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Smart Manufacturing Technologies for Printed Electronics

Saleem Khan, Shawkat Ali and Amine Bermak

Abstract

Fabrication of electronic devices on different flexible substrates is an area of significant interest due to low cost, ease of fabrication, and manufacturing at ambient conditions over large areas. Over the time, a number of printing technologies have been developed to fabricate a wide range of electronic devices on nonconventional substrates according to the targeted applications. As an increasing interest of electronic industry in printed electronics, further expansion of printed technologies is expected in near future to meet the challenges of the field in terms of scalability, yield, and diversity and biocompatibility. This chapter presents a comprehensive review of various printing electronic technologies commonly used in the fabrication of electronic devices, circuits, and systems. The different printing techniques based on contact/noncontact approach of the printing tools with the target substrates have been explored. These techniques are assessed on the basis of ease of operation, printing resolutions, processability of materials, and ease of optimization of printed structures. The various technical challenges in printing techniques, their solutions with possible alternatives, and the potential research directions are highlighted. The latest developments in assembling various printing tools for enabling high speed and batch manufacturing through roll-to-roll systems are also explored.

Keywords: printed electronic technology, printed electronics, flexible electronics, large area electronics, roll to roll

1. Introduction

Printing electronics is a special type of manufacturing, where electronic components, circuits, and systems are developed on a wide variety of substrates in a similar fashion as drawing text and figures on a paper, textile, and handicrafts [1, 2]. The difference between normal printing and printed electronics is that in printed electronics, functional material is used as ink that exhibits functionalities of insulator, conductor, and semiconductor materials, which are essential for the electronic devices [3]. In most of the fabrication of electronic devices, these materials are sprayed over the substrate with the help of printing technology as low as few nanometers thick (thin film) and few micrometers width (pattern) [4, 5]. The combination of thin films and patterns can make any electronic device to be used in the electronic circuits [6]. Although the process seems simple, but the limitations posed by the various parameters such as uniformly dispersed and stable colloidal

solutions, substrate treatments, and above all, optimized printing recipes make the printing process much more challenging [7, 8]. The prominent challenges in printed electronics are material compatibility, substrate surface energy, viscosity of the materials' solution, and compatibility of dissimilar materials in multilayer structure, technology limitations in terms of film thickness, width, and height. As compared to conventional electronic manufacturing, printing technologies are revolutionizing the incredible field of flexible/bendable electronics by providing cost-effective routes for processing diverse electronic materials on nonplanar substrates at compatible temperatures [9–12]. Simplified processing steps, reduced materials' wastage, low-fabrication costs, and simple patterning techniques make printing technologies very attractive when compared to standard microfabrication in clean room processes. Attractive features of the printed electronics have allowed researchers to explore new avenues for material processing to develop electronic devices, circuits, and systems on such surfaces, which are difficult to realize with the conventional wafer-based fabrication techniques [13, 14]. In accordance with the electronic industry roadmap, the research in this field is slowly inching toward a merge of well-established microelectronics and the age-old printing technologies. Traditionally, prepatterned parts of a printing module are brought in conformal contact to the target flexible (nonflexible) substrates, resulting in the transfer of functional inks/solutions on target surfaces [15–21]. The mechanisms to transfer inks/solutions on target substrates divide printing technologies into two main streams, where the surfaces come in physical contact in one, and in the second approach, ink is deposited through noncontacting the surfaces. The different printing technologies based on contact/noncontact approach are summarized in **Figure 1**. In contact printing process, the patterned structures with inked surfaces are interfaced physically at controlled pressures with the target substrate.

In noncontact process, the solution is dispensed through the openings or nozzles, and structures are defined by moving the substrate holder in a preprogrammed pattern. The contact-based printing technologies consist of gravure printing, gravure-offset printing, screen printing, flexographic printing, microcontact printing, nanoimprint, and dry transfer printing. The prominent noncontact printing techniques include slot-die coating, electrohydrodynamics, and inkjet printing. The noncontact printing techniques have received greater attractions due to their distinct capabilities such as simplicity, affordability, speed, adaptability to the fabrication process, reduced material wastage, high resolution of patterns, and easy control by adjusting few process parameters [6, 21–27].

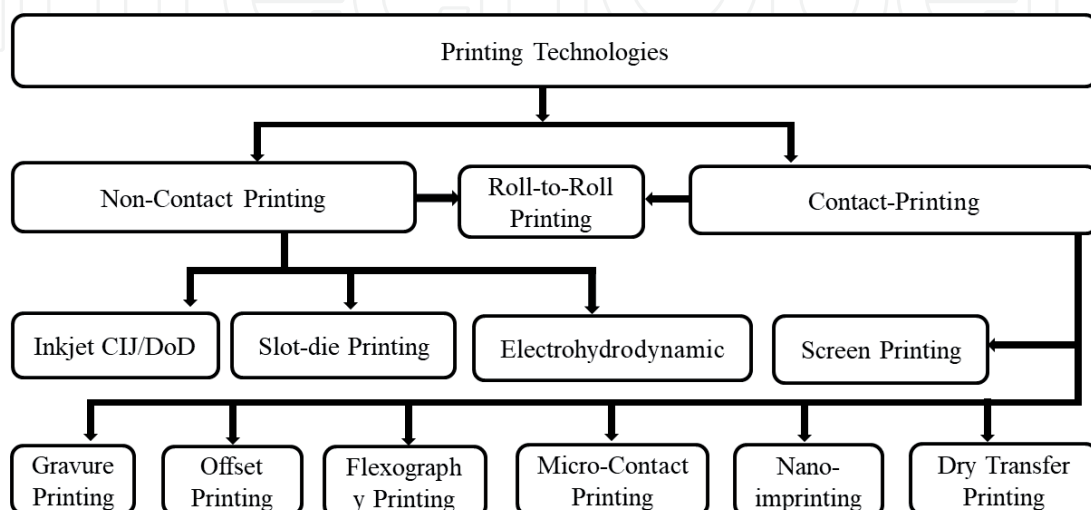


Figure 1.
The classification of common printing technologies.

2. Printed electronic technologies

The fascinating field of printed electronics is enabled by the rapid developments in printing technologies for precise deposition of functional inks in easy and cost-efficient way. The ultimate goal of developing the printed electronic technology is to revolutionize the device manufacturing and maximize the throughput by covering areas larger than wafer scales as well as increase the production through roll-to-roll processes. The attraction of printed electronic technology is that it can be executed at ambient conditions, thus enabling the fabrication of biocompatible electronics. With the help of printed electronic technologies and biocompatible materials, it is possible to fabricate electronic device on plastic substrates and even on human skin. The most commonly used and reliable printed electronic technologies are explained in the below sections.

2.1 Noncontact printing technologies

2.1.1 Inkjet material printer

Inkjet printing has gained a significant interest in recent years for processing solution-based nanomaterials and patterning on diverse substrates in a single step. Nanoparticles of the functional materials are mixed in compatible solvents to prepare printable ink. Besides, chemical-based solutions are also prepared and adjusted to the jetting parameters of the inkjet printing systems. Materials are ejected in micrometer-sized droplets through miniaturized nozzle printheads. Mainly two mechanisms for the actuation of inkjet nozzle head have been developed, i.e., thermal and piezoelectric. Droplets in very small diameters are ejected at each corresponding pulse and generated by either thermal or piezoelectric actuators used in the inkjet nozzle head. Schematic in **Figure 2** shows mechanism of droplet ejection through piezoelectric/thermal inkjet material printer. Typical nozzle diameters used for inkjet heads range from 10 to 150 μm and reservoir ink with a volume capacity of 3 ml.

