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Soft Intelligence Epidermal Communication Platform (SINTEC) A Path to A Wearable Future

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Abstract
Electronics are set to merge with our bodies to extend our perceptions [1]. Smartphones and watches will give way to the bodyNET2 : a network of sensors, screens and smart devices woven into our clothing, worn on our skin and implanted in our bodies. Wearable sensors have recently seen a large increase in both research and commercialization. Most commercial progress has been in smart adaptation of existing mechanical, electrical and optical sensors. This adaptation has involved innovations in how to miniaturize sensing technologies, how to make them conformal and flexible to ease utilization, and in the development of companion software that increases the value of the sensor data. When it comes to wireless stretchable sensor patches, often referred to as 'electronic skin', 'epidermal electronics', or 'electronic tattoos', there are until today no dedicated commercial equipment for manufacturing of such devices [3]. SINTEC is a European Union Horizon 2020 research project that will focus on demonstrating a novel large bandwidth and low-dispersion sensor network platform by utilizing stretchable electronics and the pioneering Fat-IBC. The hardware development will be on realizing an innovative rigid-stretch elastomer PCB technology using, initially, a two-layer liquid alloy circuit, pick-and-place assembly of advanced rigid modules or components, and encapsulation. Industrial partners will exploit the results in manufacturing technology, Fat-IBC, and in biomechanical and physiological applications of soft and compliant wireless intelligent patches, e.g. in preventive care, sports and fitness, and clinical medicine. In principle, the project is built on the rigid-stretch PCB technology.

Keywords : digital production, wearables, stretchable electronics, liquid metals

Introduction

The Internet of Things (IoT) has presented a world of possibilities to medicine. Ordinary medical devices that are connected to the Internet can collect valuable data and offer increased and improved control over management processes/treatments. As Peter Drucker [1] once said, "If you can't measure, you can't manage it.", and that is exactly what IoT offers to healthcare organizations, an automatic way to measure their processes in order to improve them.

Inside the Internet of Things (IoT) sector, smart wearables represent the next step in the Consumer Internet of Things wearable evolution. This market is predicted to be one of the most vigorous in the coming years. The market for wearable technology will reach accelerated CAGR of 23% to over $100BN by 2023 and reach over $150BN by 2026. By sensor type, this market is expected to be divided in motion sensor (~20%, CAGR 10%), biopotential and optical sensors (~15% each, CAGR 10% and 13%), stretch and pressure sensors (~5%, CAGR 40%), chemical sensors (~40%, CAGR 13%) and others (~5%, CAGR 12.5%). SINTEC addresses most of these sensor types: biopotential (ECG and ICG), optical (wrist sensor for PPG and PTT), motion (all the components) and the pressure sensing capabilities of the substrate will be investigated.

The global wearable devices market for healthcare wearables is expected to reach $18.9BN by 2020, growing at a CAGR of 29.9%. The non-regulated wellness, fitness, and sports wearable segment is expected to grow at CAGR of 27.8% (2015–2020). Regulated/clinical-grade wearables are the most promising product segment within healthcare wearables and is expected to grow at a CAGR of 32.9% (2015–2020).

In the report Frost & Sullivan [2] forecasted global revenues of $30BN and $61BN for 2018 and 2020, respectively. In comparison, in autumn 2017 Gartner forecasted projects sales of 310.4M wearable devices worldwide that year, generating a total of $30.5BN in revenue.

Stretchable Electronics

According to "Europe Stretchable Electronics Market By Component, By Application, By Country, Competition Forecast & Opportunities, 2017 - 2023" [3] stretchable electronics market is forecast to grow at a CAGR of 89% by 2023. Anticipated growth in the market can be attributed to increasing adoption of smart wearable, rising investments in development of touch sensitive e-skin and availability of stretchable conductive ink in Europe.

The market organization IDTechEx has recently published a report 'Stretchable and Conformal Electronics 2019-2029: Materials, components, products and 10-year market outlook' that attempts to provide a comprehensive overview of materials and components in the realm of stretchable electronics. The wide array of materials and components are identified and categorized with respect to technology readiness level (TRL) [6]. One of the conclusions of the report is that this realm of electronics solutions is changing from being a technology searching for an application, but instead maturing into a sector that will fragment into areas that are commercially viable and others continue to develop more slowly.

