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KEY MICRO MACHINING SUCCESS FACTORS

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Design and manufacturing process considerations for the creation of printed sensors and sensor-based systems

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EAB MEMBER

Introduction

The rapid commercialisation of printed sensors and sensor-based systems' time has come. As previously stated, printed sensors are the third wave in the innovation of sensors[1]. The first was discrete electromechanical and the second was MEMS/silicon, both of which have achieved maturity. Though printed technology has been available since the mid-80s when Interlink Electronics and Tekscan established patents on their force sensing resistor (FSR) technology[2], many barriers to commercialisation have existed. Chief amongst these was the availability of low-cost electronics to be used to undertake the necessary signal conditioning and computation from the sensed signal(s) and thus create a viable solution to an application opportunity. The good news is that this barrier has been overcome. It has become apparent through the recent creation of many new companies and their introduction of new products, substantial funding of the US Department of Defence (DoD), and the establishment of several conferences focused on the promotion of printed electronics, that electronics, including sensors, have reached the critical point in their commercialisation process. As such, many potential users are seriously considering their adoption. Sensors to be realised vis-à-vis the printing process include force, pressure, temperature, humidity, gas and fluid analysis, and several others[3].

> The use of mature and stable printing methods permits high-volume/low-cost manufacturing, in much the same way as integrated circuits (ICs)

Why printed?

There are several key motivating factors for the adoption of printing electronics and sensors. The use of mature and stable printing methods permits high-volume/low-cost manufacturing, in much the same way as integrated circuits (ICs) (figure 1). However, unlike ICs, printed electronics and sensors can use flexible substrates that permit them to bend (and possibly stretch) in order to conform to complex three-dimensional shapes, for example, the human arm. Also, like ICs, printed electronics and sensors can be created in a batch mode, i.e. one carrier at a time; but unlike ICs, they can also be created in a continuous and, in this case, roll-to-roll (R2R) manufacturing process, making them exceptionally low cost. Their low cost and structural conformity make them ideal for a number of applications, including wearables, which happens to be a high-growth application.

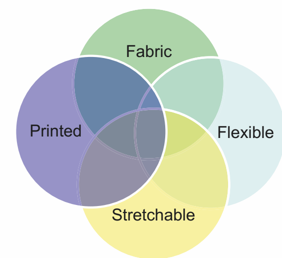
More specifically, the many factors that are driving the adoption of printed electronics and sensors include their:

- conformability to complex surfaces;
- flexibility and (possibly) stretchability;
- ability to create large area structures;
- item-to-item uniformity;
- low profile;
- lightweight;
- low-cost manufacture; and
- ruggedness/reliability.

▶ *Figure 1: The major driving factors in the adoption of printed electronics and sensors are their low cost of manufacture, many significant application benefits, including flexibility and conformability to complex structures upon which they are attached/ mounted, and ability to be produced in large sizes and arrays. (Source: Roger Grace Associates)* ▶

Why Printed / Flexible / Stretchable / Functional Fabric

Attribute	Benefit	
	Cost	Functionality
Printed	• Low Infrastructure • Low Unit (R-2-R)	• Large device size • Arraying capability • Low profile • Ease of hybrid integration • Reduced time to market
Flexible		• Application driven (especially human interface)
Stretchable		• Application driven (especially human interface)
Fabric	• Low Infrastructure • Low unit	• Application driven (especially human interface) • Large device size • Arraying capability • Low profile