The actuating element is either thermal or piezoelectric, in case of thermal actuator, a filament is embedded in the nozzle head, and upon the voltage application, a bubble is generated in the nozzle that pushes ink to the nozzle tip and generates droplets. In case of piezoelectric element, piezoelectric crystal is placed inside the nozzle, and upon the voltage application, piezoelectric crystal vibrates, and as a result, pressure exerts on the ink inside the nozzle and droplet generates. **Figure 2** shows the droplet actuation mechanism of inkjet material printer; ink is filled in the reservoir,

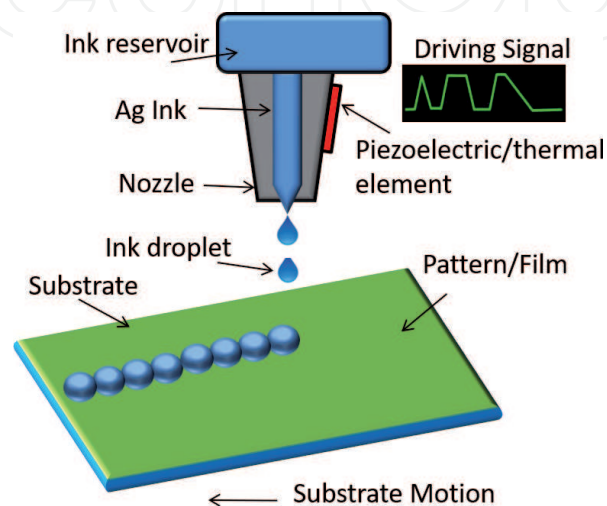


Figure 2.
Droplet's actuation mechanism of inkjet material printer.

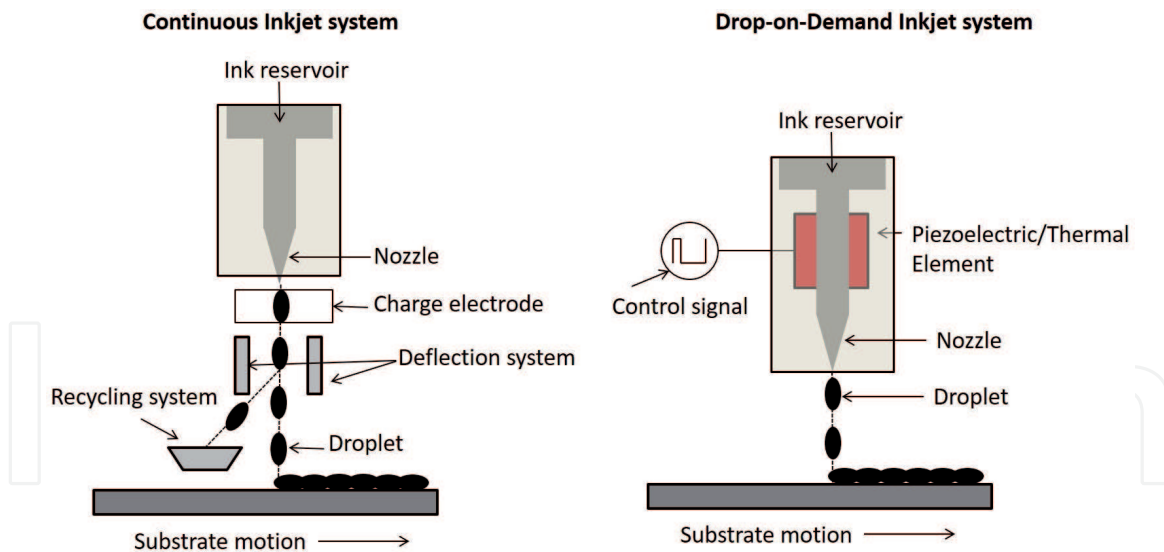


Figure 3.
Continuous and drop-on-demand inkjet systems.

and driving signal is applied to the actuating element that generates droplets according to the designed geometry. Inkjet printers are further divided into two types as continuous inkjet (CIJ) and drop on demand (DoD) systems. In continuous inkjet printer, the ink is stored in a reservoir supplied to the nozzles. A charging electrode is used to pull ink out of the nozzle and form a droplet. After droplet formation, deflection plates are used to direct the droplets on the targeted area on the substrate. This kind of printing system is used in the industry for printing on the packages such as expiry date commonly seen on boxes and drinks of liquor bottles. As the droplets are not controlled by any input signal, the CIJ system continuously produces droplets with certain frequency; hence, the unused droplets are directed to the recycling system, where the ink is stored and reused. Schematic diagram of the CIJ system is shown in **Figure 3**. On the other hand, DoD system is controlled by a digital input signal that comes from the design of the pattern. In DoD system, each droplet is generated on demand; hence, there is no need of deflection and charge electrodes. The substrate is kept perpendicular to the nozzle, and droplets sit on the substrate one by one. The substrate is moved separately through a control system synchronized with the droplet generation in order to make a pattern or thin film on the substrate. The number of nozzles in commercial inkjet printhead ranges from 1 to 128 with ink droplets as small as 1.0 pL.

2.1.2 Electrohydrodynamic (EHD) printing

Electrohydrodynamics (EHD) is another interesting type of inkjet printing systems used to deposit functional ink in the form of thin films as well as high-resolution patterns. It is consisted of high-speed camera, light source, nozzle and head, ink storage and supply mechanism, stage movement, and activity display unit as shown in **Figure 4**. Working principle of the EHD system is that the ink to be deposited on substrate is pumped from ink storage tank to nozzle with appropriate ink flow rate to make stable cone jet [28]. Positive voltage is supplied to the nozzle, and ground is connected with substrate holder. The induction of the surface charges on the pendant meniscus emerging at the nozzle outlet results in an electric stress over the ink surface. If the electric field and flow rate are in some operating range, then this will overcome the surface tension stress over the ink surface and results in deformation of the droplet at the orifice of the nozzle into a conical shape. While sweeping the high voltage from zero to a required value, different modes of the spray occur including dripping, unstable, stable, and multi jet mode as shown in **Figure 4**. For stable cone

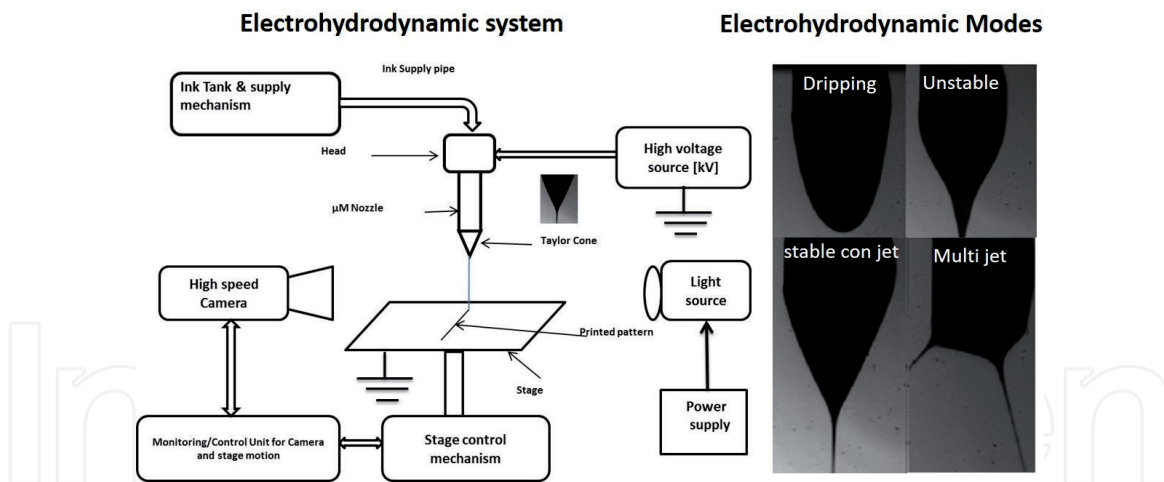


Figure 4. Electrohydrodynamic system and different modes of jetting ink.

jet, appropriate voltage and flow rate are required, which result in uniform spray. The tangential electric field acting on the surface of the ink cone a thin jet emanates at the cone apex which further breaks up into a number of small droplets under the effect of coulomb forces [29–31]. In the stable cone jet mode, EHD is ideal for printing and can be used for thin films or pattern deposition on various substrates. The cone jet expands at the substrate sides and makes spray as the distance between nozzle and substrate, i.e., standoff is increased [32]. This distance needs to be optimized to achieve stable cone jet desired for thin film deposition [5]. Whereas, during small standoff distance, cone jet is narrow and used for patterning [11, 21].