It is clear that the number of commercially produced products will increase over the next 3-5 years and these will require increasingly efficient and customized production processes. SINTEC (Soft intelligence epidermal communication platform) is a Horizon 2020 funded project that will provide soft, sticky and stretchable sensor patches that can be used multiple times and at longer periods. With its dynamic compliance and water repellent permeable encapsulation it withstands vigorous action, sweating and water making it ideal for an active life. A novel intrabody communication technique gives large bandwidth and secure consumption at low power, allowing for multiplex sensoric inputs from many nodes on the body. To demonstrate the advantages of the novel technology, SINTEC will apply it in clinical environment and in athletics performance evaluation.

The process that is being envisioned and realized in the SINTEC project is aimed at exactly these applications, where production solutions are required to complement production lines that can produce rigid printed circuit boards (PCB). Production lines for stretchable electronics, like those envisioned in the SINTEC project, will be set up at manufacturers around Europe, and the rest of the world.

General production concept

The production process for stretchable electronics that is being developed in this project is based on a digital production strategy, where a majority of the production steps are digitally controlled and designed. An example of a proposed production line, including deposition machines, inspection devices et cetera, is shown in Figure 1. A demonstration product consisting of a stretchable single-layer monitoring sensoric device will be used as a basis for the discussion of the concept production line.

Figure 1 : Concept of production line for stretchable electronics.

Preparation of soft stretchable material

To form a soft and elastic base layer for the stretchable electronic device, the process begins by preparing the material to be used as a substrate. The material class used is a silicone elastomer, polydimethylsiloxane (PDMS), which is an insulating transparent/translucent, non-toxic and gas permeable rubber widely used for microfluidic applications [7]. Covering electronic microchips with silicone rubber to protect the surface mounted components is utilized frequently to protect the electrical devices from wear. The PDMS consists of two molecular components, a monomer and a crosslinker, which are mixed in liquid form according to a brand-specific weight ratio. The mixture can be moulded with high resolution to make an inverted copy of its mould. Many PDMS-based rubbers are curable at room temperature (RT) and the process is accelerated using elevated temperatures or, alternately, slowed down in temperatures lower than RT (e.g. in a freezer). RT is considered to be within the range of 20 °C − 25 °C. The viscous material is then deposited in the desired shape and cured. Many types of silicon-based rubbers and gels are commercially available having a wide range of properties, such as hardness, tensile strength, elongation at break, viscosity during pot life and curing time. However, by combining different types of PDMS, it is possible to obtain desired traits of the blend. For a sticky, yet mechanically elastic composite, the combination of a gel and a soft PDMS could be successful. It is also possible to add several consecutive layers of different PDMS, with different properties to obtain a heterostructure composite that would exhibit mechanical stability while remaining soft and sticky at the surface.

Deposition of the base layer of soft stretchable material

To form uniform films out of the moldable uncured PDMS, several alternatives are available. A common technique, especially in the preparation of thin films, is spin coating. The technique works by spreading out a volume of liquid PDMS placed in the center of a flat wafer and by spinning the substrate at high rotational rates, a homogeneous thin layer is formed. The deposited liquid must be compatible with the surface of a flat substrate to avoid irregularities or even non-wetting.

A second approach to form a consistent base layer is by using a bar applicator as illustrated in Figure 2. The technique is commonly used to spread viscous paints and inks over a substrate or carrier sheet, using a bar applicator with gaps equivalent to the desired film thickness. The bar applicator smears out a small volume of liquid (Figure 2a) to a uniform layer (Figure 2b) on a flat, rectangular surface and therefore can be advantageously adopted for coating PDMS.

