2 2D-3D Integration for Autonomous Sensors

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2.1 Introduction

The advances in energy harvesting technologies for powering low-power sensing platforms are intimately related with low-cost fabrication methods that are compatible with low-cost, flexible substrate materials. Additive manufacturing techniques provide such a platform to fabricate sensors and electronics with low cost, implicitly generate less waste, utilize flexible and low-cost substrates such as paper and plastics, and moreover enable a very quick turnaround, on-demand fabrication and design iteration that facilitates both research and in a way revolutionizes production [16]. In this chapter, we focus on inkjet printing fabrication, an additive manufacturing technique that has shown great potential in the last decade in flexible electronics on both plastics and organic paper substrates, fabricating radio frequency electronic circuits using low-cost [17] and medium-cost equipment [16] even up to millimeter waves. Inkjet printing is suitable for fabricating solar cells, thermoelectric generators, microelectromechanical systems (MEMS) transducers, circuit components such as inductors and capacitors, and transmission lines and antennas with sufficient resolution and provides a platform for packaging and integrating, integrated circuits (ICs), sensors, and interconnects [16]. The recent advances in other additive manufacturing technologies such as 3D printing will undoubtedly help further develop this exciting field of energy harvesting assisted wireless sensor platforms.

The demands for flexible sensors keep increasing as the market rapidly grows for ubiquitous computing, logistics, wearable/implantable electronics, and the Internet of Things (IoT). Flexible sensors have many advantages, such as flexibility, and functionality. They also allow low-cost implementation over some conventional sensors when they are integrated with nanotechnology-based novel materials and cost-efficient fabrication methods such as inkjet printing technology. The flexible sensors can be mounted on rugged/curved surfaces with low cost, which allow them large-scale deployment. The lifetime of the sensor is also an important factor for stable sensing. The energy harvesting and storing technology for flexible sensors is necessary to implement standalone autonomous sensor systems. Selecting proper flexible materials such as paper, liquid crystal polymer (LCP), and polyimide for the substrate material depending on the

[1] Edited by Apostolos Georgiadis.

https://doi.org/10.1017/9781139600255.003 Published online by Cambridge University Press

application is an important step in the implementation of flexible electronics. However, it is more important to choose and understand properly the materials used for sensing functions, electronics, and energy sources as well as fabrication methods that are compatible with a desired flexible sensor application.

Inkjet printing technology is widely utilized and studied as a novel fabrication method compared to the conventional fabrication methods such as milling and wet etching. Numerous electronics utilizing inkjet printing technology such as the Internet of Things (IoT), radio frequency identification tags (RFIDs), and wireless sensor networks (WSNs) have been demonstrated [18, 19, 20]. It is an additive fabrication method that deposits the controlled amount of functionalized ink such as silver nanoparticles, polymers, and nanocarbon structures on a desired position. This technology is cost efficient and environmentally friendly because it doesn't produce any byproducts due to its additive fabrication property. Small feature sizes (less than 50 μm) and arbitrary geometries can be also easily achieved without any masking [21, 22, 23]. Inkjet printing technology has great advantages for implementation of flexible sensors because it is able to print various nanoparticle-based materials, including metals, polymers, and sensing materials. Furthermore, inkjet printing technology can print materials on very thin flexible substrate without damaging the substrate.

Inkjet printing technology has attracted significant interest from many researchers due to the development of numerous types of nanoparticle-based inks such as metals, polymers, and carbon-based materials [24, 25, 26]. The silver nanoparticle inks allow metallization of electronic components and devices using inkjet printing technology, and the development of polymer inks enables printing numerous electronic components like such as transistors, inductors, and capacitors [27, 28]. Also, inkjet printing of nanocarbon materials such as carbon nanotube (CNT) and graphene significantly improved the sensitivity, selectivity, and application spectrum of inkjet-printed flexible sensors [29, 30].

Toward standalone autonomous flexible sensor platforms, energy harvesting is one of the most important design specifications because the available energy affects the system-level design of the sensor platform. There are many types of power sources such as batteries, solar cells, and nanogenerators. The solar cells and batteries can support relatively high power, but they need large area and are not suitable for flexible electronic applications. However, nanowire-based nanogeneratrors [31], for example, are becoming a promising power source for the flexible sensors because they can convert bending motions to power by utilizing, for example, piezoelectric effects. The generated power from the nanogenerator can be stored in printed flexible capacitors, which can be used to operate the sensor platform.