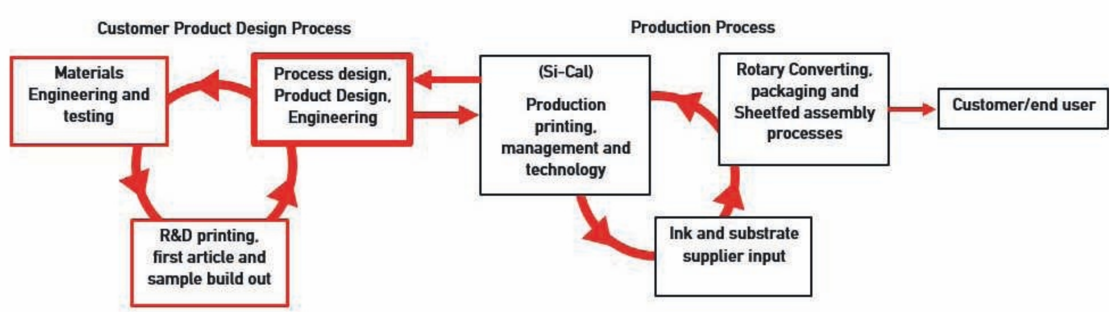


Challenges to the design and manufacturing process

A systems approach/team approach to picking the best functional elements

A primary objective of creating this article is to inform the design, development and user audiences of the several complexities inherent in the design, development and manufacturing of these products. As previously stated, the design and manufacturing approach must take on a systems-based one where the sensor must interact with other devices to create a total solution/product and fulfil a customer application opportunity[4]. The other functionalities in the total solution include signal conditioning, for example, analogue to digital (A/D) conversion, amplification, filtering as well as power creation and monitoring, and finally connectivity—these must all work together.

A major challenge is that several of these components have not yet reached the level of commercialisation such that they can be created in a printed fashion and on a flexible substrate, and thus, designs are forced to adopt a hybrid approach where the systems architect will select the circuit functionalities that make the best sense based on the system requirement and the format of the substrate, i.e. IC/silicon or printed plastic. In addition to the selection of a substrate format that optimally matches the system requirement, there are a great deal of design and manufacturing challenges associated with the integration of these functionalities, their interconnects and their final packaging as well as a rigorous test strategy and plan to consider.



▶ *Figure 2: The design and manufacturing process of printed electronics and sensors is highly complex and interactive. For the outcome to be optimally successful, there must be a high degree of interaction and cooperation between all organisations involved and especially at the front-end of the process. Each of the downstream contributors, i.e. ink and substrate supplier, printing supplier and converter supplier, act as consultants to the product designer and/or the organisation that wishes to deliver the final product to market. (Source: Hazardous Print Consulting)* ▶

▶ ***Figure 3:*** *This sheet-fed printing equipment can accommodate print areas from 495.3 x 635 to 495.3 x 965.2 mm (19.5 x 25–25 x 38 in). It takes sheet materials from 3 to 20 mm (0.118–0.787 in) thick. The layer-to-layer registration tolerance is 0.127–0.381 mm (0.005–0.015 in). (Source: GSI Technologies).* ▶

Ink and substrate selection considerations

Len Allison, business manager for Engineered Material Systems (EMS), a group company of Nagase, painted a more positive picture, saying that using polyester thin film (PTF) materials and techniques are helping to add functionality to graphics. Manufacturers of smart and low-cost proximity, force, light and electro-chemical sensors can take advantage of the fact that PTF materials provide a form factor that meets their needs, specifically that they can ideally be concealed by graphics. This form factor could be well-served on popular plastic films such as polyethylene terephthalate (PET).

If pliability, comfort and low noise are important, other substrate materials such as thermoplastic urethane (TPU) or textiles may be better suited, although they present problems in terms of dimensional stability if subjected to heat, thus curtailing their use on print receptors and printable substrates. Newer options include TPU film, resin-coated fabrics and heat-transfer inks. However, not all TPUs are alike and deciding to work with them must be on a case-by-case basis.

Useful inks include silver conductors, silver-silver chloride sensors, carbon ink resistors, force-sensing sensors, dielectric insulators and moisture-resistant encapsulants.

Allison summarised: “A platform of material and process suppliers is needed to deliver the right volume and the right integration of components, application and graphics.”

Printers

Printed, flexible (P/F) electronics and sensors can be manufactured using either a sheet-fed process, i.e. in batch fashion—similar to that used in the IC industry, where each substrate is made one step at a time—or a roll-to-roll (R2R) process, i.e. in continuous fashion. Each type of process has its pros and cons.