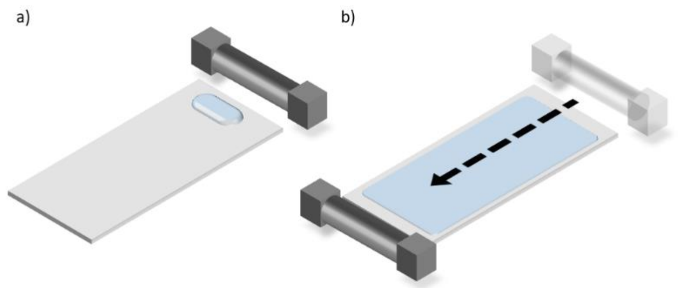


Figure 2 : Schematic illustration of thin-film coating of silicone base layer. a) An appropriate volume of uncured liquid PDMS is deposited on the carrier in front of the bar applicator. b) The bar applicator is pulled over the uncured liquid PDMS, dispensed evenly on top of the carrier.

All the techniques mentioned can be conducted in a laboratory environment requiring relatively simple and inexpensive tools. Nevertheless, variations in coating velocity and applied pressure, especially when manually coated, are inevitable. To reach better reproducibility and high precision of desired thickness, an automatized coater capable of depositing uniform layers is preferable.

The carrier of the PDMS base layer, is another important choice in the fabrication process. The material of the carrier must not react chemically with the PDMS and hinder it from curing while providing enough mechanical stability and support while transported from different workstations. Moreover, if curing is accelerated thermally, thermal stability is also required. High compatibility and adhesion to the PDMS are desirable to prevent spontaneous peeling or deformation of the PDMS when it is removed. Aside from the final device, the adhesion of the PDMS to the skin must exceed the adhesion of the carrier to ensure a successful application to the skin.

There are commercially available materials that fulfill many of the above-mentioned requirements of the stretchable base layer in the form of a plastic carrier substrate with a preformed 20 µm thick elastomer layer.

Patterning of conductive interconnects

The next step in the fabrication procedure is to create circuitry connecting electrodes, contact pads of rigid components, and other active elements. The interconnects should be capable of adapting to repeated high elongation of tens to hundreds of percent, while maintaining high conductive performance. In order to fulfill these requirements, a gallium-based liquid metal alloy was selected as a suitable candidate offering a unique combination of properties which supply a stretchable conductor of a soft epidermal electronic device and facilitates preparatory and production processes, as well. The eutectic composition of the alloy enables the metal to be liquid at room temperature, and forms channels in a bulk silicone material, which reliably adapts to the shape changes of the carrier elastomer without forming defects, such as cracks or delaminations.

Several variants of eutectic liquid metal alloys are commercially available. Galinstan is composed of approximately 68% Ga, 22% In, 10% Sn by weight, with additional small amounts of Bi and Sb [8] and has been investigated earlier. Galinstan is non-toxic and has a low viscosity, holds high electrical and thermal conductivity, and has a low melting temperature of -19 °C. The high surface tension of 670 mN/m is compensated and reduced by the creation of a thin (gallium) oxide layer (Ga_2O_3 and Ga_2O) covering the metal upon exposure of air ambiance naturally, which solves the adhesion to the silicon substrate surface [6].

The circuit designs are designed with any traditional computer-aided design tool. The goal of this project is to utilize non-contact deposition technologies to realize the designs. This could entail jet printing or jet dispensing, but it would also be feasible to use standard capillary needle deposition of the liquid metal. The presented proof-of-concept studies of the liquid conductors have been performed using a tape transfer atomization technique by Jeong et al. [10], see Figure 3.