2.1.3 Aerosol jet printing

Aerosol jet printing is an interesting technique in noncontact printing, which has attracted a significant interest in the manufacturing of high-resolution patterning. A wide variety of materials including insulators, semiconductors, and metallic conductors are processed in viscosity ranges of 1–1000 cps [1, 33]. The aerosol process is driven by the gas flows where a mist of microdroplets is generated as a result of pneumatic atomization or through ultrasonication. The capability to process a wide variety of materials and to pattern higher resolutions, as high as 10 μm on diverse substrates, makes aerosol jet printing most attractive among other contact-less printing techniques. Aerosol jet printing is divided into two main categories, i.e., pneumatic and ultrasonic, as shown in **Figure 5**. Both the techniques are based on different operational procedures and are used targeting specific set of requirements

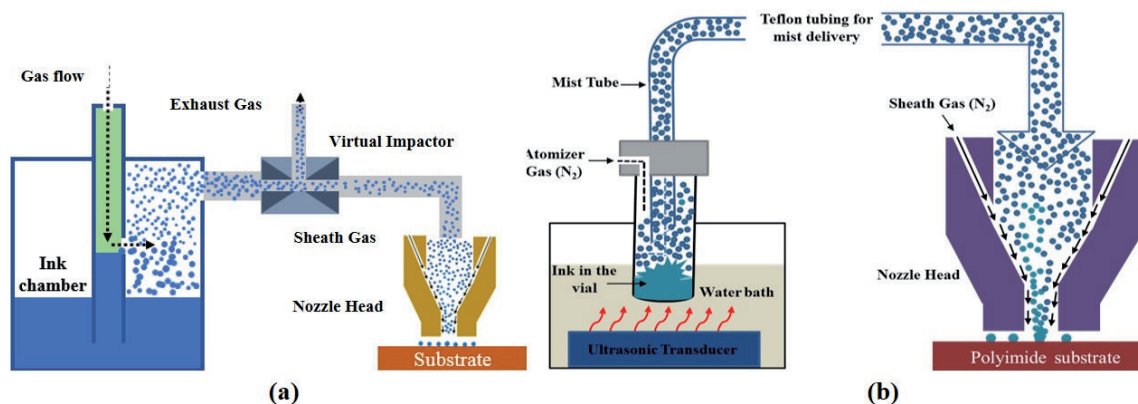


Figure 5. Schematics of (a) pneumatic and (b) ultrasonic aerosol jet printing systems.

and goals [1, 34]. For instance, in pneumatic atomizer, aerosol mist is generated by supplying pressurized air/gas inside a closed chamber containing the ink, which results in the generation of microdroplets close at the ink and air interface. The microdroplets ranging in $\leq 5 \mu\text{m}$ diameter are entrained in the supplied gas and are driven toward the nozzle printhead. Whereas in the second case, the ink contained in a delicate vial is subjected to ultrasonication, and microdroplets are generated as a result of ultrasonic pressure waves. The microdroplets in the size ranges of $\leq 5 \mu\text{m}$ are entrained in the atomizer gas, which is driven toward the nozzle printhead. Another accompanying gas, i.e., sheath gas flow along with the nozzle orifice size, leads to define the pattern size to be printed on the target substrate. Pneumatic atomizer requires more materials, i.e., more than 10 mL, and is usually used for wide area printing. On the other hand, ultrasonic aerosol system requires about 0.5 mL of solution and can be used for printing at very high-resolution patterns, i.e., down to 10 μm , for instance. The annular gas flow reduces the size of the mist inside the carrier tube, which is accompanied by the sheath gas at the nozzle printhead. This sheath gas flow further converges the aerosol stream and reaches the surface at higher impact. The aerosol mist is ejected in the form of an intact jet, and the stage speed adjusted in such a way that the desired patterns are deposited in a continuous fashion.

2.1.4 Slot-die coater

Slot die is a special deposition technique, where the material is printed on a moving substrate and installed directly on a roll-to-roll system, as shown in **Figure 6**. The solution is directly dispensed off the slot-die printhead in a controlled manner. The slot-die coating is executed in two steps, where a uniform and stable flow of the coated material is achieved in the first phase. In the second phase, other processing parameters such as standoff distance between the slot-die opening and the target substrate speed of the rolling substrate and sintering conditions inline to promote a multilayer structure coating capability [35, 36]. System is connected to a continuous flow of materials into a temporary reservoir at the printhead and applied at appropriate amount on the rolling substrate as shown in **Figure 6**. This type of coating technique is ideal for large area deposition, such as solar cells and light emitting diodes, where high-resolution patterning is not required. Besides optimizing the rheological properties of the ink/solution, system specific parameters such as speed of the roll play a significant role in establishing the process in safe and stable operating mode. The coating process can also be affected by various defects such as uncontrolled

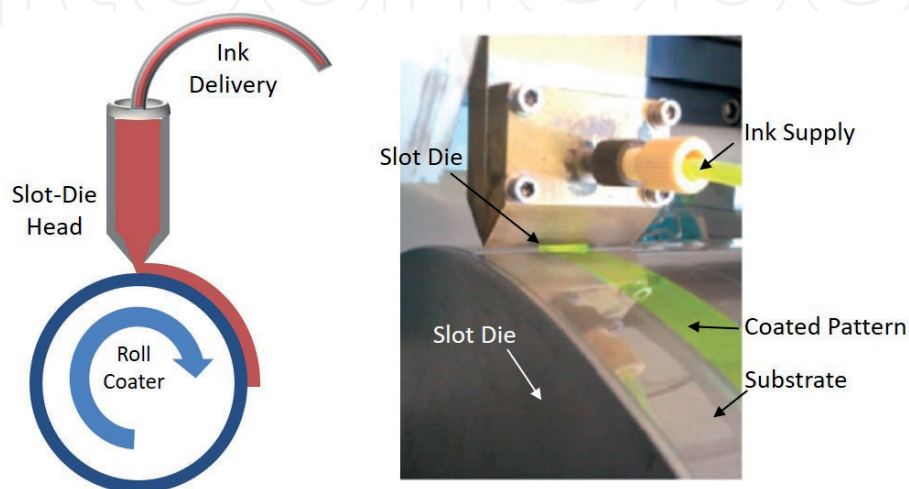


Figure 6.
Slot-die coater schematic and slot-die coater in operation diagram.

meniscus, resulting in dripping out of the solution, air bubbles entrap, and ribbing. Proper control at the start-up and shut-down cycles is highly demanding, as minor deviations could lead to deposition of the materials at unwanted positions on the substrate. Proper tuning of the material and process parameters is needed; otherwise, it would result in the wastage of the coating solution and also compromising on the shape of the patterns. This could also significantly affect the thin film quality and result in deviating from device real dimensions [17, 37, 38].

Materials' properties such as viscosity and surface tension along with the system parameters, i.e., slot size and gap, standoff distance, and decreased dip lip length, reduce the dimension of the printing jet. Proper adjustment of these parameters leads to shortening the trial time required to reach the steady-state conditions [38]. Despite the high-speed coating capabilities, the challenges involved in reaching stable operating conditions make the process less attractive than other printing systems and are adopted seldomly in the manufacturing of printed electronic devices.

2.2 Contact-based printing technologies

In contact-based printing techniques, prepatterned structures of the printing tools are physically brought in conformal contact to the target substrate. Similarly, micron-scale dispensing nozzles are also used for high-resolution patterning by contacting the target surface in a similar fashion as drawing. Almost all the techniques used in contact-based printing are precise and rapid; therefore, these techniques are used by the industry for the mass productions.

2.2.1 Screen printing

Screen printing remains the top priority when it comes to rapid, fast, and large area manufacturing. The technology has been using from the early developmental stages of microelectronic industry, especially for printing electrodes and interconnections. Screen printing is advantageous when compared to other printing systems as it is more versatile, and processing is simple, capable of reproducing similar structures in large batches with minimum dimensional variations. Results are duplicated by repeating the similar printing parameters and optimized solution pastes [12, 39].

