable technologies that distinguish from others due to their unique characteristics related to conformability, large-area, low cost and wide range manufacturability [17]. Reference [8] contributes with the authors and refers to PE as a fast expanding technology that enables the fabrication of low-cost, large-area and flexible electronics, like OLED displays, batteries, RFID tags, antennas and etc. Several researches [7] [18] [19] name the technology's compatibility with roll-to-roll fabrication as the leading influencer to scale up the production processes on flexible substrates to high volumes and large areas at low costs. Contrary to conventional electronics manufacturing processes that require high temperatures, PE technology performs fabrication at lower temperatures allowing the use of lower-cost temperature-sensitive flexible materials, like plastics, thin films, paper and cardboard [20].

Furthermore, the other relevant feature of PE is the manufacturing of thin, lightweight and environmental-friendly devices [21]. The emerging field of additive manufacturing contributes not only to low cost but also to a minimal material waste for numerous applications including displays, distributed sensing, energy management, and smart packaging [19] [22]. Reference [17] claims that technology has a great potential to become mature enough to be concurrent with the IoT that would highly increase the intelligence performance of smart packaging.

In addition, PE connects nanotechnology with printing techniques by utilizing nano-based conductive inks that are being developed and improved since the beginning of first PE application. Plus PE is compatible with already well-established traditional printing techniques, like screen printing, flexography, gravure printing, ink-jet printing and other [22]. In general, there are three major parts of PE technology that has to be taken into consideration by manufacturers: conductive inks, printing substrates and printing techniques.

B. *Nanomaterials and Conductive Inks*

Innovations and development of the packaging are based on mainly two aspects: observable changes in consumer demand and development of new technologies [23]. Regarding the latter, the industry is always in search of new packaging materials and technologies to further improve either products quality or packaging functionality [24]. Reference [23] contributes to the authors and states that nanotechnology is identified as a promising enabler of advanced characteristics and increased functionality in packaging materials. As a result, nanotechnology-enabled packaging materials have been broadly investigated and became a major area for innovation. At the moment, the main appliance and incorporation of nanomaterials into consumer packaging aim to overcome challenges related to food preservation and sustainability [24] [25]. However recent advances in conductive nanomaterials have allowed the fabrication of printed electronic circuits with advanced sensing, signal processing and conditioning, and communication capabilities that can be employed to smart interactive packaging applications [20]. For instance, a broad range of nanomaterials, including silver nanowires (AgNWs), graphene, single-walled carbon nanotubes (SWNTs), and copper have been increasingly investigated due to their applicability for printed wireless communication systems [26] [27] [28]. A study presented by [27] fabricated the electric capacitive sensor for humidity sensing capability via screen printing with silver-based conductive ink on cellulose-based substrates. Research [28] employed SWNTs ink to manufacture thin-film-based supercapacitors for powering transistors and displays printed on paper-based substrates.

Graphene, the allotrope of carbon nanotube, has shown the significant potential for large-volume applications due to its favorable characteristics as high electrical conductivity, electrochemical stability and mechanical flexibility, light-weight and low cost [19] [22]. The ability to tune ink rheology and control the dispersion viscosity enables to integrate graphene into high-throughput and low-cost production methods as screen printing. The study carried out by [22] presented printed high-resolution graphene patterns as source and drain electrodes with favorable electrical conductivity and bending tolerance that are significant parameters for printed and flexible electronics. In general, graphene conductive ink is already employed to construct transistors, diodes, oscillator and other passive RF components, like transmission lines and antennas, both on plastic and paper substrates [26]. Also, graphene is a promising material for fabrication of micro-supercapacitors electrodes [19].

Photoluminescence properties-possessing nanosubstances are also beneficial tools for informing users about the changes around the product and the packaging and adding extra value to products. Regarding thermochromic ink, the printed conductive lines change the color due to the generated heat when the voltage is applied [29]. As a result, flexible printed thermochromic displays can be utilized for various consumer packaging applications.

In general, nanoparticle inks possess higher conductivity prior to conductive polymer inks and flake inks, and therefore they are more feasible to PE applications [30] [31]. Thus researchers are aiming to develop nanoparticle inks for inkjet, flexography, spray coating and screen printing techniques that can be treated on cost-efficient flexible substrates at low temperatures [31]. Silver is the most common metal used for conductive ink due to favorable conductance, low oxidation, easy sintering and profound electrical properties [30] [31]. However, the need for more sustainable materials and the volatile silver price have led researchers to examine alternative materials, such as copper [31]. Copper has already shown its potential for electrodes used on thin film transistors (TFT) [31]. On the other hand, at the moment high conductance can only be achieved in complex sintering processes, therefore there is a need for further development of copper to transform copper-based inks a potential commercial alternative to silver [31].

C. Printing Substrates

At the present day, there is a wide range of different materials for products‘ packaging that are suitable for PE technology, including polymers, plastics, and cellulose-based substrates. The characteristics of the printing substrates have significant importance in the fabrication of electronics [7]. Due to the emerging shift from sheet-to-sheet- printing to R2R printing substrates have to possess a certain degree of flexibility [22]. Commonly used substrates for R2R manufacturing are thin glass, polymer films, metal foils, and recently emerging cellulose-based paper and cardboard [22] [30]. Each material possesses distinct advantages and disadvantages prior one another, at the same time each particular application requires a different type of substrates.

Since glass and polymer films are transparent, they are used for optoelectronic applications, like OLED or LECs, that allows building structures where the light passes through the substrate [22]. Thinner glass possesses favorable barrier and bending properties prior to thicker glass, thus the former is more preferred in respect of R2R manufacturing [18]. However flexible plastic and paper substrates, such as polyimide, polyethylene terephthalate (PET), cellulose diacetate, are becoming more common for PE-enabled consumer packaging applications since they are already utilized in the packaging industry.