In this chapter, novel materials and fabrication technology for flexible sensors are introduced. The characteristics of nanomaterials including silver nanoparticles, printable polymers, and carbon-based materials such as CNT and graphene are presented, and inkjet printing technology is discussed as a novel fabrication method for flexible sensor system. The state-of-the-art nano-technologies

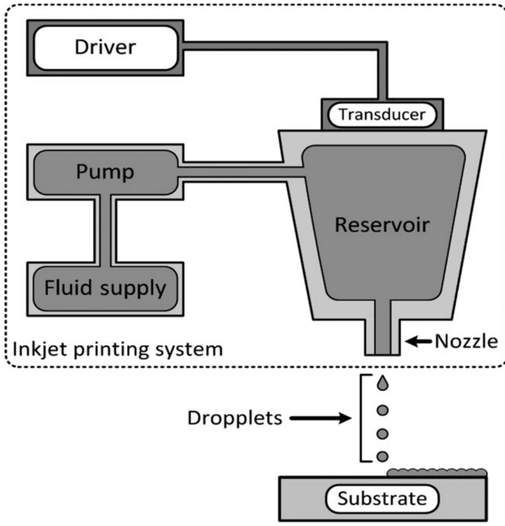

Figure 2.1 Inkjet printing system.

for energy harvesting such as nanowire-based nanogenerators and printed flexible capacitors are also introduced.

2.2 Inkjet Printing Technology

Inkjet printing enables the implementation of printed electronics on various flexible and organic substrates. Inkjet printing is able to print numerous materials such as metals, carbon-based nanostructures, and polymers [24, 25, 26]. It is a cost-efficient, environmentally friendly, and fast fabrication method due to its additive fabrication properties.

2.2.1 Types of Inkjet Printing

The concept of inkjet printing is relatively simple, and it is presented graphically in Figure 2.1. A liquid ink in a reservoir is jetted on a substrate through a nozzle. A desired pattern can be printed by moving the nozzle or substrate to deposit the ink drops on the correct positions.

There are two main inkjet printing methods: the continuous inkjet (CIJ) method and the drop-on-demand (DOD) method, which are shown in Figure 2.2a and 2.2b respectively. CIJ ejects ink drops continuously from the reservoir at a constant frequency (50 kHz–170 kHz), as shown in Figure 2.2c. The ejected drops are charged by charging plates, and the charged drops are directed by a pair of electrodes to print on a substrate or to a gutter for reuse. The advantages of the CIJ method are the high velocity of the ejected ink drops and the high drop ejection frequency. The high velocity of the ink droplets allows

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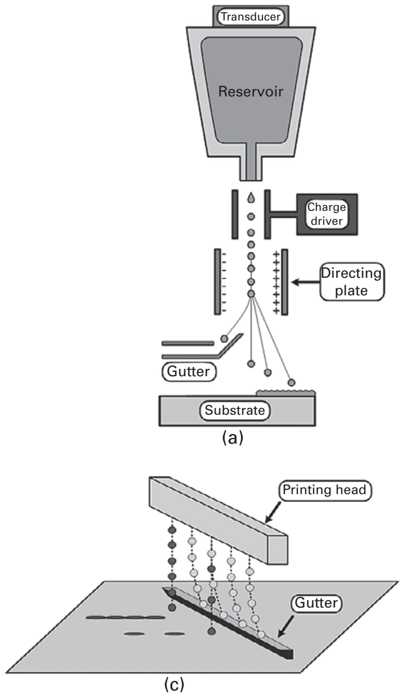

Figure 2.2 Continuous and DOD inkjet printing.

for a relatively long distance between a substrate, and a printing head and the high ejection frequency allows for high-speed printing. The continuous ejection of the ink mitigates the clogging of the printing nozzles. Therefore, volatile solvents such as alcohols can be printed easily. However, the CIJ system requires inks that can be electrostatically charged, and continuous viscosity monitoring is necessary.

DOD printing is similar to CIJ in that a transducer generates a pressure in order to eject a drop of ink. However, the ejected drops are not directed by electrostatic plates. A signal is sent to the transducer, and the transducer ejects the ink drop when it is needed, as shown in Figure 2.2d. DOD printing can use a wider range of inks with varying viscosities and surface tensions, and a higher printing resolution can be achieved compared to the CIJ method. However, clogging of the nozzles happens easily due to the ink drying and the inconsistent use of the nozzles.

There are several types of actuators such as piezoelectric, thermoelectric, and electrodynamic, which generate a pulse in the reservoir in order to eject the ink drop as shown in Figure 2.3. The piezoelectric and the thermoelectric actuators generate the pressure pulse in the reservoir while the electrodynamic actuator creates an ink drop by disturbing the surface tension of the meniscus formed at the end of the nozzle. The thermoelectric actuator generates heat

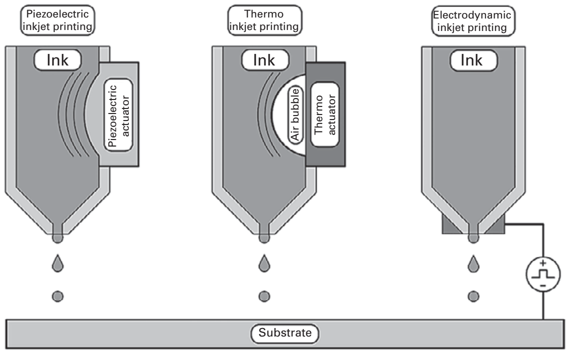

Figure 2.3 Actuator types of the inkjet printing technology.

