Abstract

Personalized Health Monitoring (PHM) is a growing field in the medical community that is intended to address the needs of patients requiring regular monitoring of biodata from a distance. Successful efforts have been made in recent years to solve this problem using wearable electronic sensors/devices. The most effective designs utilize flexible electronics: sensor arrays mounted on polymer substrates that can be wrapped on the skin. While immensely useful due to their inherent advantages in conformability, comfort, and lightweight structures, the challenge lies in finding effective ways to manufacture these devices on a mass scale. Roll-to-Roll (R2R) printing promises high-throughput, high-fidelity fabrication via multiple different methods of imprinting conductive patterns on the substrate. This review examines the applications of these different methods and some of the results that have been demonstrated thus far.

Keywords: Additive Manufacturing, Flexible Electronics, Health Monitoring, Medical Devices, Roll-To-Roll Printing, Wearable Sensors, Polydimethylsiloxane, Polymeric Substrates, RFID electronics, Silver Electrodes

Abbreviations: CNT: Carbon Nanotubes; µCP: Microcontact Printing; NIL: Nanoimprint Lithography; PDMS: Polydimethylsiloxane; PHM: Personalized Health Monitoring; R2R: Roll-to-roll; UHF RFID: Ultra-high frequency Radio Frequency Identification

Introduction

Humans have long enjoyed the utility of wearable medical devices since the invention of the first pair of eyeglasses in Northern Italy, around 730 years ago [1]. Only three centuries later, the first hearing aids (ear trumpets) were used to assist the partially deaf in Europe. Founded on simple material properties and ergonomic principles, these devices are examples of passive technological aids that greatly enhanced the quality of life of the wearer while minimizing obstruction into daily activities. In recent years the development of new additive manufacturing methods, especially Roll-to-Roll (R2R) flexible electronics printing technologies, and the miniaturization of computational platforms have unlocked the potential for wearable medical technology that fulfills considerably more advanced functions.

Researchers and engineers around the world have already developed prototypes of different wearable electronic devices that incorporate sensors, microfluidics, and even haptic feedback for personalized patient applications. As with any emergent technology, developing intelligent fabrication methods is essential to reduce the cost of these products and maximize the accessibility to the public. R2R allows large-scale manufacturing of these and other kinds of flexible wearable devices [2-4]. Among the primary applications of wearable electronics is Personalized Health Monitoring (PHM) [5,6]. Oftentimes patients with non-critical conditions that require frequent monitoring are unable to receive on-time regular check-ups due to factors such as distance from clinics, scheduling conflicts, and general inconvenience (Figure 1) [5].

In such cases, wearable monitoring systems such as the one developed at the Tyndall National Institute in Ireland (Figure 1) can be highly useful for physicians who are able to track their patients’ biometric readings every 30 minutes, allowing them to respond in case of an emergency [5]. However, the electronics and substrates are rigid, and unwieldy—this is where flexible electronics can make a large contribution. Sensor electronics, whether optical, chemical,
physical, or other, are either embedded into or printed on flexible polymeric substrates which are then placed in contact with the skin [6]. Figure 2 shows a capacitive pressure sensor array embedded in a thin elastomeric "skin-like" membrane. In this configuration, the brittleness of the silicon-based sensors is negated by their being imprinted onto the Polydimethylsiloxane (PDMS) film. Researchers note the potential for this device as a form of touch-sensitive artificial skin [7]. Using a similar concept, other groups have developed flexible sensors that detect a wide variety of biomarkers and are capable of real-time data transmission [7-9].

![Figure 1: Tyndall-DMS Mote, a patient monitoring device which transmits blood pressure readings, etc. [5].](image)

The device in this example was created via microcontact printing, a form of soft lithography in which the Polydimethylsiloxane (PDMS) substrate is stamped with a conductive ink pattern [10,11]. The ink is generally made using some form of gold or silver, but research has demonstrated the effectiveness of carbon nanotubes as a high-performance medium too [12]. A major advantage of contact-based lithographic methods such as microcontact printing (µCP) or Nanoimprint Lithography (NIL) is that they are scalable for bulk manufacturing [2]. The difference between the two methods is that NIL utilizes thermal imprinting [13]. This can be done by integrating the stamp/press into an R2R system, similar in layout to the old process for printing newspapers [2,14]. Figure 3 shows an example of this in an R2R NIL machine for thermal imprinting polymer film [13].