GSI Technologies offers both approaches to its customers, several of which are sensor developers. It provides its customers with a choice of manufacturing methods for creating their products, working with them to determine the best solution for their requirements based on product specifications, total cost and production run volumes. There is a need for pre-prototype design collaboration between the printer, ink and substrate manufacturer, designer and converter if one desires an optimum design.

▸ ***Figure 4:*** *This Roll-to-Roll (R2R) flatbed screen printing equipment can accommodate a print area of 495.3 x 711.2 mm (19.5 x 28 in). It takes sheet materials from 1 to 15 mm (0.039 to 0.591 in) thick. The layer-to-layer registration tolerance is 0.152 mm (0.006 in). (Source: GSI Technologies).* ▸

The costs of screens, plates, rotary screens and gravure cylinders, which are dependent on width, detail and type, are all very high. Other factors for consideration include: R&D; mock-ups; material set engineering cost; print testing for design validation; film testing for stability; lifespan testing for product shelf life; and conductive-inks testing for printability, electrochemical compatibility, adhesion and curing.

The decision as to which printing process to use in order to create a viable product requires a great deal of analysis and trade-off. Customarily, small-volume requirements are addressed by sheet-fed approaches (figure 3) and large-volume production requirements migrate to R2R approaches (figure 4) after being breadboarded in a sheet-fed approach.

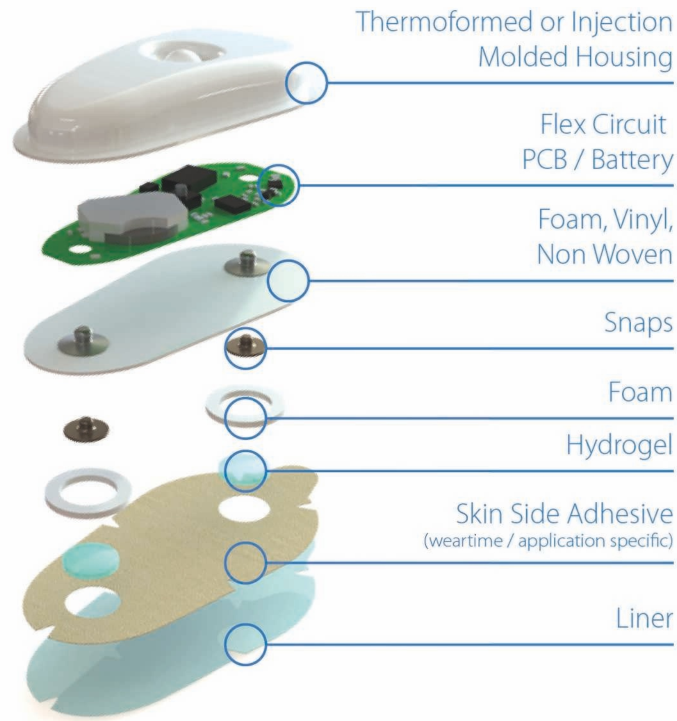
Sheet-fed screen printing is considered the best and most cost-effective approach for low-volume development, where more than three electronics components need to be added. It is better for thicker, 3 to >15 mm (0.118–>0.591 in) films as thin films can cause processing issues; a minimum thickness of 3 mm (0.118 in) is required and ≥4 mm (≥0.157 in) thick films are preferred. It is also better for higher cost films and scenarios involving more than 8–10 functional ink layers.

Additionally, the sheet-fed process allows for printing in a wider 762+ mm (30+ in) format versus around 508 mm (20 in) for the R2R process. From a line and spacing perspective, the superior performance of sheet-fed is 100 µm (0.004 in) versus 150 µm (0.006 in) for R2R.