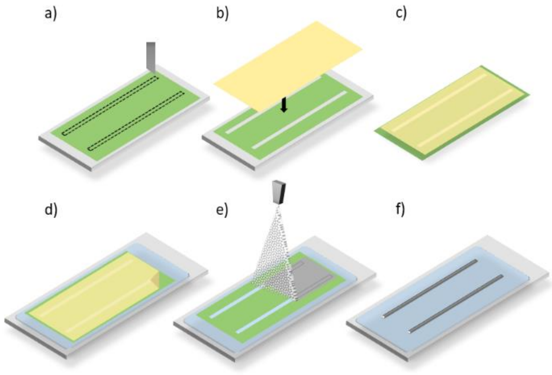


Figure 3 : A schematic illustration of the atomization process, patterning the liquid alloy. a) An adhesive tape is cut with a cutter plotter blade according to the pattern design. b) After the cut parts have been removed, a weakly adhesive transfer tape is placed on top of the tape mask. c) Once the transfer tape is supporting the tape mask, it can be removed from its carrier. d) The tape mask is placed on the stretchable substrate and the transfer tape is removed. e) The liquid alloy is deposited using liquid atomization using an airbrush spray pen. f) After deposition of the liquid alloy, the tape mask can be removed and the pattern is transferred to the stretchable substrate.

Modification by acidic vapour

In an oxidizing environment, such as ambient air conditions, the surface of Galinstan is covered with a nanometer-thin layer of oxide [11], which increases its viscosity and wettability to non-metallic materials. When interfaced with PDMS, the oxide adheres to its surface during patterning. However, the oxide might cause irregularities of the patterned Galinstan which may initiate stress accumulation in the encapsulating layer. Local areas of stress accumulation impose a very high risk of rupture when the device is stretched.

A strategy to remove irregularities is to temporarily remove the oxide using acidic or alkaline reagent or its vapour (e.g. hydrochloric acid (HCl) vapour [9, 12]). However, vapour application must be either local or precisely controlled to maintain the oxide shell, guaranteeing wettability and adhesion to the PDMS surface.

Interconnect inspection

The inspection of the deposited interconnect lines and pads is often required in order to reach production yield goals. While the inspection of solder paste deposits is well developed and a large number of system providers are available, the optical properties of liquid metals can introduce spurious results. Development is ongoing to ensure that reliable quantitative results from inspection devices can be made available for these materials.

Assembling the rigid electronic components and contacts

After the quality of the interconnection lines has been ensured, the mounting of rigid components onto the stretchable substrate follows. The rigid components for the hybrid stretchable patch demonstrator include an electronic chip consisting of integrated sensors and antennas powered by a primary cell battery or an accumulator of coin cell dimensions with solderable interface points. The sensor module, depicted in Figure 4, allows low energy Bluetooth (BTLE) connection with a smartphone via a mobile app for streaming of the monitored functions in real time.

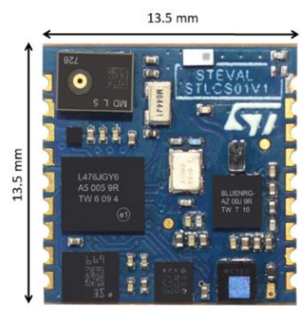
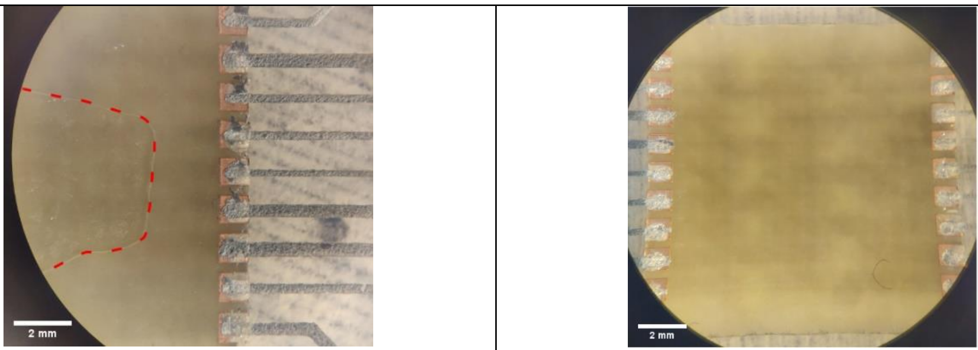


Figure 4 : The sensor module used in the demonstrator patch [10].

A battery is also mounted using a pick-and-place step. Thanks to their thin disc form, coin cell batteries are used as a power source for the BTLE sensor package patch to supply the sensors and Bluetooth communication module mounted on the sensor package. Since the liquid alloy interconnect circuit is positioned in a single layer, both the plus and minus pole of the coin cell battery need to be accessed from the same side with the patterned circuit lines. Both of the components mentioned here are extracted from trays.