![Figure 2. Flexible sensors displaying deformations [7].](image)
Another type of device is mounted directly on the skin like a tattoo, sandwiched between ultra-thin polymer layers [14,15]. Ultra-High Frequency Radio Frequency Identification (UHF RFID) is used in many applications for human monitoring, and one research group used inkjet printing to deposit silver nanoparticle inks onto tattoo paper so they can be easily transferred to the skin. These tattoo tags are ultra-thin (1-5µm) compared to screen or etched tags (tens of µm) [14]. This technology has a great advantage over current forms of human monitoring devices that utilize bulky wrist/armbands or ankle bracelets containing the RFID electronics.

Print Methods Comparison

| Applications | Screen printing | Inket | Lithography (µCP, NIL) | Flexography |
|--------------|-----------------|-------|------------------------|-------------|
|              | Voice recognition module on thin film (polyimide). Large area flexible sensor array on thin film. Graphene high res patterned flexible circuit. | Passive UHF RFID skin tattoo tags. Sensing electrodes for electrochemical analysis | Microfluidic devices on polymer substrate, Cellulose biosensing films. The elastomeric sensor array on PDMS | CNT array sensors (optical, chemical tactile) on the ultra-thin polymer membrane |
| Pros         | Low cost; high potential throughput. Large area; Simplicity | Relatively low cost; versatile choice of ink/substrates | Bulk-scaling potential; very high speed; high fidelity pattern | CNT stamp microstructures are resistant to roof collapse |
| Cons         | Low-resolution patterns compared to photolithography and etching. Limited materials | Slower speed compared to contact-based methods; Inefficient energy-wise | Requires complex feedback control system to manage print forces and alignment at the microscale | Slow speed; limited for large area stamps. Requires complex fabrication of nano porous stamps |
| Refs         | [16-18] | [3,4,14] | [2,3,7,13] | [15] |

Table 1 provides a visual aid to summarize the print methods that have been most successful at fabricating flexible electronic devices for PHM applications thus far. The intent is not to convey that one print method is superior in all aspects to others, but to demonstrate that different methods have varying levels of effectiveness depending on the applications. For example, due to inherent limitations screen printing methods will never match the high-resolution of inkjet printing [4,16]. However, screen printing is vastly superior for a large area, high throughput fabrication of lower resolution electronics as well as being much more energy-efficient. Meanwhile, lithographic methods such as µCP can produce super-high-resolution patterns in large areas at high speed. But since they are contact-based and rely on premae stamps, they still lack the customizability of inkjet printers which can be easily reprogrammed to produce different patterns [3].

Conclusions and Future Perspectives

Wearable sensors printed onto polymeric substrates have major advantages over outdated rigid designs due to their low cost, lightweight, flexibility, and comfort [6]. The emergence of higher throughput, lower-cost manufacturing methods for flexible electronics will have a great impact on the field of Personalized Health Monitoring. This paper has gone over the most viable methods used to fabricate these devices in large quantities and explored the capabilities of each. A combination of methods both contact and non-contact (i.e., µCP and inkjet) could be integrated into an R2R system that would be capable of fabricating a wide range of devices on a large scale. This composite system would utilize the best features of each of the components i.e., the processing speed and high resolution of µCP combined with the adaptability of inkjet. Other print methods such as flexography or screen printing could also be included. A prototype of such a system should be designed and tested with the results being the subject of further study.

Acknowledgment

Thanks are owed to the researchers and authors of the various groups cited; whose work enabled the writing of this review.

Conflict of Interest

The author declares no conflict of interest. This work is supported in part by the National Science Foundation (grant no. CMMI1916866 and CMMI1942185). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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