Screen printing process can be established following the two different assemblies, i.e., in flatbed and installing a rotating surface [23, 40]. Flatbed systems are usually employed for low-throughput production and lab-level research activities. Whereas rotary systems are installed on a fast production platforms such as R2R, where all the solution and printing parameters are optimized first and applied afterward for high-speed production of devices. **Figure 7** shows schematics of flatbed and rotary screen printing systems. The system setup is simple, which contains screen, squeegee, press bed, and substrates placed on the movable stage. In flatbed systems, the printable solution is applied on the screen, and a squeegee is used to coat the ink all the way over the structured mesh on the stencil. A controlled pressure ensures the dispensing of ink through the holes in the mesh, and the squeegee recollects the extra ink for the consequent layers. Flatbed screen printers are ideal for the optimization of the process and structures on a small-scale lab level research. For high-speed production, a folded screen with squeegee inside the rotating and ink filled in a tube are applied on a continuously rotating system. However, the screens for rotary screen systems are expansive and challenging to clean in case of material clogging [23, 41]. The print quality in both the approaches is affected greatly by the similar set of parameters such as solution viscosity, print speed, angle and geometry of the squeegee, standoff between screen and substrate, and mesh size [42–44]. Material properties are tuned separately to have the right viscosities and surface tension for complete dispensing through the screens.

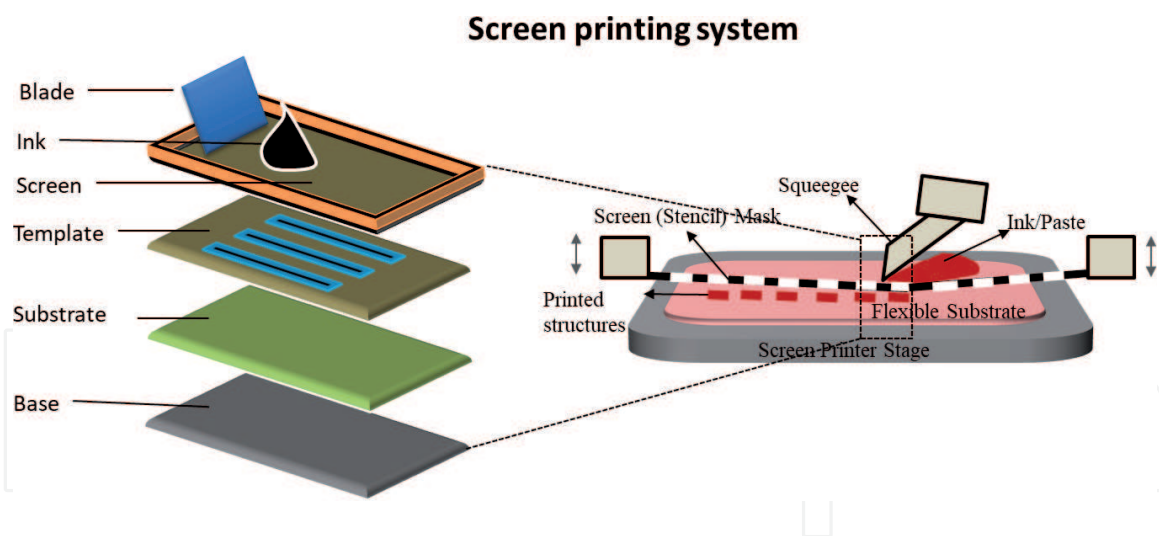


Figure 7.
Flatbed and rotary screen printing systems.

Viscosity of the pastes used with screen printing is kept higher than other conventional printing technologies in order to avoid undesired flow through the screen masks [27, 45]. Screen printing is used for both printing patterned structures and coating larger areas [46]. Pattern resolution in the ranges of 80–100 μm can be achieved after proper tuning the solution properties and optimizing the screen printing parameters. A good compromise between the surface energies of the substrate and the surface tension of the ink is desired to achieve higher resolutions [45, 47, 48]. The type, material, and strength of mesh used in the screen also contribute to the high-resolution patterning through screen printing. Different materials such as nylon, polyester, and stainless steel are used in the screen mesh. For printing stability during mass production, a screen made of stainless steel mesh with three times more in strength than conventional stainless steel mesh has also been developed [43, 49]. The possibility of printing relatively thick layers could enable printing of low-resistance structures, also with conducting polymers, by compensating the high-volume resistivity with a thicker layer [6].

Screen printing has been successfully used for demonstrating various fabricated devices. For instance, an all-screen printing has been adopted for developing thin film transistors (TFTs) [50–52]. OLED devices are also presented by exploring the different process parameters, such as viscosity and mesh count, and their effect on the printed structures [43]. An advanced screen-printing approach is adopted to develop multilayer high-density flexible electronic circuits connected through holes with embedded passive and optical devices [42]. Printing interconnect lines between discrete devices on a same substrate or tape out for data reading are usually printed with screen printing. Screen printed electrical interconnects for temperature sensor on PET substrate are reported by Shi et al. [48]. Screen printing does not require high-capital investment like many other manufacturing techniques, and setup can be established at lower installation costs. A high-speed production line can be established by assembling rotary printing setup along with supplemental methods such as inkjet, vapor deposition, and laser/flash photonic sintering tools [49, 53]. Although the advantages and attractions using screen printing are higher, there are also some challenges that need to be addressed. Printing multiple layered structures, higher wet thicknesses, and exposure of the ink to ambient environment while remaining on the screen bed present more risks for developing repeatable and reliable electronic devices. The rapid evaporation of solvents and surfactants from the printing paste, when the system is idle and ink applied on the screen lead to blockage of the screen masks [54]. Therefore, proper tuning of the material properties and developing reliable procedures are highly desired for developing a repeatable printing recipe.

2.2.2 Gravure printing

Gravure printing is the most prominent and representative technique in the contact-based printing category. Structures are transferred through a prepatterned surface, where the solvent is deposited on the target surface upon contacting. The engraved structures are designed in cylindrical shaped objects, and substrate controlled through moving rolls of the system represents a typical R2R process. The gravure printing tools consist of a large cylinder electroplated with copper and engraved with microcells, as shown in **Figure 8**. The microcells are engraved by either using electromechanical means or using laser [23, 26, 41, 55]. The physical contact between the printing surface and the substrate leads to wear and tear of the engraved structure; therefore, chrome electroplating is performed for protecting it from deterioration. The size of engraved microcells is responsible for ink pickup from the reservoir lying beneath the cylinder or filled with dispensing nozzles from the top. The extra ink is removed from the surface using a doctor blade to avoid cross contamination or unwanted deposition of ink on the substrate.

Surface properties of the substrate and rheological properties of ink are tuned to promote the efficient deposition. Capillary action of the ink plays a significant role in complete transfer of the ink from microcells of the engraved cylinder to the substrate. Pressure on the impression cylinder is also properly controlled to expedite the ink transfer and to reduce the deterioration of contacting surfaces. Width and depth ratio of the microcells in the engraved cylinder also plays a significant role in manipulating the ink transfer [41]. Viscosity and surface tension of the desired material solution have to be in acceptable ranges to prevent the bleeding out of the solution from the microcells. The optimal viscosities help in rapid prototyping by increasing the printing speed and allow full emptying of the ink from engraved microcells [56].