R2R screen printing is suitable for 1 to 15 mm (0.039 to 0.591 in) thick films incorporating multiple layers of functional inks. It has a faster throughput and thus can be more cost-effective. Typical production speeds for printed electronics are 2.8 x 3.7 m^2/min (30 x 40 ft^2/min), which is significantly faster than the sheet-fed process. Also, R2R requires far less handling and is easier to keep clean. There is uniform shrinkage and handling of films.

Furthermore, registration in the R2R process is better and simpler. The colour-to-colour registration tolerance is 0.152 mm (0.006 in) for R2R versus 0.102 mm (0.004 in) for sheet-fed. This is because the sheet-fed process requires camera alignment and therefore slows down to match the R2R process.

In sum, there is a great deal of discussion necessary to provide clients with the optimum solution for their current production requirements.



▸ ***Figure 5:*** *An exploded view of a flexible wearable medical sensor, which is a composite made up of four layers of material including a flex circuit and battery. (Source: Biomedical Innovation)* ▸

Converters/integrators

Converters are essentially contract manufacturers such as Biomedical Innovations, a Nissha Medical Technologies company. It plays a critical part in the integration, encapsulation, interconnection and packaging of devices. Chris Healy, vice president of Biomedical Innovations, pointed out that design for manufacturing (DfM) of printed electronic products in terms of the sensor and interconnects involved is fundamentally important for converters from the outset. He added that materials factor into a design. All providers must collaborate intimately at the front-end of the design and manufacturing process.

> **“From a line and spacing perspective, the superior performance of sheet-fed is 100 µm (0.004 in) versus 150 µm (0.006 in) for R2R.”**

Healy stressed the need for a detailed understanding of: the application’s environmental conditions; components that come into contact for reaction; shelf life; maximal use of materials and thus minimal waste; processing under high tension; stretching and registration; cutability; the rotary versus steel rule; die life, which depends on the materials

Two specific applications that GSI Technologies has been instrumental in creating are a printed automotive seat heater and handheld micro pipette.

involved; and flexibility of the printed electronic product system circuit to fit the contour of the human body. An excellent example of the various layers and materials used to create a printed electronics device for a medical application is provided in figure 5.

Healey conceded that in terms of manufacturing equipment available, it is mostly custom in nature due to the newness of printable electronic technology, influencing factors being the number of stacked layers, foam housing and the numbers of wires to be attached. He also said that business decisions and the perceived time-to-market quantities are always factors that clash with a printed electronics product design.

Applications

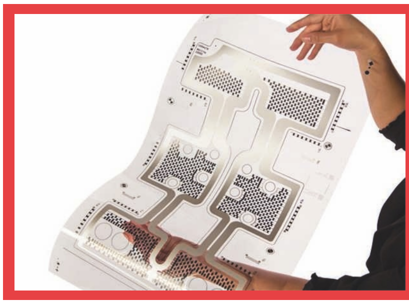
Applications abound for printed sensors and sensor-based systems. There is no shortage of demand for these products, with the biomedical, consumer, wearable electronics and commercial arenas leading the way. Specifically, products are becoming more prevalent in health, fitness, entertainment and medical applications. Garmin's Forerunner, Fitbit's Ace, Epson's Moverio and Misfit's Shine are just a few of many examples. Additionally, P/F sensors and sensor-based systems have found applications in other market sectors, including automotive, robotics and security.

Two specific applications that GSI Technologies has been instrumental in creating are a printed automotive seat heater and handheld micro pipette.

Printed automotive seat heater

P/F electronics has a long history in automotive applications. Approximately two decades ago, the FSR technology developed by Interlink Electronics and Tekscan became a production reality as an advanced airbag deployment sensor for determining the seat-print and weight of a front-seat passenger in Volvo vehicles. Major benefits of the printed sensor array included its low cost, flexibility and ability to be realised in large-scale formats/arrays.