In general, plastic polymers are hydrocarbon compounds obtained from basic hydrocarbon as ethane and methane or derived from natural gas and petroleum [32]. Plastics can be formed into a wide range of beneficial products, since they are fluid, moldable, heat sealable, easy to print and, most importantly, they are easy to integrate into existing production line [25]. On the one hand, plastics obtain satisfactory mechanical properties at low cost, provide high barrier properties, but on the other hand, the recyclability is a fatal struggle for the industry [25]. From the viewpoint of sustainable development, paper substrates are preferable. Also, paper is cheaper and withstands thermal annealing or sintering used in R2R printing better [7]. However conventional paper products have a highly porous and rough surface, are hygroscopic, and have low resistance to high temperature and heat that complicates the fabrication of flexible devices [25] [33]. As a result, to control and improve paper’s permeability, strength, smoothness and optical characteristics, it is often loaded with various additives, like binders, fillers and pigments [7]. Another way to enhance surface properties is to coat papers with plastics to reduce surface roughness and porosity [7].

Another sustainable alternative to paper is cellulose diacetate or cellulose film that obtain auspicious biodegradable and biocompatible properties [34] [35]. Cellulose diacetate is an attractive material for PE since it is already commercially available, easily biodegrades in the soil, possesses high transparency and mechanical flexibility that makes it attractive for gas sensing and OLEDs layers [34]. Cellulose foil is also a promising alternative to plastic substrates due to its dielectric properties, flexibility and toughness [35].

D. Printing Techniques

Traditional printing methods are highly reliable and well-established in the graphical industry [36]. Nevertheless, there are some inherent restrictions in terms of the materials' processability. A decade ago, [37] claimed that even though such traditional printing techniques are potential, however they have to be modified to cope with particular conductive inks and materials employed for printing, since they differ from traditional printing inks. After a decade, the majority of printing techniques, different pre- and post-printing processing and treatment are fully adapted and improved, and commercially available to produce printed electronic components. Various researches either named as promising or investigated the potential of the following fabrication methods for PE: flexography [7], screen printing [22] [27] [29] [39], gravure printing [44] [47], ink-jet printing [19] [34] [39] [47].

In general, printing technologies are divided depending on whether the ink transfer has direct physical contact with the substrate or not [18]. All contact printing techniques, such as offset, gravure, flexography and screen printing, use pre-defined mold or stencil with defined printing pattern [18]. Consequently, changes in the printed pattern require a new design of the printing rolls. However, the main advantage is a wider range of ink viscosities and layer thicknesses that result in higher resolution [18]. In a case of non-contact printing technologies, ink droplets are produced to the substrate at some distance, therefore pressure sensitive functional layers are not damaged [18]. The strength of printing technologies is their capability to produce high resolution patterned structures.

IV. ANALYSIS

A. Radio Frequency and Identification Tags

The recent growth in the development of the standardization of communication protocols and the increased interest in object-human interaction has highly influenced the design freedom for innovative smart packaging applications [6] [21]. Radio Frequency Identification is based on automatic identification technology and can be referred as a trace and track system based on ultra-high frequency. Reference [26] describes it as a fundamental building block in communication systems to transmit and receive signals including antennas, transmission lines, active circuits and various amplifiers. In fact, printed electronics has empowered this technology, and it became one of the next generation wireless communication system widely used today by manufacturing, logistics providers, and supply chain management industries. The successful appliance of RFID into these economic areas was mainly impacted by technology's capabilities to identify, manage and categorize the flow of data. Moreover, the advancement in technologies has influenced the size miniaturization, cost reduction, energy saving, and large-scale production of RFID tags. In general, RFID tags usually consist of three main components: (1) a silicon chip or tag, (2) antenna inlays, called a transponder or integrated circuit that enables to read or write data, (3) and application host, where the tag is embedded, e.g. a thin polymer film, polyester or polyamide [4].

RFID tag embedded into packaging enhances the way the information about the product is stored, disclosed or transferred. For example, RFID tags with smart sensors can identify not only different locations but also monitor various characteristics of the surroundings as humidity, light exposure, temperature and etc., to store and record such data and finally transmit it to inform the users about changes [38]. A study by [39] have presented the fabrication and characterization of a printed RFID tag compatible with EPC Gen 2 RFID standard with multiple sensing capabilities, i.e. integrated force sensor, opening detector and temperature sensor. The smart system was directly screen printed on a cardboard box to monitor packaging conditions throughout the supply chain, such as applied force to the package, occurred opening, shock events, and temperature of the surrounding environment.

Different techniques from screen printing to inkjet printing have been used to fabricate RFID tags directly on the selected substrate, like paper, cardboard, plastic and etc. [39] [40] [41]. Reference [21] has manufactured the RFID tag with an organic photodiode to control the exposure of packed products to light. The main parts of the tag, including antenna, interconnectors and photodetector, were printed using silver nanoparticles via inkjet printing, whereas silicon chip and capacitor were built-in. In a context of packaging, this technology is essential to obtain products' status through the supply chain, improve the inventory management as well as reduce logistics costs [21].

B. Near Field Communication Tags

NFC is a short-range communication technology enabling the interaction between compatible objects, like smartphones and smart packaging. The development of NFC-driven smart packaging was facilitated by PE and IoT capabilities to integrate electronic intelligence into everyday products. Reference [42] defines NFC as a wireless close-range connectivity technology that provides reliable, secure and efficient data exchange. In comparison to RFID tags, NFC tags have been already widely integrated into mobile devices such as smartphones and tablets, therefore no specific reader is required [30]. On the other hand, NFC band works only at a short read range contrary to RFID that enables transmission within a few meters. NFC tag usually comprises an initiator and a target which consists of a chip with storage memory and antenna. The initiator actively generates power to a passive target. Reference [30] presented a study, where antenna coil, circuit tracks and contact pads of NFC tag were manufactured via inkjet printing on a paper substrate, and a microprocessor and a chip were added subsequently. Such tags with integrated sensors can be utilized to measure a large number of different parameters, including chemical contamination, temperature, humidity, and other [30].

In addition, NFC tag is rewritable, stored data can be encrypted and protected with a password due to write-once-read-many (WORM) memories [43]. As a result, the big data concept allows market analysis in terms of consumer habits, behavior, and preferences, thus it creates an interactive link between businesses and users, and adds value to the product.