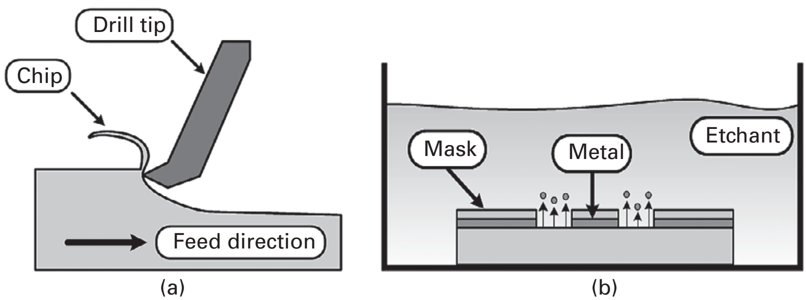

Figure 2.4 Subtractive fabrication methods: (a) milling and (b) wet etching.

causing vaporization of the ink in the reservoir to form a bubble, which ejects a droplet through a nozzle. Small drop sizes and high nozzle density are the advantages of a thermo actuator, but it has limitations on usable ink types. The inks should be able to be vaporized as well as to withstand high temperature. The electrodynamic actuator is able to create an ink drop of a very small size but has disadvantages such as low nozzle density, system complexity, and slow printing speed. The piezoelectric actuator utilizes a piezoelectric material in the reservoir to generate a pressure pulse to eject an ink drop. This type of inkjet printing technology is widely used in the research area because the piezoelectric actuator is compatible with a wider variety of inks.

2.2.2 Inkjet Printing Technology as a Fabrication Method

Inkjet printing technology is an additive method unlike a subtractive method including the wet etching and milling techniques. The wet etching and the milling techniques are widely used fabrication methods due to advantages such as rapid prototyping at low cost. The milling technique cuts and the wet etching technique washes away the unwanted materials selectively, utilizing a milling machine or an etchant as shown in Figure 2.4.

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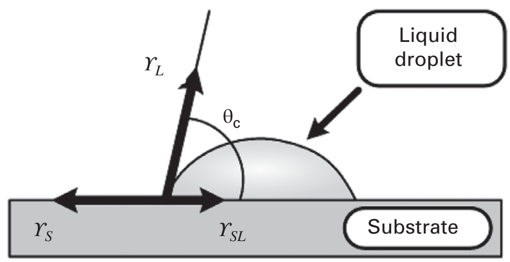

Figure 2.5 Surface energy.

The milling technique requires a milling machine, substrate, and cutting bits that have a size equal to or smaller than the smallest feature size of the desired pattern. A variety of features such as holes and slots can be created by the milling process, and this process is compatible with lots of materials, including metals and ceramics with tolerance down to 25 μm. However, a lot of byproducts are formed like chips and rough edges because of the cutting of the drill bit (Figure 2.4a). This method is suitable to process hard and relatively thick materials, but can be hardly used on thin flexible substrates as the bit removes part of the substrate. The wet etching technique is also commonly used to fabricate a printed circuit boards (PCBs). The etchants are solvent containing highly corrosive acids that dissolve a metal or a substrate (Figure 2.4b). The used etchants combined with the discarded materials form waste produced by the fabrication process, and they require special treatment for safety and environmental protection reasons.

Inkjet printing technology is a more efficient and environmentally friendly fabrication method compared to those conventional fabrication methods. It drops ink on an exact desired position. Therefore, there are no wasted materials because the inkjet printing produces no byproducts such as the acid etchant. In addition, a reasonably high resolution down to 50 μm can be achieved with high repeatability and without any special surface treatment such as masking. It is possible to improve the printing resolution to submicrometer values [23]. Furthermore, inkjet printing is compatible with very thin or flexible substrate because it doesn't damage the substrate surface.

2.2.3 Inkjet Printing and Surface Energy

Each substrate has different physical surface properties such as roughness and surface energy that result in different inkjet printability [22, 32]. The surface energy of the substrate is a very important factor because it determines substrate wetting. The difference in surface free energy between the printed ink drop and the substrate determines whether the ink wets the substrate surface (spread on the substrate) or not (forms a ball on the surface). It can be defined by the contact angle θ_c as shown in Figure 2.5.

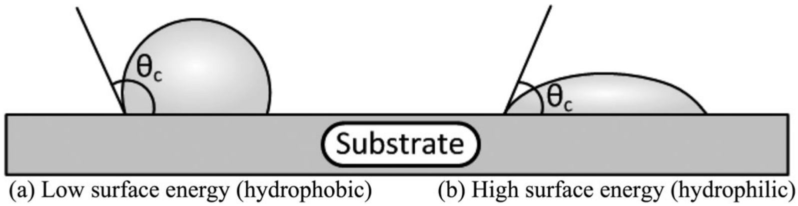

Figure 2.6 Low and high surface energy.