An advanced version of gravure printing, i.e., gravure offset uses an extra elastic blanket to avoid potential risks occurring from the deteriorations of the contacting surfaces, as shown in **Figure 8**. The elastic blanket serves as an intermediate step between the contacting surfaces, where the ink from engraved microcells is picked up by the blanket and transferred finally on the target substrate. This avoids the direct interface between the patterned cylinder and the substrate. Few of the printing parameters affecting significantly the print quality are speed, pressure, and blanket's dimensions plus thickness. Surface properties of the blanket and its thickness combined with the speed are more dominant factors that control and enhance the efficient transfer of the ink [16, 41, 57]. The limited time of contact and

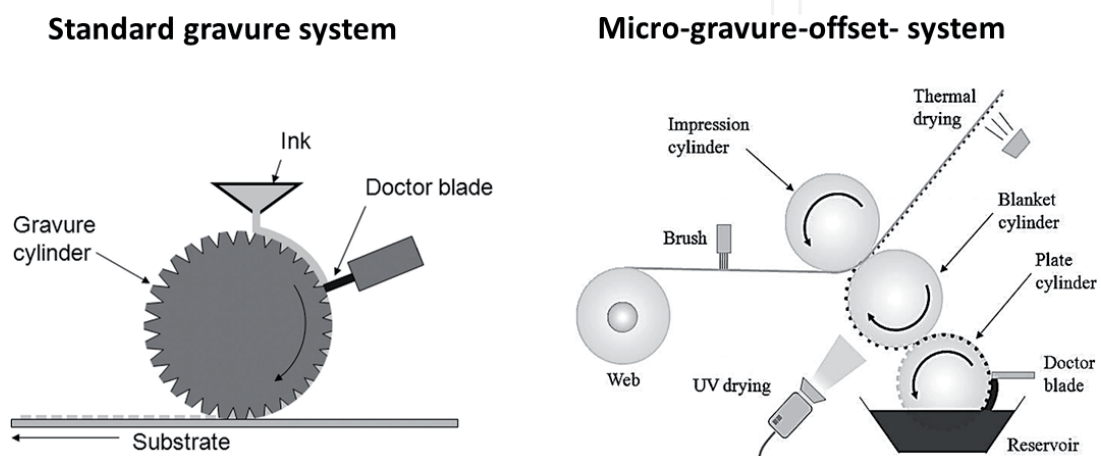


Figure 8.
Schematic of a typical standard and microgravure-offset printing process.

higher speed also enable high-resolution patterning on the substrate and increase reliability of the system. Reliability of gravure offset is more critical for assembling in a high-speed production line of printed electronics on rollable substrates [58]. Combinations of various manipulating forces such as adhesive force between the blanket and the ink, cohesive force within the ink when on the blanket, adhesive force between the ink and the gravure, and adhesive force between the ink and the target substrate are of particular importance to control and tune for efficient transfer of ink. A complete dispensation of the ink is desired as a minor mismatch or open hole within the pickup ink can lead to incomplete printing of the structures [16, 59]. Speed of the roll is also a main contributing factor to optimize for complete transfer of the ink, and a uniform impression pressure in suitable ranges would increase the uniformity of the print edges and product yield. Despite the advantages offered by using an intermediate medium of transfer, gravure offset also poses some serious challenges. For instance, the lifespan of the blanket is of serious concern, as continuous absorbance of the ink leads to saturation of the surface and needs to be changed quite often. Prolonged use of the blanket greatly affects the resolution of the printed patterns on target substrates as it reduces temporarily the ink viscosity, which results in spread out of the ink during the setting process [60]. Therefore, a proper and timely maintenance of the printing tools, especially the blanket, is needed to avoid undesired printing structures.

2.2.3 Flexographic printing

Flexographic printing ensures high-speed printing and produces high-resolution patterned structures as compared to gravure and gravure-offset printing approaches [23]. A rubber- or polymer-based plate with elevated patterns on the surface and developed through photolithography is used in flexographic printing. The plate is attached to the printing cylinder as shown in **Figure 9**. A wide variety of ink including but not limited to solvent-based, wafer-based, UV-curable inks and two parts chemically curing inks, etc. can be processed to pattern high-resolution structures on target surfaces [18, 61, 62]. The Anilox cylinder picks up the ink from the reservoir, and upon contacting the inked areas with the plate cylinder, it transfers the ink and prints on the running substrate between plate and impression cylinders as shown in **Figure 9**. Transfer of the ink is more efficient in flexographic printing and results in very thin patterns with sharper edges. Amount of ink pick up is controlled predominantly by the Anilox roll, where the size and frequency of the engraved cells

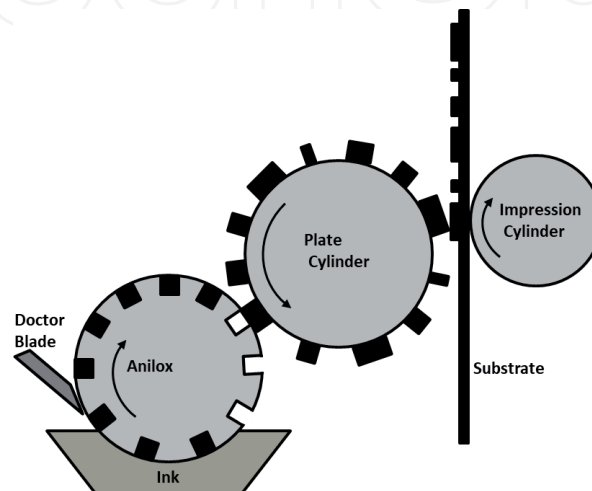


Figure 9.
Flexographic printing schematic diagram.

are responsible indirectly. A proper balance between the solution properties such as nanoparticles mixing ratios plus the carrier fluids is essentially required for filling the Anilox engraved cells. Relatively higher-solution concentrations are required within the specific range of viscosities to achieve good resolution patterns [18, 61, 62]. Typical resolution obtained with flexographic printing is in the range of 50–100 μm ; however, further higher resolutions down to ~ 20 μm could be made possible by proper tuning the solution properties and process the parameters [18, 61, 62]. Film quality printed with flexography is uniform as compared to other competitive printing technologies [60]. Film instability and dewetting of the printing plates cause many defects such as open lines, overlapped lines, and edge waviness. Controlling the load pressure and cell aspect ratio is very critically important to avoid these issues, especially in the case of targeting high-resolution printing and high-end devices. Maintenance plus observation of the engraved cells is very important, as the blockade or erosion of any of the cells could lead to discontinuous printed patterns. An acceptable margin in terms of resolution needs to be allowed, as the pattern dimensions could vary as a result of pressure from impression cylinder on the flexible or polymer plate [18, 27, 61–63]. An optimum range of width and thickness is needed for the printed patterns to decrease the ohmic losses and also increase the efficiency of the printed devices [47]. For thick film deposition through flexographic, several printing passes with similar parameters are required, which also minimize sheet resistance. Repeating the same procedure needs proper alignment of the equipment for subsequent layers, which adds to the complexities of the system [64]. The current technology limits the highly desirable features such as high-switching speed and reduced supply voltage that are needed for many applications. These limitations result in degraded device parameters such as charge-carrier mobility, parasitic capacitances, and overlay precision registration accuracy [65]. Challenges to overcome for fine patterning are surface irregularities and pores, nonuniform films, ragged lines, and nonavailability of suitable functional materials [66].

2.2.4 Microcontact printing (μCP)

Microcontact printing is a special type of contact-based printing approach, where an inked surface is brought in conformal contact and transfers the patterns on target surface. The contact is controlled through micromanipulation, and surface conditions are set to release and receive the ink consequently. A conformal contact of prepatterned elastomeric stamp with precise control and alignment to the target surface on micron scale is key requirement for successful transfer of the structures. A master mold is developed using conventional microfabrication or photolithography techniques, and multiple copies of the stamp with desired structures are reproduced. A moldable and elastomeric material is usually used to develop the stamp, which can easily be casted into the master mold and delaminated without causing any degradation of the microscale structures on stamp surface [3, 19, 67, 68]. Poly(dimethylsiloxane) (PDMS) is the frequently used elastomer due to its extraordinary properties as compared to other elastomers such as polyurethanes, polyimides, and cross-linked Novolac resin. PDMS has few distinguishing properties such as conformability to larger areas, deformable to mount on nonplanar surfaces, elasticity for easy release, isotropic, and optically transparent. Low-surface free energy, chemical inertness, and durability for multiple uses make PDMS an attractive candidate for the purpose of using it as a stamp [19, 68]. Microcontact is an effective rapid prototyping technique for preparing the substrates and patterning a wide range of materials that are sensitive to light and chemical etchants. The lower surface energies offered by PDMS stamp due to elasticity of siloxane chain and the lower intermolecular forces between the methyl groups promote the peeling