For instance, ThinFilm provides highly scalable printed electronics solutions by deploying printed NFC tags for various consumer and industrial applications. The developed OpenSense™ technology is used for authentication and fraud protection applications. NFC OpenSense™ tags working principle is dual: firstly users instantly get relevant information by tapping their phone on the product; secondly label is incorporated onto the bottle in such a way that if the bottle is open, the antenna of NFC tag will be broken and, for instance, improper opening accident will be registered on the tag. The other NFC technology SpeedTap™ has the instant identification capability, therefore it greatly possesses targeted marketing and track& trace capabilities (thinfilmnfc.com).

C. Smart Sensors

Wireless networks and IoT have facilitated the replacement of analog sensors to digital sensors due to fast and convenient connection to the internet. Reference [5] states that sensors are leading innovation in a broad scope of applications regarding their productive data handling. The recent development and improvement in sensors-enabling technologies, as PE, IoT, nanotechnology and other, have the impact on reducing the cost and the size of sensors, as well as spreading the usage of this smart technology to new market segments, such as agriculture, medical, semiconductor, transport, construction, and, most importantly, consumer packaging industries. Reference [21] contributes that the combination of the low production cost and the high production throughput allow the realization of low power wireless sensors, as well as the growth of IoT.

Reference [38] claims that PE enables the manufacture of light-weight, rollable, bendable, portable and foldable, thus they can be directly applied to any object disregarding its shape. Consequently, a broad range of sensors has already been developed for packaging monitoring. Generally, sensors can be incorporated into packaging in several ways: (1) directly printed, (2) placed as a label, or (3) laminated. There are various sensors with multiple capabilities applied in the packaging industry that can be divided into two groups:

a) Monitoring and Informing Sensors: Aim to perform surveillance functions and to enhance the protection function of the packaging [5]. This group encompasses temperature, relative humidity, gas, moisture content, oxygen, chemical, opening and other sensors. [27] and [7] presented studies where electronic capacitive sensors for humidity sensing capability were manufactured via a screen printing and inkjet printing, respectively, with silver-based conductive ink on paper-based substrates. Whereas [39] has designed and fabricated a printed passive RFID tag with an opening detection, force and temperature sensors on a cardboard box. Both studies emphasized the significance of communication protocol, as RFID, that processes and digitalizes data that later is stored on a memory chip for future access.

b) Interactive Sensors: Allow objects to become interactive and connected to digital services via the internet. Such sensors are based on IoT and capacitive touch concepts, especially in packaging to further enhance the communication capability regarding marketing and branding. A study by [44] manufactured active matrices based on single-walled carbon nanotubes using gravure printing that can be utilized as a multi-touch sensing sheet.

In connection to PE, sensors can be printed using traditional gravure printing, screen printing and ink-jet printing processes with silver-based conductive ink.

D. Touch Sensors

Reference [45] noted that there are many touch screen products commercially available as capacitive touch screens, resistive touch screens, touch pads, touch sensors. Touch sensors are intended to add value in either (1) monitoring the packages and surrounding environment, or (2) providing interactivity for pre- and post-purchase applications.

In general printed sensor changes its capacitance, resistance or any other active characteristic due to the touch or manipulation. Then changes are readout by wireless communications link, as RFID, NFC tags, ZigBee, Bluetooth, Wi-Fi or simple analog wire solution. And finally, visual or digital changes appear on screen or are transmitted to the database for further analysis. For instance, capacitive touch pads detect changes in capacitance due to the contact with fingers by using the electrical impedance across the tip of a finger and the effective capacitance of the human body [46].

Low-cost, sustainable touch devices have the potential to contribute to future developments in flexible paper electronics for smart packaging as speakers and displays in order to enable new types of consumer-oriented interactive solutions. According to [45]: “The sensor technology has been developed to be easily integrated into high quality prints targeting applications such as large area touch sensitive commercial stands, flat keyboards at point-of-purchase and touch and manipulation surveillance in logistic chains.” The author put emphasis only on pre-purchase-based point of view, where printed touch sensors have an influence on purchase decisions since 70% of all purchasing decisions are made in store. However, touch sensors technology is highly applicable in the use environment as well, where user by interacting with touch sensor-based packaging experiences higher functionality, engagement and entertainment.

E. Logic and Memory

Memory and logic are two main elements that have the ability to enable complex printed circuits, as well as enhance the capability of printed electronics [47]. According to the authors, memory array ensures that identification or history information is maintained, whereas logic reduces power consumption and improves circuit stability. For instance, printed memories applied for smart packaging can store the key codes for anti-counterfeiting purposes related to risk management and safety monitoring [43]. In their work [47] fabricated scalable circuits of organic logic and memory on flexible plastics by roll-to-roll printing techniques as ink-jet and gravure printing. The developed circuit is suitable for sensor networks, smart tags, packaging, and other.

For packaging applications, memory is required to be cost-efficient and maintain stability after long-term storage and multiple reading operations [43]. Therefore recently WORM memories were founded as suitable solutions. A research by [43] manufactured WORM memories using AgNWs meshes via dispensing and bar coating techniques that permit low cost and large area efficient manufacturing. In their study, the fabricated memories can be fused with low voltage and low current that allows them to be programmed and read through NFC-enabled mobile devices. However, even though the process is efficient, the expensive equipment is needed [43].

F. *Light-Emitting Devices*

References [41] and [48] state that conventional display techniques such as light-emitting diodes (LEDs) and liquid crystal display (LCD) provide high-performance visual applications, but also consume a high amount of power, and are fabricated on conventional glass substrates. As a result, according to [49], the industry is keen to develop more flexible, lightweight, biodegradable, low-power consuming, and cost-efficient light-emitting devices. The shift to more sustainable materials and methods to produce such devices is feasible and already in progress. Some literature carried out studies towards alternative lighting and display devices:

a) Organic Light-Emitting Diode (OLED): Commonly investigated printed OLEDs have potential, however they require highly controlled thicknesses of each layer, and only operate efficiently on smooth surfaces as plastic [36]. Highly renewable paper-based substrates are too rough and porous for such lighting sources [49].

b) Electronic Paper Display (EPD): In comparison to traditional paper display, EPD possesses preeminent qualities of light reflectivity, flexibility, cost-efficiency, and image bi-stability which refers to keeping the color for a particular length of time without energy supply [41].