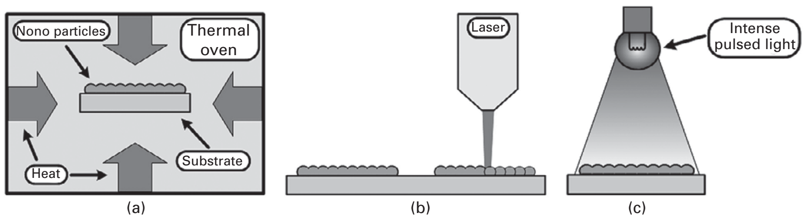

Figure 2.7 Sintering processes: (a) thermal sintering, (b) laser sintering, and (c) UV plasma sintering.

Young's equation (2.1) describes the balance of forces caused by a liquid droplet on a dry surface that results in a one-dimensional force equilibrium along the solid boundary

$$\gamma_S = \gamma_L \cdot \cos\theta_c + \gamma_{SL}, \tag{2.1}$$

where γ_S is the solid surface energy, γ_L is the liquid surface energy, and γ_{SL} is the solid/liquid interfacial surface energy. A hydrophobic surface has a high contact angle $\theta_c > 70°\text{C}$ that indicates a low surface energy γ_S, while a hydrophilic surface has a low contact angle $\theta_c < 30°\text{C}$, which indicates a high surface energy γ_S as shown in Figure 2.6. Too high of a contact angle θ_c is hardly able to form a continuous printed layer, and too low of a contact angle θ_c results in drop spreading.

2.2.4 Sintering Process

A sintering process is necessary to evaporate the solvent and make the printed silver nanoparticles conductive. The conductivity of the inkjet-printed metal is dominated by the sintering process. Therefore, it is very important to understand the properties of sintering processes and select the proper sintering process for each application. Many kinds of sintering processes are used, such as thermal, laser, and ultraviolet (UV) plasma sintering [33, 34, 35, 36].

The most widely used sintering process is thermal sintering. It is relatively simple and easy to apply to inkjet-printed nanoparticles. This process heats both the printed nanoparticles and substrate together as shown in Figure 2.7a.

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A sintering duration, a temperature ramping ratio, and a sintering temperature are the most important parameters of thermal sintering. Usually the inkjet-printed silver nanoparticles require about one hour of sintering at a temperature of 180°C to get a saturated conductivity value. A longer sintering interval is required when a lower sintering temperature is utilized.

The ramping ratio is another important factor necessary in order to make a continuous and uniform printed layer from the inkjet-printed nanoparticle inks. For example, the inkjet-printed silver nanoparticles can't form a continuous even surface if the ambient temperature changes too rapidly. If the temperature ramps too fast, cracks on the metal layer are produced. The sintering temperature is the most important factor that determines the quality of the inkjet-printed nanoparticles and sintering duration of the inkjet-printed nanoparticles. For instance, the conductivity of the inkjet-printed silver nanoparticles is a function of the sintering temperature, and less time is required as the sintering temperature increases. However, it should be noted that sintering temperature and time should be selected after taking account of the substrate's temperature durability as well as the desired conductivity of the printed silver nanoparticles. The thermally sintered silver nanoparticles have a resistivity of about 180 $\mu\Omega{\cdot}$cm–8.3 $\mu\Omega{\cdot}$cm depending on sintering temperature and printed number of layers, which is about 5.2–112.5 times of that of a bulk silver (1.6 $\mu\Omega{\cdot}$cm) [36].

Laser sintering utilizes a laser to sinter the printed nanoparticles at room temperature. Thermal sintering may damage the substrate due to the high heat required to melt nanoparticles together while the laser sintering is able to sinter the inkjet-printed nanoparticles selectively as shown in Figure 2.7b. This process heats the printed nanoparticles at very high temperature with very little heating of the substrate, and consequently it requires shorter time than the thermal sintering process. The laser sintering is sometimes applied to the thermally sintered silver nanoparticles to increase the conductivity. A laser power, a scanning speed, and a radius of the laser focus are the most important parameters in this process. The laser power and scanning speed should be adjusted so that the printed nanoparticles absorb the majority of the heat from the laser. The radius of the laser focus determines the resolution of the sintering process. The reported laser-sintered silver nanoparticles have a resistivity of about 9.1 $\mu\Omega{\cdot}$cm which is about 5.7 times that of a bulk silver [36].

UV plasma sintering is the fastest sintering processes among the various sintering processes at room temperature without damaging substrate, and this method is briefly described in Figure 2.7c. The printed nanoparticles are exposed to an intense pulsed flash light that has a broad spectrum in visible range. This process takes only a few milliseconds, and the intense pulsed light is generated by an arc plasma phenomenon in the flash lamp. The UV sintered silver nano-particles have a resistivity of about 4 $\mu\Omega{\cdot}$cm–8 $\mu\Omega{\cdot}$cm, which is about 2.5–5 times that of bulk silver [34].