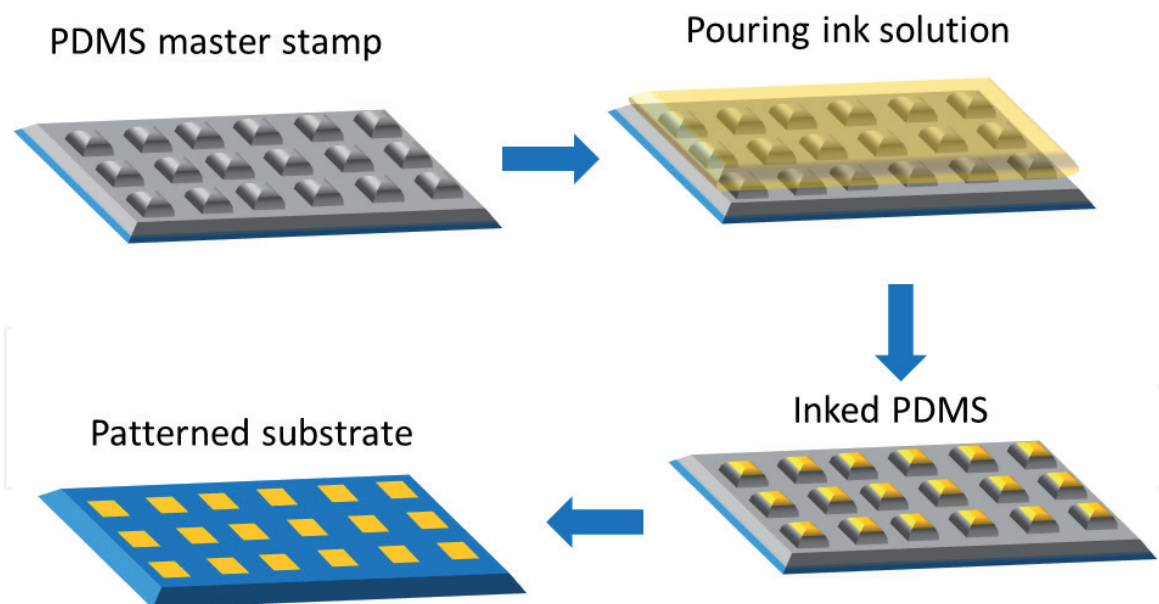


Figure 10.
Microcontact printing (μ CP) steps during processing.

and stamping capabilities, which are ideal for microcontact printing. Surface energies of the stamp and target surface play a significant role in efficient transfer of the ink. For instance, a higher energy of PDMS stamp is desired for the pickup of ink from the donating surface, whereas higher energy than the PDMS stamp is desired for the receiving surface to complete detachment of the ink. To avoid collapsing of the stamp during peeling or capillary action during inking, a specific ratio of the height to width of the features on the stamp is required [69]. **Figure 10** shows schematic of the process flow of typical microcontact printing approach.

Robustness of the stamp by having sufficient flexibility and mechanical strength for maintaining the dimensional integrity of the printable structures is of great importance. Elastomeric properties of the stamp material enhance the efficient ink delivery by providing a good interface between stamp, ink, and target substrate. Submicron scale is challenging to reach as due to the elastomeric nature of stamp, it tends to collapse, and noncontact areas of the stamp also interface with the substrate leading to uneven printing. Besides the printing tools and processing condition, chemical composition of the ink also contributes to the microcontact process. For instance, polar molecules are challenging to print with stamp because of the hydrophobicity of the PDMS. Therefore, treatment at right conditions of the PDMS stamp is central for stamping such type of materials [19]. Similar challenge faced by the flexographic technique is microcontact printing, as diffusion of molecules in the unpatterned areas of the stamp broadens the feature size and thus results in unwanted printing or stamping of the materials besides the intended structures [27, 70, 71]. Repeated use of the same stamp results in swelling due to the absorption of the ink and results in deterioration of the micron-scale structures on the stamp. A proper check and observation of the stamp are needed because the continuous use can cause pairing, buckling, or roof collapse of the microstructured patterns upon physical contact. Therefore, for reproducing the similar structures on target substrate, full operating conditions need to be explored considering especially the applied pressure, peeling the stamp from master mold, polarity of the molecules, and so on to guarantee uniform printing [69–71].

2.2.5 Nanoimprinting (NI)

Nanoimprinting, as the name suggests, is used to produce structures at nanoscale by using an imprint approach. NI uses mechanical and physical deformation of wet

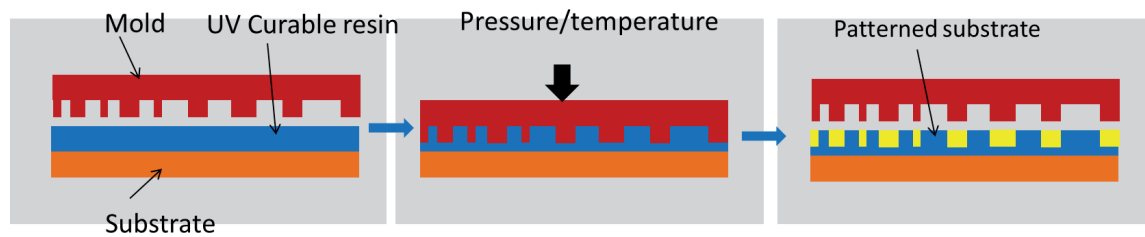


Figure 11.
Nanoimprint steps for patterning the substrate.

layers through molding accompanied by different thermal procedures. The NI operating principles are quite straight forward, as shown in **Figure 11**. As against micro-contact printing, NI uses a mold having nanoscale structures developed through standard clean room processes and is pressed against a uniformly coated wet surface at controlled pressure and temperature. A thin-residual layer of polymeric material is intentionally left underneath the mold protrusions and acts as a soft cushioning layer that prevents direct impact of the hard mold on the substrate and effectively protects the delicate nano-scale features on the mold surface [72]. Resist filling and demold characteristics are the two primary and critical processing steps affecting the print quality and throughput. Controlling the pressure precisely is central during the demolding process, which helps in maintaining the imprinted patterns at the desired dimensions [15]. Various approaches are adopted for executing NI process such as thermal, ultraviolet (UV), step and flash, and roller imprinting. They are all selected on the basis of type of material and processing conditions. In UV-NI process, transparent medium is required for allowing the UV light to penetrate through and in-situ sintering of the imprinted structures. UV-IN is thus considered the most reliable and robust approach among the practiced NI procedures. Common materials for the molding in UV-IN are quartz and silica, which are molded by using very high resolution electron beam lithography techniques [72–75].

Compared to the quartz and mechanically rigid, polymer-based molds are advantageous as they can replicate nanostructures over larger areas. Besides, the material cost is lower, and it can be used to develop manufacturing platform at depreciated costs. The mechanical molding makes the process a bit challenging embarking into new challenges compared to the traditional manufacturing processes [76]. The spatial confinement of solution-based materials in nanoscale ranges gives rise to drastic changes in the physical, electrical, and chemical properties as compared to the patterned structures in micro or macrostructures. NI offers several advantages such as very high resolution patterning, high pattern transfer fidelity, 3D patterning, covering large areas, reduced fabrication steps, high throughput, and lower processing cost. However, the challenges faced by NI process overshadow the attractions and keep it restricted for a special case of uses. The overlay alignment, template fabrication, defect control, yield, and seeking a suitable application with a good payback are few of the critical challenges faced by NI process [15, 22, 72, 75, 77]. Probability of defect density is higher, and the mechanical and physical inability to withstand the uneven pressures on the molding masks lead to the lateral and vertical collapse of the nanostructures. This adds to the reproducing cast, and attaining repeatable structures with similar dimensions are challenging due to the less margin in dimensional variability. The thermal-based NI involves in-situ heating while applying the mask on the wet film, and slight variations in the temperature or thermal mismatch between the mask and the printed materials could lead to deterioration of the pattern structures on the mask. Time required, i.e., 10–15 min per replication for heating and cooling cycles, is longer than other soft printing techniques [74]. The thermal budget of about 125°C is challenging for some of the plastic substrates with lower glass transition temperature, which can create dimensional instabilities. Several electronic devices

have been presented by different research groups following the NI manufacturing. The NI process is ideal for a single-layer structure, as perfect alignment at nanoscale on multilayer devices is a challenging task. As a final goal to transfer the NI process on a R2R manufacturing, introducing multilayer steps and misalignment of the stamp during the imprint needs to be taken care of [69, 70, 78–80].