c) Electrochromic Display (EC): Comparing to EPD devices with the driving voltages over 10V, EC displays can be refreshed by 1.5 V. As a result, EC displays save the complexity of charge pump design [41].

d) Electroluminescent Display: Reference [50] presented fully printed electroluminescent displays on various types of packaging including plastics and cellulose-based substrates by spray coating techniques. The inks were based on carbon nanomaterials and silver nanoparticles. The advantage of proposed fabrication techniques is that the entire electronic device is fully and directly printed on the substrate, thus it could be easily integrated into an existing production line. Moreover, carbon- and graphene-based electrodes possess favorable mechanical strength and easy processing prior to conventional indium tin oxide ITO and fluorine doped tin oxide FTO materials.

e) Thermochromic Display: A study [29] investigated the possibility to print thermochromic displays on cardboard packaging via screen printing to monitor, for instance, the light exposure of the surrounding environment. In this case, the extreme change, like applied electrical power, is able to damage the microcapsules of thermochromic ink and thereby trigger the color difference of the packaging.

f) Light-emitting Electrochemical Cell (LEC): LECs are more forward technology in the field of PE in comparison to OLEDs that enables large-scale and cost-efficient manufacturing carried out by conventional printing methods [34]. The entire fabrication process is simplified by thickness-independent single-active-layer device architecture. A study by [34] demonstrated the fabrication of fully biocompatible/biodegradable LECs devices via inkjet printing and blade coating on cellulose diacetate substrate. Despite the apparent shortcoming in performance, the study targeted the potential use in sustainable applications, as smart packaging. On the other hand, [36] presented state-of-the-art devices had a shelf lifetime over six months that confirms the suitability for smart packaging. Moreover, [49] proposed a solution that provided a good fit between lighting devices and paper-based products. Authors reported the fabrication of flexible and light-weight LEC device on paper substrates using handheld airbrushing method. The constructed device is highly flexible and displays a uniform light emission.

G. *Thin Film Transistors*

Reference [51] states that low cost printed carbon nanotube-based TFTs can be utilized in a broad range of flexible electronics and IoT applications as sensors, logic circuits, displays, RFID tags and other. Various researchers have investigated the potential applications of printed TFTs. For instance, researchers [52] have manufactured TFT on flexible polyethylene naphthalene (PEN) substrate in ambient conditions at maximum 150 °C temperature. Other research [22] have demonstrated all-printed, foldable organic TFT on untreated glassine paper substrates based on screen and inkjet printing techniques and graphene.

Moreover, [53] reported the technique to develop source/drain electrodes of organic field-effect transistors (OFETs) combining two mass printing technologies (flexographic and gravure printing). Plus [51] developed a solution of fully printed CNT-TFTs using an aerosol jet printing technique. The use of single-walled carbon nanotubes into TFTs has been intensively studied due to (1) their preeminent electronic, thermal, mechanical properties, (2) compatibility with solution-based processing and low-cost mass production printing, (3) broad application for flexible, interactive electronics. Based on results from carried out researches, it is concluded that all-layer printed, flexible TFTs are readily compatible with flexible substrates, ensure favorable electrical characteristics, and can be applied in emerging electronics.

H. *Supercapacitors and Batteries*

There is a strong interest in thin and flexible energy storage devices for interactive packaging, radio frequency and consumer-oriented products applications. Energy supply is one of the essential components of sophisticated electronic devices, and it is necessary for electronics to operate. According to [54] energy storage devices, such as batteries, capacitors and supercapacitors, can be efficiently produced by printed electronics technology. In fact, even though the majority of electronic elements require precise resolution and exceptional smoothness of the surface, energy storage devices are not that demanding and are able to operate printed on the rough surfaces of paper-based substrates efficiently. Reference [28] has fabricated single-walled carbon nanotubes thin film-based supercapacitors with printed anode, cathode and separator by ink-jet printing on a paper substrate. Utilized nanomaterial-based ink has excellent absorption rate to cellulose-based substrates. In fact, such a light-weight paper-based supercapacitor can be employed to power various paper electronic devices as transistors, sensors and displays. Moreover, printed energy storage structure is applicable for high-speed printing, is cost-efficient and could be disposable.

Recently, the micro-supercapacitors (MSCs) have shown auspicious potential for microscale, flexible, on-chip energy storage devices, providing fast charge/discharge rate, long cycle life and high power density compatible with integrated electronic circuits [19]. Researchers have fabricated MSCs devices with graphene and ion gel inks via inkjet printing in a high-throughput and cost-efficient manner for smart packaging applications.

I. *Summary of Potential Printed Electronic Elements*

Table 1 contains a summary of investigated potential printed electronic elements and devices that are feasible to apply to smart interactive packaging ranging from small parts as logic and memory to the entire systems as RFID tags. The given Table 1 illustrates the current state-of-the-art status of PE appliance to packaging including (1) the specific type of printed elements, (2) the main used materials and conductive inks to produce printed elements, (3) the main printing techniques to fabricate electronic elements, (4) the evaluation of the manufacturing processes in terms of succession and complexity. The fabrication of printed elements refers to a fully printed process, if all active and passive layers are produced by printing methods enabled by PE. Likewise, the fabrication refers to a hybrid, if some of the components are manufactured by conventional electronic methods. The electronic elements are considered directly printed, if they are composed already onto the final substrate. On contrary, if the printed element is firstly fabricated on one substrate and afterwards glued, laminated or attached to the final product, then the electronic elements are considered as hybrids.