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2.3 Nanomaterials

2.3.1 Silver Nanoparticles

Among the numerous metal nanoparticle inks, the silver nanoparticle ink is one of the most widely used ink for the inkjet-printed conductor because of its relatively high conductivity and low sintering temperature compared to copper (Cu) and gold (Au) ink. The majority of printed nanoparticle inks are not conductive before the sintering process because the printed silver nanoparticles are coated with a polymer, which helps maintain the nanoparticles in ink form. The sintering process is necessary to make the printed nanoparticles conductive since this process burns off the polymers and impurities in the solvent. Moreover, the bonding strength of the printed silver traces with the substrate is increased, and the nanoparticles create a percolation channel for the electrons. The conductivity of the printed silver nanoparticles is affected by the numbers of printed layers, sintering temperature, and nanoparticle concentration of the ink.

The surface of deposited inkjet-printed silver nanoparticles is shown in Figure 2.8a, where a Veeco Atomic Force Microscope (AFM) has been utilized to scan the surface of an inkjet-printed sample [37]. The measured arithmetic average R_a is about 11.4 nm while the root mean squared R_q roughness is about 14.4 nm, as shown in Figure 2.8b. The mechanical and electrical properties of the inkjet printed nanosilver particles are thoroughly studied in [32, 38]. The pull-off breaking force of the printed silver nanoparticles is about 50 N, while Young's modulus of the thermally sintered silver trace is a function of the sintering temperature.

The water contents of the substrate affect on the adhesion strength of the printed traces to substrate rather than conductivity of the printed conductors [32]. The sheet resistances of the printed traces with different printed layers at different sintering temperature are measured using Cascade's four-point probe station as shown in Figure 2.9a. The sheet resistance decreases when the number of printed layers and the sintering temperature increase. It is because the high sintering temperature helps to form a good channel for electron flow and adding more layers increases the particle density, which results in an uniform solid structure. The conductivity σ can be extracted using the cross-section area A, the length l, and the resistance R of the printed patterns of the trace as shown in (2.2):

$$\sigma = \frac{l}{A} \cdot \frac{1}{R}. \tag{2.2}$$

The extracted conductivities are shown in Figure 2.9b. The maximum conductivity value of the inkjet-printed silver nanoparticles is $1.2107 \cdot 10^7$ S/m, which is about 18.75% of silver's bulk conductivity ($6.4 \cdot 10^7$ S/m). This value is almost the same as the conductivity of bulk iron ($1.04 \cdot 10^7$ S/m). It suggests that the inkjet-printed nanoparticles can be used for implementing microwave devices such as RFIDs and sensors.

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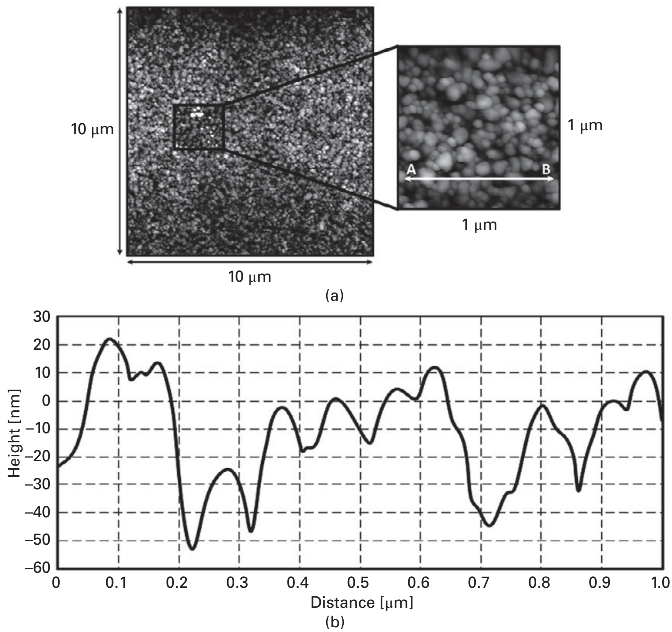

Figure 2.8 (a) The surface of the inkjet-printed nanosilver ink. (b) Cross section of the line AB. ©2013 IEEE. Reprinted, with permission from [37]

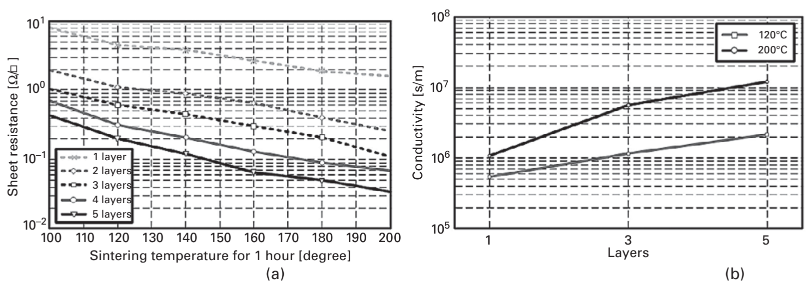

Figure 2.9 (a) Sheet resistance and sintering temperature and (b) extracted conductivity of the printed silver traces [36].