2.2.6 *Transfer printing*

Transfer printing is relatively a new technique to fabricate flexible electronics through physical transfer of prefabricated structures using a stamp [81]. Microstructures in the shape of wires or membranes are developed using standard photolithography processes in clean room, etched underway, and then used a stamp to pick and stamp on a target surface. Transfer printing can be executed in two ways such as direct transfer and stamp-assisted transfer. In direct transfer, an adhesive coating is performed on the receiving surface, and the donor wafer is directly contacted with it. After releasing, the structures are transferred to flipped surfaces on the target surface. Whereas, stamp-assisted transfer is completed in two steps: in first, the microstructures from donor substrate are picked up the stamp, and the stamp is contacted with the target substrate, thus transferring the structures with the top processed surface facing upward. The elastomeric stamp usually developed by using a PDMS is used, where the viscoelastic properties of the stamp are exploited to detach the fabricated structures from donor substrates and place them deterministically on a secondary substrate [82–86]. This technique is ideal for developing high-speed electronic devices on unconventional substrates, by merging both organic- and inorganic-based materials. The heterogeneous integration of these dissimilar materials helps in reducing the cost and maintaining the reliability of developed electronic circuits and systems [87]. The lower cost comes from the large area processing units such as inkjet printing for the electrodes and interconnections as well as insulator layers, where the high-mobility semiconductor layers are integrated into discrete circuit or into full circuit through stamp-assisted transfer technology. This is an effective approach toward manufacturing of high-end devices on larger areas as the state-of-the-art processing of electronic grade silicon, and other compound semiconductors in clean rooms constitute high level of purity, surface smoothness, control over crystallinity, doping levels, and types, resulting in higher carrier mobilities.

The structures are developed and finished in clean room processes and under-etched afterward to release and be ready for the PDMS transfer. **Figure 12** shows schematics of the processing steps involved in transfer printing approach. Here, the structures are shown in the shape of wires, which are released from the underlying layers using the relevant etchants. Tethered points are designed as per the dimensional requirements and are sufficient enough to keep intact the released structures with the donor wafer before contacting the PDMS stamp. The dimension of tethered points is essential and useful for efficient transfer, especially for structures with dimensions in the micron scale. The conformal contact of soft elastomeric stamp having surface activated temporarily through oxygen plasma with the microwires or microribbons guarantees the efficient pickup. The wires attach to the stamp surface and, when peeled back, retrieve the microstructures with fast speed, enhancing the kinetic control of adhesion [88]. The rate-dependent adhesion and printing of the solid structures with high-peel velocity (typically 10 cm/s) and low-stamping velocity (~1 mm/s), respectively, have been investigated [89]. The mechanics of kinetic dependence of switching of adhesion between the microstructures and the stamp has its origin in the viscoelastic response of the elastomeric materials, i.e., PDMS. Adhesiveless stamping like this is very valuable for wafer-based microstructure printing to operate it from moderate to high temperatures [82].

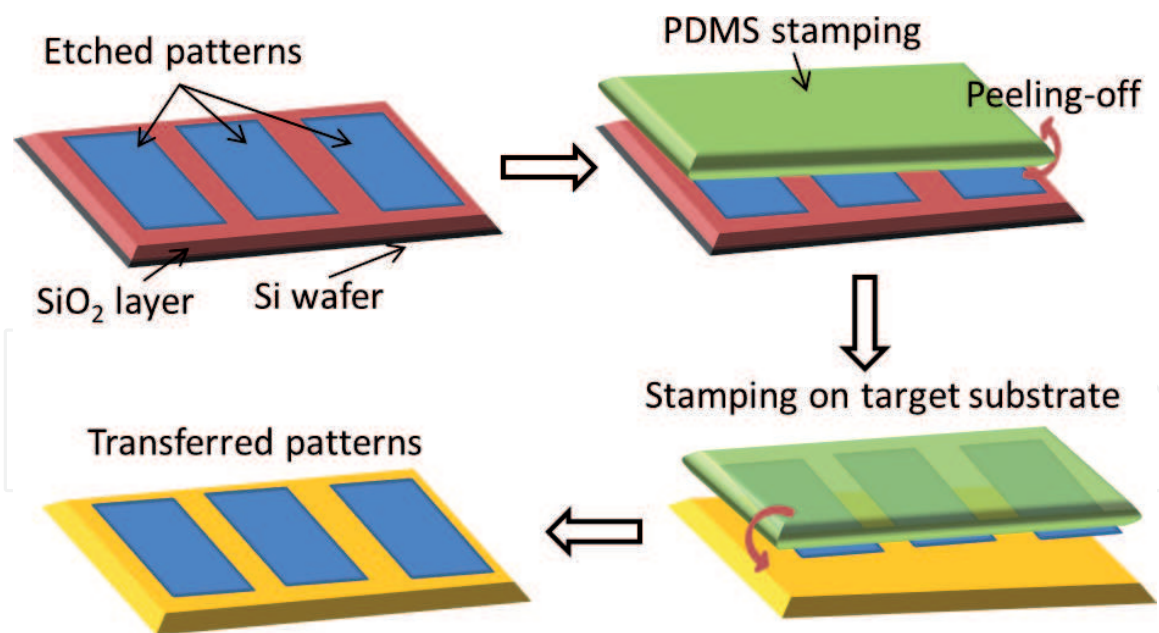


Figure 12. Conformal contact of polymeric stamp with the Si patterns, pickup of patterns by peeling off the stamp, and patterns transferred to final substrate.

3. Mass production perspective

Developing printing technologies is motivated by the development of fast and efficient production line by assembling different manufacturing units, substrate treatments, and sintering after fabrication, as shown in **Figure 13**. The highly optimized techniques on lab level are merged together to develop a single manufacturing platform. The scope of such developments is rendered from the high-speed text printing-based technology. A similar approach is foreseen to establish for batch manufacturing of electronic components and systems on larger areas as much higher speeds. Printing processes matured at lab level need to be transferred to large-scale fast production lines with the same level of performance. However, assembling different printing techniques into a single production platform inline is a challenging task, as all the processing parameters and conditions need to be properly tuned and need to be in close ranges of the process conditions, especially when the substrate is moving at higher speeds as 5–50 m/min. Therefore, investigation of the optimal and matching processing conditions is desired for the new arrangement, which is not at all obvious, especially when considering that there are boundary conditions

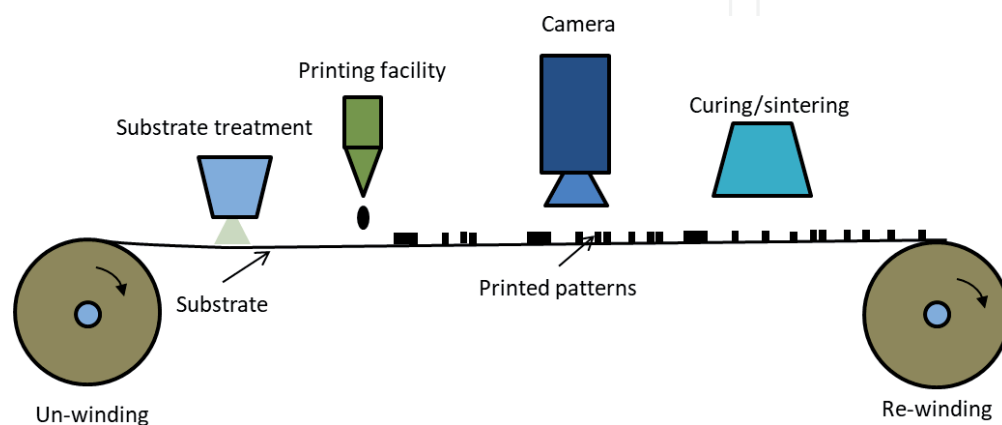


Figure 13. Schematic illustration of typical roll-to-roll system where different deposition, patterning, and sintering modules are installed.