TABLE I. THE SUMMARY OF POTENTIALS OF PRINTED ELECTRONICS

Printed electronic elements	**Manufacturing Characteristics of Printed Electronic Elements**					
	Conductive ink and materials	***Printing techniques***	***Printing substrates***	***Fully printed / hybrid***	***Directly printed / hybrid***	***Reference***
RFID tag	Copper oxide Silver ink	Brush-painting method	Wood Cardboard	Fully printed	Directly printed	[40]
RFID tag with force, temperature sensors, opening detector	Silver ink	Screen printing Inkjet printing	Cardboard box	Hybrid	Directly printed	[39]
Conductive text, interconnectors for LED, 3D antennas	Silver ink	Pen-on-paper method	Paper-based substrates	Fully printed	Directly printed	[48]
Electroluminescent display	Silver ink for electrodes	Spray coating with airbrush	Cans, cardboard boxes, PP bottles	Fully printed	Directly printed	[50]
Capacitive humidity sensors	Silver ink	Screen printing	Recycled paper, cardboard, poly-carbonate, PET foil	Fully printed	Directly printed	[27]
Circuits of organic logic and memory	Silver ink	Inkjet printing Gravure printing	Polyethylene naphthalate (PEN)	Fully printed	Not specified	[47]
Write-once-read-many memory for NFC	Silver nanowire meshes	Dispensing and bar-coating	Polyethylene terephthalate (PET)	Fully printed	Hybrid	[43]
Light-emitting electrochemical cells	Silver ink ITO, PEDOT:PSS	Inkjet printing Blade coating	Cellulose diacetate (CA)	Fully printed	Hybrid	[34]
RFID with organic photodiode (OPD)	Silver ink PEDOT:PSS, PEI	Inkjet printing Spray deposition	Polyethylene naphthalate (PEN)	Hybrid (SMD inductor silicon chip, capacitor)	Hybrid	[21]
Graphene patterns, S&D electrodes	Graphene ink	Screen printing	Polyimide films	Fully printed	Directly printed	[22]
Micro-supercapacitors (MSCs)	Graphene and ion gel inks	Inkjet printing	Polyethylene terephthalate (PET)	Fully printed	Hybrid	[19]
Humidity sensor	Porous silicon (pSi), silver ink	Spray coating Flexography Inkjet printing	Multilayer coated paper	Fully printed	Directly printed	[7]
Thermochromic display	UV thermochromic ink, silver ink	Screen printing	Cardboard	Fully printed	Directly printed	[29]
Active matrix for multi-touch sensors	Silver ink, $BaTiO_3$ ink, SWCNT ink	Gravure printing	Polyethylene terephthalate (PET)	Fully printed	Hybrid	[44]
RFID tag antennas	Silver ink Copper ink	Inkjet printing	Polyimide Cardboard	Fully printed	Directly printed	[55]
NFC antenna coil, circuit tracks, contact pads	Silver ink	Inkjet printing	Paper	Hybrid (soldered microprocessor, chip)	Directly printed	[30]

V. Discussion

The discussion part is twofold. First, authors present value of chain as a set of activities of the manufacturing processes that have to be taken into consideration by packaging manufacturers, printing houses or CPG brand owners that aim to integrate PE technology into their manufacturing processes to deliver a valuable product, i.e. PE-enabled smart interactive packaging. Then the presented value chain is placed into a TM context and aligned with the existing theory of technology base and TM activities [11], technology development capabilities [13] and the overall TM framework [15].

A. Value Chain of Manufacturing Activities

Based on findings, there is a broad range of potential electronic elements that are feasible for smart interactive packaging applications. In general, the majority of printed electronic elements and devices consist of similar fabrication processes most commonly including the utilization of silver or graphene nanoparticle inks and inkjet or screen printing methods. However, printing techniques, pre- and post-treatment processes, conductive inks and materials might differ depending on the application. In general, it is essential to optimize the interplay between (1) conductive ink properties, as surface tension or viscosity, (2) printing substrate characteristics, as surface porosity, roughness and mechanical flexibility, and (3) printing processes parameters, as cell volume and raster of the printing cylinder for a precise control [53]. As a result, a more detailed methodology of the entire fabrication including pre- and post-printing processes should thoroughly consider and describe each counterpart of the PE technology step by step:

1) The Design of Electronic elements: Likewise the traditional printed media materials have to be designed using specific design, layout and publishing software, printed electronic elements follow the same principles. Thus, several schematic layouts have to be designed to illustrate graphically (1) the sequential arrangement of each separate element of the electronic device, (2) the technological scheme of each manufacturing process, and (3) the graphical layout of printing processes in succession layer by layer.

2) Preparation of Ink: Since traditional printing inks are customized for specific printing techniques purposes, the conductive ink has to be processed first to meet the requirements. Processing methods might include filtration to remove larger nanoparticles, heating to remove ethanol, degasation, cross-linking with other chemical compounds. Finally, a composition of the ink is stirred for a particular length of time to improve its chemical, physical and performance properties. For instance, silver nanoparticle ink is usually coated with a polymer to prevent agglomeration in the dispersion that might negatively affect the ink binding to a substrate. However, such polymer coatings result in lower conductivity, therefore the post-processing is necessary to obtain optimal electrical properties [30].

3) Preparation of Substrate: In order to obtain higher printability performance, the surface of the substrate usually has to be pre-treated to enhance surface energy, reduce roughness, improve surface smoothness, prevent higher penetration of inks into substrates, and to remove any remaining particles that are particularly relevant and essential for paper-based substrates commonly used in packaging. Substrate preparation might include deposition of a few different layers, coating, calendaring. In this particular case [52] PEN polymer was cleaned with ethanol and dried by a nitrogen flow before printing to remove remaining substances. Whereas [56] coated paper with kaolin clay as an initial smoothing layer. The lack of insufficient or inappropriate pre-treatment processes might result in non-adhering and non-conductive printing patterns [35]. The key disadvantage of the most commonly used silver nanoparticle ink is unstable contact lines formed on highly hydrophilic paper surfaces. Therefore, especially for paper and cardboard packaging applications, printing substrates must be pre-treated. Generally, pre-treatment processes ensure effective printing process and the smooth surface to facilitate the continuous formation of passive and active layers.

4) Printing Process: PE technology is based on printing and post-treating all the layers in succession. Therefore the key feature during printing processes is the succession of printed layers that form printed electronic elements. Each layer has different electronic, mechanical and physical properties, thus they can be divided into dielectrics, conductors (electrodes) and semiconductors that further forms transistors, resistors, capacitor and other in terms in the fabrication of more sophisticated electronic devices as light-emitting displays. Antennas and printed circuits have simpler fabrication sequence. It is essential for the primer layer to ensure a proper layer formation of conductive ink printed on top of it since it reduces the absorptiveness and the roughness of the substrate [52]. For instance, the fabrication of TFT begins with printing the first layer with silver ink, then post-printing procedures take place as drying, curing, and sintering at a specific temperature for a particular length of time. Later two layers of dielectric ink are printed, dried, cured and cross-linked. The third layer consisted of S-D printed electrodes with silver ink is printed and sintered. Finally, an organic semiconductor film is printed and dried for better formation and protection. Consequently, the printing process is highly dependent on the application and requires a suitable functional ink formulation for a specific technique since each method possess different restrictions regarding processability of material [36].