2.3.2 Inkjet-Printable Polymers

Polymers are usually flexible materials and form compounds of repeating structural units such as a plastic and a polyimide. Polymers have numerous applications for flexible electronics such as a spacer, an insulator, or a sensing material. The importance of polymers in electrical engineering has critically increased as the demands for flexible electronics increase. Recently, inkjet-printable polymer inks have been developed, and their performance is reported [39, 40, 41, 42]. Polymer-based dielectric inks utilizing SU-8 ($\epsilon_r = 4$) [43], polyvinylpyrrolidone (PVP) ($\epsilon_r = 3$) [44], and polymethyl methacrylate (PMMA) [45] inks are

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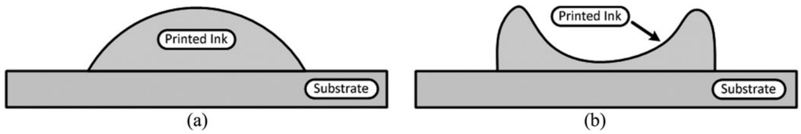

Figure 2.10 Inkjet-printed ink: (a) normal ink droplet and (b) coffee ring effect.

formulated for printing multilayer electronic components such as capacitors. Those polymers are widely used because they have a strong chemical resistance after the printing and sintering processes. The inkjet printing process of the polymer is similar to that of silver nanoparticles. Similarly with the sintering process, a cross-linking process is necessary after printing polymer inks in order to link polymer chains.

There are two types of cross-linking methods: heat and UV cross-linking. The heat cross-linking process consists of heating the printed polymers in the oven at a high temperature (usually higher than 180°C). The UV cross-linking process consists of exposing the printed polymers to a UV flash light.

SU-8 is a well-known photoresist and it is suitable for inkjet printing. The low-temperature UV cross-linking process is compatible with the inkjet-printed SU-8, and a low viscosity can be maintained with high polymer content by weight [46]. PVP is a polymer that is used as an insulation layer for field effect transistors (FETs), and inkjet-printed PVP has been reported in [40]. PVP ink has a higher viscosity at a low polymer concentration by weight in a solvent. PMMA is another commonly used polymer as a display device and a dielectric layer for transistors [47], and it has been demonstrated to be inkjet printable [45].

A coffee ring effect is a common problem of inkjet printing technology, especially in the inkjet printing of polymers as shown in Figure 2.10 [38]. This effect results from higher evaporation flux at edges of inkjet-printed patterns, and capillary force drives flow of liquid to the edges to compensate for the evaporation losses. The coffee ring effect can be suppressed by controlling evaporation of the solvent by combination of a low and high boiling solvent [48, 49]. In this way, the coffee ring effect can be suppressed and a homogeneous polymer film can be formed.

2.3.3 Nanocarbon-Based Materials (Graphene and Carbon Nanotubes – CNTs)

Carbon nanomaterials such as CNT and graphene are a very promising research area for electronic devices. Both CNT and graphene consist of latices of carbon atoms, but their geometries are different. CNT has a cylindrical geometry while graphene has a planar geometry. The diameter of a CNT is in nanometer scale, while the length of the tube is in the micrometer scale, which results in a very high length-to-diameter ratio. Both nanocarbon materials have unique electrical and mechanical properties. Especially graphene has lots of promising properties

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such as high electron mobility and thermal conductivity of 2,105 $cm^2V^{-1}s^{-1}$ and 5,103 $Wm^{-1}K^{-1}$, respectively. Both CNTs and graphene are used to implement gas sensors or electronic components such as transistors due to their high reactivity to gas molecules and electron mobility. Gas sensors utilize the impedance change of the CNTs and graphene at high frequency when they are exposed to gases such as a carbon dioxide (CO_2) or ammonia (NH_3) [50, 51, 52]. The selectivity of the nanocarbon-based sensors can be improved when the nanocarbon structures are functionalized to the specific gas molecules [53]. Also, electronic components such as diodes and transistors are reported utilizing CNTs and graphene [54, 55, 56], where nanocarbon materials are utilized as a channel of a Schottky diode [55] or a transistor [54, 56].

Nanogenerator technology is aiming to generate the green and sustainable energy for small electronic systems such as mobile and portable electronics. Many types of nanogenerators are reported and demonstrated using piezoelectric effects. Nanotechnology-based capacitors are also actively studied because capacitors are one of the most important electronic components in energy harvesting technology. The advances in inkjet-printing technology have led to significantly improved performance of nanotechnology-based inkjet-printed capacitors. Inkjet-printed capacitors don't require the sequence of photolithography and etching steps, although the capacitors are multilayer structure (metal–insulator–insulator, MIM) because inkjet-printing technology is a purely additive fabrication process. In the next section, nanowire-based nanogenerators utilizing piezoelectric and pyroelectric effect are introduced and nanotechnology-based capacitors for energy harvesting are presented.