(i.e., materials, solvents, multilayer processing, overlay registration accuracy, drying temperature, speed, etc.) involved in fast R2R processing [20, 23, 53, 90].

R2R as a commonly shared platform has the potential for a continuous and high-throughput process for deposition of diverse materials on large substrate rolls (often called “web”) [53, 90]. Besides the instrumentation and hardware for control system, R2R line is equipped with several rollers over which the web (flexible substrates) passes with controlled tension. As described in Section 3, these webs are the backbone of a R2R system and should be accurately controlled during passage through different rollers and processing sections.

4. 3D packaging

Packaging is an important step during electronic fabrication, which enables user to interface with electronic devices, circuits, and systems. In printed electronics, devices are relatively large size as compared to conventional technologies and easy to handle. However, they need packaging to protect from the ambient environment such as humidity, light, and temperature.

On the other hand, the device itself needs protection from the user touches as it can damage the thin films and patterns. 3D printing (also called additive manufacturing) is a manufacturing technology, which is based on imposing the material layers to create the 3D objects. A 3D object is fabricated through melting filament material with controlled temperature and flow rate in combination with X, Y, and Z axis control, as shown in **Figure 14**. The object is design in CAD tool, i.e., AutoCAD or any other tool that can create 3D structures and converted into printer supported file format. The file is then loaded into the printer to create the object in 3D form. There are several ways to create a 3D object, which defines the types of 3D printers.

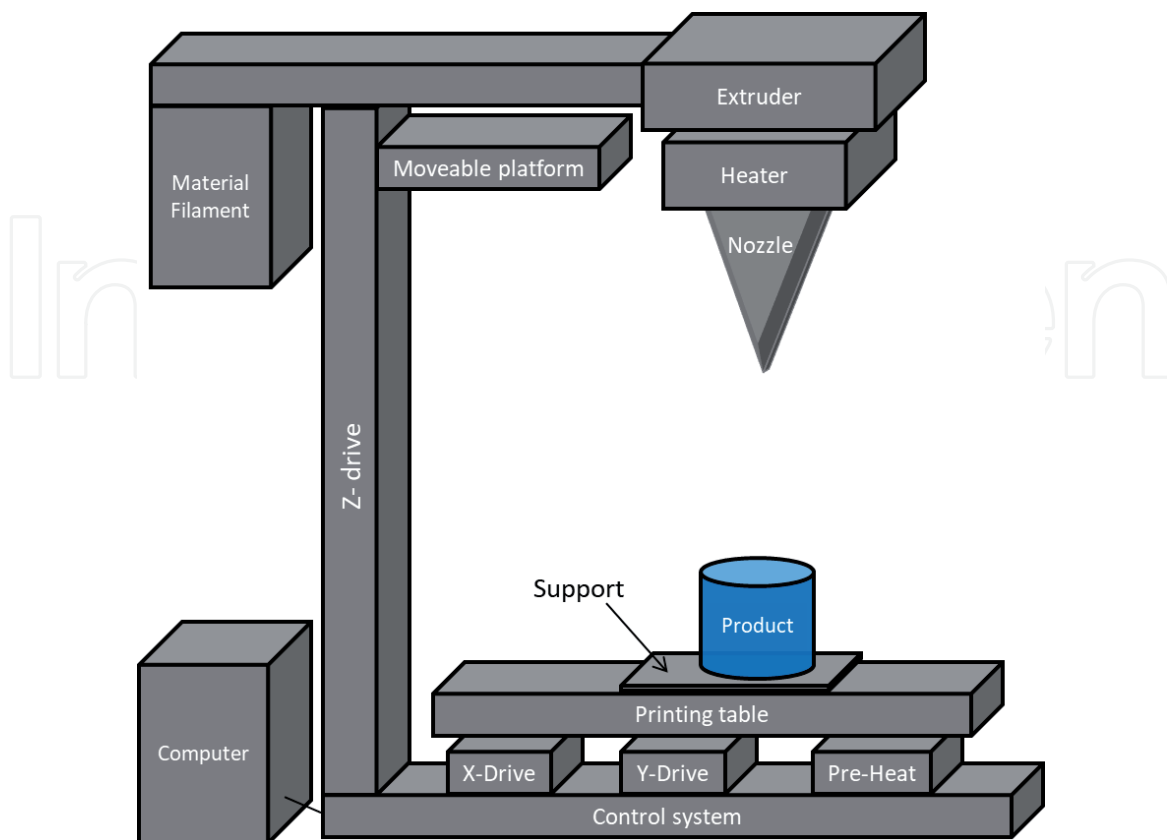


Figure 14.
3D printing system schematic diagram.

4.1 Fused deposition modeling

The development of 3D object is made by either microdrops or melt near-field electrospinning of melted thermoplastics of consecutive layers, which solidifies after a certain time. Commonly used filament materials are PVA, PLA, ABS, nylon, and some composites. This 3D printing technology is often used in the rapid prototyping objects.

4.2 Stereolithography

Stereolithography (SLA) uses a UV laser instead of melting the filament through heater and making microdrops. An SLA printer uses two mirrors in combination with UV laser, known as galvanometers, positioned on the X-axis and on the Y-axis. Both galvanometers rapidly aim a laser beam across a vat of resin, the area under light beam selectively curing and solidifying a cross section of the object inside this build area, building it up layer by layer and forming a 3D structure.

4.3 Digital light processing (DLP)

This 3D printing technology is almost the same as stereolithography, the only difference that instead of laser and two mirrors, DLP uses image of the 3D object to make one layer and repeat until the job is finished. DLP is much faster than SLA as it uses digital image array to produce a structure in the vertical sequential order frame by frame. The digital image of the target object is consisted of small rectangles called voxels. This 3D printing technology is based on selective laser sintering (SLS), and commonly used materials are thermoplastic powders (Nylon 6, Nylon 11, and Nylon 12). Potential applications of this technology are functional parts, complex ducting (hollow designs), and low run part production. This technology can be used for strong and elastic mechanical property parts and also for the complex geometry printing.

4.4 Selective laser sintering (SLS)

SLS 3D technology creates an object with powder bed fusion technology and polymer powder. Working of this technology, i.e., polymer powder, is preheated to a temperature slightly below the melting point. Then, a very thin layer of the powdered material is deposited with the help of a blade normally 0.1 mm thick on the object platform. The surface is then scanned with a CO₂ laser beam, as it selectively sinters the powder and solidifies a cross section of the object according to the designed geometry. Same as SLA 3D technology, the laser is precisely focused on to the correct location with the help of two galvos. Once the entire cross-sectional area of the object is scanned that creates one layer of the object, the build platform will move down one layer thickness in height to make the next step happen. The powder recoating blade deposits a new layer of the powder on the top of prescanned layer, and the laser will sinter the next cross section of the object area the same as previous layer. This process is continuous until the object is created.

5. Conclusion

Commonly used and advanced printed electronic technologies were discussed briefly in this chapter that covers almost all the technologies to fabricate electronic devices, circuits, and systems. Although the printed electronic technologies come

with their limitations of scalability, mass production, and life time, it is not perfect replacement of the conventional electronic technology; however, it allows free design, rapid prototyping, and unlimited application areas, especially low-temperature fabrication. Printed electronic technology benefits from new printing techniques, solution-based materials, and the combination of other manufacturing processes. Printing technology has a prominent impact on the electronic industry, such as flexibility and biocompatibility; otherwise, it was impossible to achieve with the conventional techniques and materials. Different printing technologies, processing requirements, operation, materials, and fabrication limitations were highlighted. The possibility of combining printing technologies to enable mass production of the devices, circuits, and systems, i.e., R2R system, was also presented. Moreover, it was discussed that 3D printing plays an important role in the packaging and test platform fabrication for the printed electronics. At present stage, printed electronics suffers from limitations such as operating frequency, scalability, mass production, shelf life, and robustness. However, as the research is continuous in the field, breakthroughs are expected in near future to meet all these challenges.

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Conflict of interest

Authors declare no conflict of interests.

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