5) Post-printing Processes: It is important to carry out post-printing operations after each layer is printed and after the entire elements is produced in order to functionalize the printed layers, control the layer formation, improve conductivity and other electrical properties. Usually, post-printing processes are various temperature based operations, sintering, UV-curing, UV ozone treatment, photonic annealing using xenon lamp suitable for heat-sensitive surfaces [22] [56]. Consequently, the post-printing processes depend on the printing substrates characteristics. For instance, for paper and cardboard packaging some sintering techniques are harmful due to their sensitivity to temperature.

6) Assembly of the Entire Device: If the electronic device is not fully-printed by traditional printing techniques, PE-based printed parts and conventionally manufactured parts have to be assembled into one device. They could be cured by heating, conductive resin, or other methods. At the moment, only some passive parts of electronic devices can be printed as antennas, circuits, pads, whereas active elements as chips and capacitors are embedded to the final device after the passive parts have been printed. As a result, even though passive parts are printed by R2R techniques, the final step is taken in the sheet-to-sheet additional equipment.

7) Integration onto the Final Product: If the electronic device is not directly printed on the final object, as products' packaging, the additional operation has to be added to the production line to apply printed electronic element to the final product.

Furthermore, since it is essential to optimize the interplay between each constituent part of printing process, as surface tension of inks and raster of the printing cylinder a precise control, several tests can be conducted to test various quality, duration and accuracy parameters, such as conductivity and surface resistance tests [53].

B. TM Activties and Technological Capabilities

In relation to TM theory, the presented value chain for manufacturing processes can be conceived as a part of exploitation activity in the model of six generic TM activities (identification, selection, acquisition, exploitation, protection and learning) presented by [11]. According to the authors, exploitation refers to commercialization including implementation, absorption and operation of technology, and marketing. Consequently, the given value chain activities are related to the operation aspect and contribute to the technology transfer from the R&D, where the hypothesis of PE-enabled communication devices appliance onto consumer packaging is examined, to manufacturing. Furthermore, since the presented value chain is a part of TM activities, it coherently contributes to the technology base and core business processes, named as strategy, innovation and operations [15].

In general, technological capabilities are defined as proficiencies to make the effective use of technological knowledge, therefore presented value chain of manufacturing processes can also be conceived as a part of operations capability and technology development capability presented by [13]. The former is the collection of daily routines that are fixed in skills, knowledge and technical systems to perform the given production at a given time [13]. In terms of the printing industry, the traditional operational capabilities are well established and usually include five out of seven described value chain activities: the design of elements, preparation of ink, preparation of substrate, printing process, and post-printing processes. However, the integration of PE technology into existing company's operations regarding manufacturing requires to build, integrate or reconfigure the core operational capabilities. For instance, although the traditional printing industry is well-prepared to prevent potential strength and stability failures of the paperboard packaging by applying various surface treatments to improve the surface of the paper, the appliance of conductive inks requires additional pre-treatments particularly relevant for electrical performance that is not considered during the traditional printing process. Consequently, the activity of "preparation the substrate" has to be reconfigured and adjusted to PE technology requirements. Likewise, traditional inks largely differ from the conductive ones, thus the latter has to possess supplementary physical, electrical, morphological, rheological, and other characteristics that are achieved through additional pre-treatment processes. Furthermore, based on the findings, the integration of PE technology also builds new activities/capabilities, named as an assembly of the entire device and integration onto the final product, that are out of the scope of core capabilities. This assumption follows the technology development capability concept presented by [13] that refers to the ability that a company has to interpret the current state of the art and transform their technology to change or create operations capacity or any other capability to reach a high level of technical-economic efficiency.

VI. Conclusion

This paper investigated and presented the current state-of-the-art of PE technology including relevant technical knowledge and development status achieved in printed elements. Gathered knowledge encompasses the key three enablers of PE: conductive inks, printing substrates, and printing techniques. The development status includes the required resources, techniques, and the evaluation of the manufacturing processes in terms of succession and complexity. Moreover, based on the gathered knowledge, paper presented the value chain of seven manufacturing activities that have to be taken into consideration by companies that aim to integrate PE into their manufacturing processes. The proposed value chain of manufacturing activities can be used as guidelines to reconfigure or create new technological capabilities to address the technology change.

Regarding the potential of PE to be applied for smart packaging, at the moment, the currently commercially available or on-the-research level developed electronic devices utilized by PE technology are still at some point including either hybridization, some parts of conventional electronics, or are printed on plastic films and then transferred to the final product. Therefore currently the only economically viable options for manufacturing cost-efficient and large-area electronic components for smart interactive packaging are related to straightforward and modest applications as RFID and NFC tags with simplistic sensing capabilities. However, more sophisticated applications, such as light-emitting displays, still require more complex and manifold manufacturing processes, as well as a higher number of enabling passive and active components. Even though some parts of such advanced devices can be produced by PE, the overall design still contains conventionally manufactured parts that in the end will be assembled into one device.

Furthermore, the investigated PE-enabled smart packaging applications are mainly enhancing the protection and preservation functions of the packaging with the use of RFID or NFC tags with incorporated temperature, humidity or opening sensors that benefits supply chain operations. On the other hand, the potential improvement of communication function by additional graphics, as light-emitting devices, might enhance end consumer engagement and contribute to unique value creation. The main challenge in the state-of-the-art appliance of PE into smart interactive packaging lies in the overall vision to be able to print the whole system simultaneously in the same production line. The development of new combinations of nanomaterials and printing substrates might facilitate such ambition. Therefore the technology is still at the development level.

REFERENCES

[1] E. Loucanova, M. Kalamarova, and J. Parobek, “The innovative approaches to packaging-comparison analysis of intelligent and active packaging perceptions in Slovakia,” Studia Universitatis "Vasile Goldis" Arad-Economics Series, vol. 27, no. 2, pp. 33-44, 2017.