2.4 Nanowire-Based Piezoelectric Nanogenerators

The piezoelectric effect is the generation of electron charges in certain solid materials such as crystals and ceramics when they experience mechanical stresses such as pressure or vibration, as shown in Figure 2.11. This effect was discovered by French physicists Paul-Jacques Curie and Pierre Curie in the 1880s, and it is widely used in numerous applications nowadays such as a sound detector, an electronic clock generator, and a voltage generator [57]. In 2006, the first zinc oxide (ZnO)-based nanowire nanogenerator has been reported using the piezoelectric effect [58]. The ZnO nanowire generated a voltage or a current when an AFM tip sweeps across the ZnO because of the coupling between the piezoelectric and semiconducting properties of the ZnO nanowire, as shown in Figure 2.12a. The proposed design generates an open-circuit voltage of 9 mV. In 2008, ZnO nanowire was bonded horizontally on a flexible substrate and an AC electric energy was generated by bending the substrate as shown in Figure 2.12b [59]. A single ZnO wire with a diameter of 4 μm and a length of 200 μm on flexible kapton substrate generated 20 mV–50 mV and 400 pA–750 pA respectively. As another example, an integrated ZnO nanowire-based nanogenerator has been

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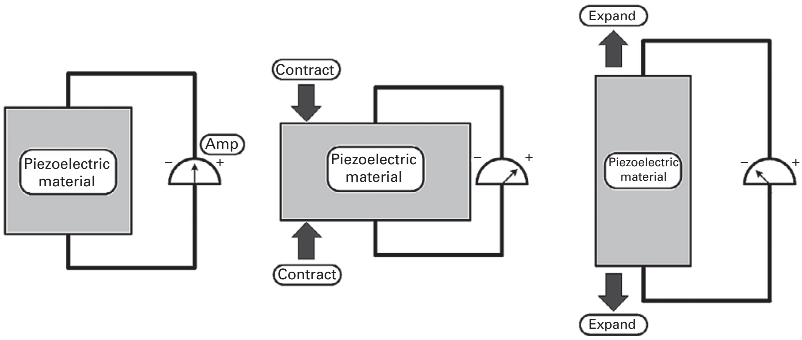

Figure 2.11 Piezoelectric effect.

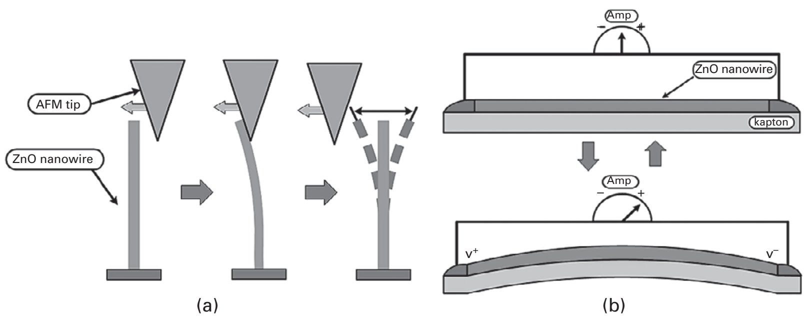

Figure 2.12 (a) The resonance vibration of a nanowire after being released by the AFM tip [58] and (b) bending of the substrate and a piezoelectric potential [59].

reported that obtained a peak open-circuit voltage of 37 V and a peak short-circuit current of 12 μA using an 1 cm^2 of nanowire array [60].

2.5 Nanotechnology-Based Capacitors

A capacitor is an electronic component that saves electrical energy. There are numerous types of capacitors such as ceramic, electrolytic, and mica capacitors on the market. A capacitance C of a capacitor is the ability of the capacitor to store an electric charge. Basically, a capacitor can be briefly modeled as a parallel plate capacitor, as shown in Figure 2.13. Its capacitance can be written as

$$C = \epsilon_0 \epsilon_r \frac{A}{D}, \tag{2.3}$$

where ϵ_0 is the vacuum permittivity ($\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m), ϵ_r is the dielectric constant (or relative permittivity), A is the area of the metal plate, and D is the

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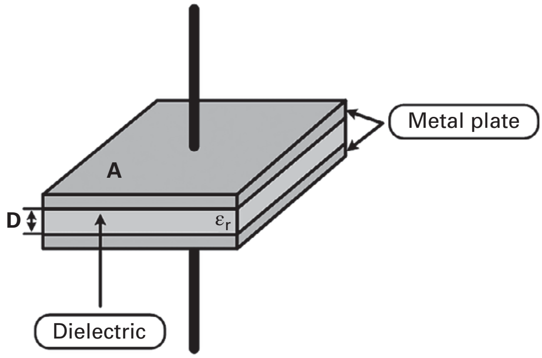

Figure 2.13 Parallel plate capacitor.

distance between the metal plates. The electrical energy (E) stored in a capacitor of capacitance C is equal to

$$E = \frac{1}{2}CV^2, \tag{2.4}$$

where V is a voltage across the capacitor and the capacitor can store electrical energy until it experiences breakdown that is determined by the dielectric material. The stored electrical energy can be used as a source like a battery until it releases all of the stored electrical energy.

Low-leakage capacitors have some important advantages over batteries, and consequently they are used to collect and store harvested ambient RF energy like, for example, that from TV and radio signals [15]. The number of charge–discharge cycles of capacitors is higher than that of batteries, and they present low internal thermal losses that are expressed by an equivalent series resistance (ESR). Therefore, capacitors can source or sink larger amounts of charge compared to a battery. Furthermore, capacitors are very stable because they are not volatile when exposed to harsh environments, and there is no degradation from shallow discharge like, for example, with nickel-cadmium (NiCAD) batteries. Plus, capacitors are more environmentally friendly because they don't utilize heavy metals and they do require a dedicated waste disposal process like batteries do.