Fast forward to 2010 and GSI Technologies helped a global supplier of automotive seat comfort systems to manufacture a self-regulating, ventilated passenger seat heating system (figure 6). At the heart of the system were positive temperature coefficient (PTC) heaters, which were produced by GSI Technologies. The heater element circuits comprised silver and PTC carbon inks on a 0.127 mm (0.005 in) in thick, heat-stabilised polyester. They were produced on automated cylinder screen press lines. The printed sheets were then packaged and shipped to an assembly location for die cutting and lamination of protective insulating layers. Attachment of the wire harness was carried out at the customer's assembly facility.



▶ ***Figure 6:*** *A positive temperature coefficient (PTC) heater element circuit for a self-regulating, ventilated passenger seat heating system. The circuit comprises silver and PTC carbon inks on a 0.127 mm (0.005 in) thick stabilised polyester. (Source: GSI Technologies)* ▶

What makes this application so significant is that GSI Technologies supplied all prototype, development validation and production validation heater elements. The company also undertook the development, construction and validation of several end-of-line test platforms, three of which were to support production volumes.

This application demonstrated the need for close cooperation and partnership between a printed electronics manufacturer and its customer to create a cost-effective and robust solution that could pass the rigours of automotive applications via a well-planned and executed reliability test programme.

Handheld micro-pipette

GSI Technologies partnered with a manufacturer of medical devices to produce a one-time use sensor for its handheld micro-pipette, which measures and data logs the count and size of cells and/or particles (figure 7). The resolution, accuracy and repeatability of the micro-pipette is on-par with benchtop machines that cost 10 times that of the device. Additionally, it can be used in a lab hood environment, which saves time by eliminating the need to transport samples to a benchtop machine typically shared by several technicians.

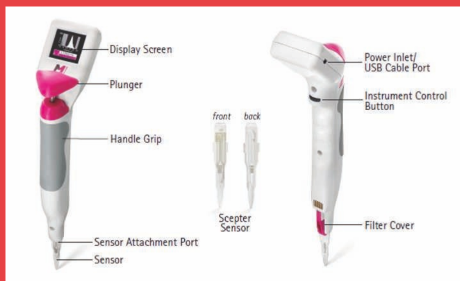


Figure 7: A handheld micropipette that measures and data logs the count and size of cells. The one-time use screen-printed sensor electrode approach replaced the previous copper/Kapton flex circuit design and provided the customer with a cost competitive and enhanced reliability solution. (Source: GSI Technologies)

GSI Technologies produced the screen-printed sensor electrodes that replaced the manufacturer's previous copper/Kapton flex circuit design. It also created six holes in the device using a ballistic punch that is capable of punching 300 holes in a single stroke. It subcontracted with one of its partner companies to laser drill 40 and 60 µm size holes in the material.

Less than six months from the contract start date, GSI Technologies had executed its lab-to-fab model, which successfully produced a cost-competitive and more reliable solution to the medical device manufacturer's requirements compared with the previous design approach.

Conclusion

The need for P/F electronics and sensors is being fuelled by several high-volume applications including wearables, the IoT, disposables and e-health. Janusz Bryzek, in his Trillion Sensors Initiative[5], has emphatically opined that the industry must move to lower cost sensors to be able to achieve this goal of manufacturing a trillion sensors per year. It is widely accepted in the industry that the cost of plastic or paper-based sensors can be at least two orders of magnitude less expensive on a cost-per-area than silicon-based sensors[1]. This alone is a significant benefit in the widespread adoption of P/F electronics and sensors. Additionally, their inherent ability to flex and possibly stretch is critical in many applications that cannot use non-flexible parts, for example, MEMS that are manufactured from silicon.

It is the authors' belief that the major challenge in the commercialisation of printed electronics and sensors is to overcome the current adolescence of the technology and to facilitate the collaboration of various participants in the design and manufacturing processes presented above. This is a natural evolution to achieving maturity. The importance in this endeavour is team work, where all of the suppliers in the value chain, i.e. ink and substrate, printing, converting/integrating, bringing to the table their experience and knowledge of printed electronics and sensors' functional use, become involved with prototyping companies and product manufacturers at the beginning of the process and act as consultants in their specific areas of expertise. ●

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