[2] R. L. Underwood, “The communicative power of product packaging: creating brand identity via lived and mediated experience,” Journal of Marketing Theory and Practice, vol. 11, no. 1, pp. 62-76, 2003.

[3] A. Mumani and R. Stone, “State of the art of user packaging interaction (UPI),” Packaging Technology and Science, vol. 31, no. 6, pp. 401-419, 2018.

[4] C. Nandanwade Priyanka and D. Nathe Parag, “Intelligent and Active Packaging,” International Journal of Engineering and Management Sciences, vol. 4, no. 4, pp. 417-418, 2013.

[5] H. E. Nilsson et al., “System integration of electronic functions in smart packaging applications,” IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 2, no. 10, pp. 1723-1734, 2012.

[6] J. Lydekaityte and T. Tambo, “Business perspectives of smart interactive packaging: digital transformation of brand's consumer engagement,” In Proceedings of the 8th International Conference on the Internet of Things, 2018, p. 29: ACM.

[7] T. Jalkanen et al., “Fabrication of porous silicon based humidity sensing elements on paper,” Journal of Sensors, vol. 2015, p. 10, 2015.

[8] J. Arrese, G. Vescio, E. Xuriguera, B. Medina-Rodriguez, A. Cornet, and A. Cirera, “Flexible hybrid circuit fully inkjet-printed: surface mount devices assembled by silver nanoparticles-based inkjet ink,” Journal of Applied Physics, vol. 121, no. 10, p. 9, 2017.

[9] D. Berg, H. S. Mani, Y. G. Marinakis, R. Tierney, and S. Walsh, “An introduction to Management of Technology pedagogy (andragogy),” Technological Forecasting and Social Change, vol. 100, pp. 1-4, 2015.

[10] E. Berman, E. Vasconcellos, and W. B. Werther Jr, “Executive levers for the strategic management of technology: leaders must have the tools to move their firms toward the use of technology as a strategic resource,” Business Horizons, vol. 37, no. 1, pp. 53-62, 1994.

[11] D. Cetindamar, R. Phaal, and D. Probert, “Understanding technology management as a dynamic capability: a framework for technology management activities,” Technovation, vol. 29, no. 4, pp. 237-246, 2009.

[12] S. K. Kim, “General framework for management of technology evolution,” The Journal of High Technology Management Research, vol. 24, no. 2, pp. 130-137, 2013.

[13] P. A. Zawislak, A. Cherubini Alves, J. Tello-Gamarra, D. Barbieux, and F. M. Reichert, “Innovation capability: from technology development to transaction capability,” Journal of technology management & innovation, vol. 7, no. 2, pp. 14-27, 2012.

[14] J. Jin and M. Von Zedtwitz, “Technological capability development in China's mobile phone industry,” Technovation, vol. 28, no. 6, pp. 327-334, 2008.

[15] R. Phaal, C. J. Farrukh, and D. R. Probert, “Technology roadmapping—a planning framework for evolution and revolution,” Technological forecasting and social change, vol. 71, no. 1-2, pp. 5-26, 2004.

[16] D. Savastano, "The growing market for conductive inks: conductive ink manufacturers are seeing more flexible and printed electronics systems reach pilot production and manufacturing stages," Ink World Mar.-Apr. 2014: 61+. Business Insights: Essentials.

[17] S. K. Garlapati, M. Divya, B. Breitung, R. Kruk, H. Hahn, H., & S. Dasgupta, “Printed electronics based on inorganic semiconductors: From processes and materials to devices,” Advanced Materials, vol. 30, no. 40, p. 55, 2018.

[18] R. Abbel, Y. Galagan, and P. Groen, “Roll-to-Roll fabrication of solution processed electronics,” Advanced Engineering Materials, vol. 20, no. 8, p. 30, 2018.

[19] W. J. Hyun, E. B. Secor, C. H. Kim, M. C. Hersam, L. F. Francis, and C. D. Frisbie, “Scalable, self-aligned printing of flexible graphene micro-supercapacitors,” Advanced Energy Materials, vol. 7, no. 17, p. 8, 2017.

[20] T. N. Ng et al., “Printed dose-recording tag based on organic complementary circuits and ferroelectric nonvolatile memories,” Scientific reports, vol. 5, p. 7, 2015.

[21] A. Falco, J. F. Salmerón, F. C. Loghin, P. Lugli, and A. Rivadeneyra, “Fully printed flexible single-chip RFID tag with light detection capabilities,” Sensors, vol. 17, no. 3, p. 12, 2017.

[22] W. J. Hyun, E. B. Secor, M. C. Hersam, C. D. Frisbie, and L. F. Francis, “High-resolution patterning of graphene by screen printing with a silicon stencil for highly flexible printed electronics,” Advanced Materials, vol. 27, no. 1, pp. 109-115, 2015.

[23] Y. Wyser et al, “Outlook and challenges of nanotechnologies for food packaging,” Packaging Technology and Science, vol. 29, no. 12, pp. 615-648, 2016.

[24] E. L. Bradley, L. Castle, L., and Q. Chaudhry, “Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries,” Trends in food science & technology, vol. 22, no. 11, pp. 604-610, 2011.

[25] D. Raheem, “Application of plastics and paper as food packaging materials-an overview,” Emirates Journal of Food and Agriculture, vol. 25, no. 3, pp. 177-188, 2013.

[26] X. Huang et al., “Highly flexible and conductive printed graphene for wireless wearable communications applications,” Scientific reports, vol. 5, p. 8, 2015.

[27] M. Mraović, T. Muck, M. Pivar, J. Trontelj, and A. Pleteršek, “Humidity sensors printed on recycled paper and cardboard,” Sensors, vol. 14, no. 8, pp. 13628-13643, 2014.

[28] L. Hu, H. Wu, and Y. Cui, “Printed energy storage devices by integration of electrodes and separators into single sheets of paper,” Applied Physics Letters, vol. 96, no. 18, p. 4, 2010.

[29] U. Kavćić, M. Mraović, S. Bračko, and D. Muck, “Printed thermochromic displays,” Coloration Technology, vol. 135, no. 1, pp. 60-66, 2019.