The advances in nano- and inkjet printing technology enabled the implementation of inkjet-printed flexible capacitors [39, 40, 41, 42]. Polymer-based inks such as SU-8 photoresist and PVP are developed and inkjet-printed as an insulator layer between two metal plates. Those two polymers are widely used because they have strong chemical resistance after cross-linking.

Flexible inkjet-printed capacitors that have a self-resonant frequency (SRF) around 3 GHz have been demonstrated in [42]. Dielectric inks made from SU-8 and PVP were printed between silver nanoparticle ink electrodes on a flexible polyimide substrate. A photo of the PVP-based prototypes is shown in Figure 2.14. The area of the printed capacitors was 1.5 × 1.5 mm^2 and the

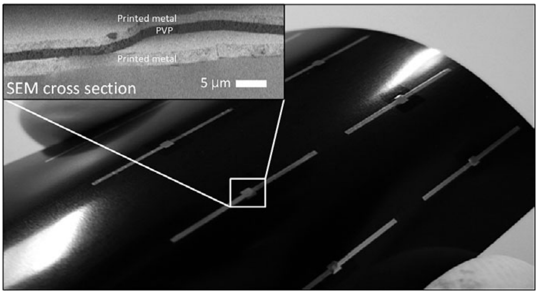

Figure 2.14 Inkjet-printed parallel plate capacitors on polyimide. ©2013 IEEE. Reprinted, with permission from [42]

thickness of the inkjet-printed SU-8 was 4 μm while that of the inkjet-printed PVP was 0.8 μm. The capacitance of the SU-8 based capacitor was about 20 pF and it had a self-resonance frequency around 3 GHz, while the capacitance of the PVP-based capacitor was about 50 pF for the same metal area with a self-resonance frequency of 1.9 GHz. The SU-8-based capacitor has a higher self-resonance frequency because of the larger thickness of the inkjet-printed polymer dielectric than that of the PVP-based capacitor. The maximum Q factor value was approximately 4 due to the thin metal layers ($\sim$ 1.5 μm) and the step-discontinuity at the edges of the dielectric.

2.6 Problems and Questions

1. What are the drop-on-demand (DOD) and continuous inkjet printing (CIJ) methods?

2. Why is a sintering process required after printing nanoparticle ink?

3. What are the thermal, laser, and UV plasma sintering processes?

4. What are the piezoelectric and pyroelectric effects?

5. Find the capacitance of the parallel plate capacitor shown in Figure 2.15 (do not consider any fringing effect and let $\epsilon_o = 8.8510^{-12}$ F/m). Find the stored energy when a voltage of 5 V is applied to this capacitor.

6. Find the conductivity (σ) of a printed line shown in Figure 2.16. The profile follows a curve defined by the equation $y = -0.0048x(x-1)$, the length (l) of the line is 10 mm, and the resistance (R) of the trace is 2.0 Ω.
7. Which one of the two surfaces (a) and (b) shown in Figure 2.17 is hydrophilic and which one is hydrophobic?
8. What is the coffee ring effect and how can we suppress this phenomenon?

https://doi.org/10.1017/9781139600255.003 Published online by Cambridge University Press

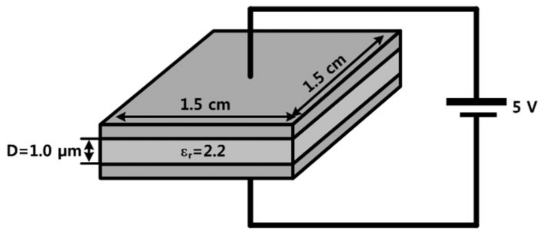

Figure 2.15 Parallel plate capacitor.

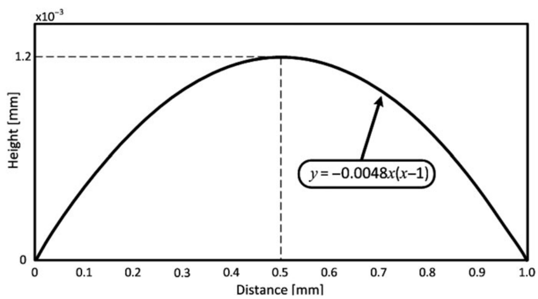

Figure 2.16 Cross-sectional profile of a printed line.

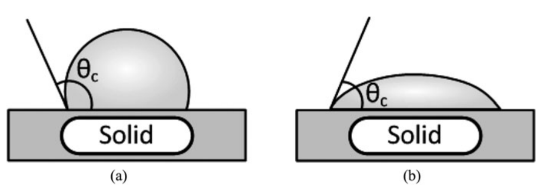

Figure 2.17 Hydrophylic and hydrophobic surfaces.

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