[30] E. Balliu, H. Andersson, M. Engholm, T. Öhlund, H. E. Nilsson, and H. Olin, “Selective laser sintering of inkjet-printed silver nanoparticle inks on paper substrates to achieve highly conductive patterns,” Scientific reports, vol. 8, no. 1, p. 9, 2018.

[31] C. Paquet et al., “Photosintering and electrical performance of CuO nanoparticle inks,” Organic Electronics, vol. 15, no. 8, pp. 1836-1842, 2014.

[32] P. Asgari, O. Moradi, and B. Tajeddin, “The effect of nanocomposite packaging carbon nanotube base on organoleptic and fungal growth of Mazafati brand dates,” International Nano Letters, vol. 4, no. 1, p. 5, 2014.

[33] A. Barhoum, P. Samyn, T. Öhlund, and A. Dufresne, “Review of recent research on flexible multifunctional nanopapers,” Nanoscale, vol. 9, no. 40, pp. 15181-15205, 2017.

[34] J. Zimmermann, L. Porcarelli, T. Rödlmeier, A. Sanchez-Sanchez, D. Mecerreyes, and G. Hernandez-Sosa, “Fully printed light-emitting electrochemical cells utilizing biocompatible materials,” Advanced Functional Materials, vol. 28, no. 24, p. 8, 2018.

[35] A. Samusjew, A. Lassnig, M. J. Cordill, K. K. Krawczyk, and T. Griesser, “Inkjet printed wiring boards with vertical interconnect access on flexible, fully compostable cellulose substrates,” Advanced Materials Technologies, vol. 3, no. 4, p. 6, 2018.

[36] G. Hernandez-Sosa et al., “The compromises of printing organic electronics: a case study of gravure-printed light-emitting electrochemical cells,” Advanced Materials, vol. 26, no. 20, pp. 3235-3240, 2014.

[37] P. Harrop, “Printing high-volume electrical and electronic devices,” GATFWORLD, vol. 18, no. 3, p. 26, 2006.

[38] K. B. Biji, C. N. Ravishankar, C. O. Mohan, and T.S. Gopal, "Smart packaging systems for food applications: a review," Journal of food science and technology, vol. 52, no. 10, pp. 6125-6135, 2015.
[39] J. Fernández-Salmerón, A. Rivadeneyra, F. Martínez-Martí, L. F. Capitán-Vallvey, A. J. Palma, and M. A. Carvajal, "Passive UHF RFID tag with multiple sensing capabilities," Sensors, vol. 15, no. 10, pp. 26769-26782, 2015.
[40] E. Sipilä, J. Virkki, J. Wang, L. Sydänheimo, and L. Ukkonen, "Brush-painting and photonic sintering of copper oxide and silver inks on wood and cardboard substrates to form antennas for UHF RFID tags," International Journal of Antennas and Propagation, vol. 2016, p. 8, 2016.
[41] J. Shen et al., "Interactive UHF/UWB RFID tag for mass customization," Information Systems Frontiers, vol. 19, no. 5, pp. 1177-1190, 2017.
[42] D. Pigini and M. Conti, "NFC-Based Traceability in the Food Chain," Sustainability, vol. 9, no. 10, p. 20, 2017.
[43] L. Zhu et al., "Silver nanowire mesh-based fuse type write-once-read-many memory," IEEE Electron Device Letters, vol. 39, no. 3, pp. 347-350, 2018.
[44] W. Lee et al., "A fully roll-to-roll gravure-printed carbon nanotube-based active matrix for multi-touch sensors," Scientific reports, vol. 5, p. 10, 2015.
[45] T. Unander, H. E. Nilsson, and B. Oelmann, "Printed touch sensor for interactive packaging and display," In Polymers and Adhesives in Microelectronics and Photonics, 2007, pp. 12-17: IEEE.
[46] A. D. Mazzeo et al., "Paper-based, capacitive touch pads," Advanced Materials, vol. 24, no. 21, pp. 2850-2856, 2012.
[47] T. N. Ng et al., "Scalable printed electronics: an organic decoder addressing ferroelectric non-volatile memory," Scientific reports, vol. 2, p. 7, 2012.
[48] A. Russo, B. Y. Ahn, J. J. Adams, E. B. Duoss, J. T. Bernhard, and J. A. Lewis, "Pen-on-paper flexible electronics," Advanced materials, vol. 23, no. 30, pp. 3426-3430, 2011.
[49] A. Asadpoordarvish et al., "Light-emitting paper," Advanced Functional Materials, vol. 25, no. 21, pp. 3238-3245, 2015.
[50] G. Wroblewski, M. Sloma, D. Janczak, A. Mlozniak, and M. Jakubowska, "Electroluminescent structures with nanomaterials for direct printing of interactive packages and labels," In Proceedings of the 2014 37th International Spring Seminar on Electronics Technology, 2014, pp. 357-360: IEEE.
[51] C. Cao, J. B. Andrews, and A. D. Franklin, "Completely printed, flexible, stable, and hysteresis-free carbon nanotube thin-film transistors via aerosol jet printing," Advanced Electronic Materials, vol. 3, no. 5, p. 10, 2017.
[52] E. Sowade et al., "All-inkjet-printed thin-film transistors: manufacturing process reliability by root cause analysis," Scientific reports, vol. 6, p. 15, 2016.
[53] G. C. Schmidt et al., "Modified mass printing technique for the realization of source/drain electrodes with high resolution," Organic Electronics, vol. 11, no. 10, pp. 1683-1687, 2010.
[54] K. Suganuma, *Introduction to Printed Electronics*. Springer Science & Business Media, 2014.
[55] Y. Ren, J. Virkki, L. Sydänheimo, and L. Ukkonen, "Optimisation of manufacturing parameters for inkjet-printed and photonically sintered metallic nanoparticle UHF RFID tags," Electronics Letters, vol. 50, no. 21, pp. 1504-1505, 2014.
[56] G. Grau, R. Kitsomboonloha, S. L. Swisher, H. Kang, and V. Subramanian, "Printed transistors on paper: towards smart consumer product packaging," Advanced Functional Materials, vol. 24, no. 32, pp. 5067-5074, 2014.