Underfill

After the placement of rigid components, the empty space found between the component and the substrate must be filled, see Figure 5 a) and b) to both provide adequate adhesion to the substrate, as well as to stabilize the contact points of Galinstan by conforming to the shape of the liquid alloy. By adding low viscous PDMS in contact of the rigid component, the liquid is subjected to the capillary force and will creep inward, completely filling the void. The underfill process is performed with a needle or jet dispensing technology.



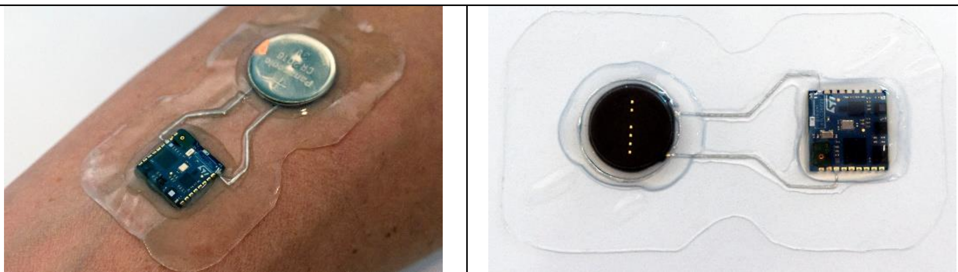
a) b)

Figure 5 : Micrographs of the backside of a rigid component mounted on liquid alloy circuitry and encapsulated. The Galinstan lines are in contact with the copper contact pads on the rigid component. The rigid components are encapsulated by a) high viscous PDMS only, where an air pocket is formed and marked by dotted line and b) completely underfilled by low-viscous PDMS and no air pocket is formed

Final encapsulation

The final encapsulation is performed by applying uncured PDMS to cover the rigid components and the interconnects, as well as parts of the substrate. The encapsulating layer fixes rigid components in place and protects the liquid interconnect from smearing while also sustaining the circuit integrity during elastic strain. The uncured PDMS conforms to the shape of the patterned liquid alloy and maintains its shape during curing, which forms the channel of the interconnect in direct accordance to the conductor. Just like the substrate layer, the properties of the encapsulating layer could be engineered by mixing different types and brands of PDMS or creating hetero structures by adding several layers of PDMS rubbers with different properties. In a production environment, the application of PDMS would be performed using a conformal coater.

Compared to the base PDMS layer that will adhere to the skin, the encapsulating layer will protect the device from outer stress, such as objects brushing against the patch, weather and humidity. The encapsulation layer could be dyed in a customized color to appear more natural and agreeable to the user. The device is cured and later cut in an appropriate form using a cutter plotter or a laser cutter. The final stretchable wireless sensor patch that was produced to test the manufacturing technologies is shown in Figure 6.



a) b)

Figure 6 : The final stretchable wireless sensor patch that was produced to test the manufacturing technologies in two versions a) with embedded battery and b) with an external charging interface.

Stretchable electrodes

The stretchable electrodes used in the electrophysiological patch are made of a composite consisting of conductive material in a form of solid particles incorporated into soft and stretchable matrix. The concentration of conductive particles in the composite should reach or even exceed the percolation threshold to achieve a stable conductivity through the bulk of the material and to provide signal transfer from a hydrogel in contact with the skin, through interconnects to a measuring unit. On the other hand, the amount of incorporated particles should not counteract the stretchability and softness of the matrix.

To ensure stable signal transmission during long-term monitoring, high adhesion to the skin is required. Therefore, an adhesive and conductive hydrogel containing Ag/AgCl is used and mounted on the stretchable electrodes of conductive composite. The adhesive hydrogel should adapt to the unevenness of the skin and provide high conformability and comfort while also compensate for the salt secretion occurring through the skin. When removed, it should not leave residues.

Interesting aspects

The circuit design mentioned above has been based on a single circuit layer. For more advanced circuit designs, multiple layers will be necessary, which in turn will introduce vertical interconnect accesses (VIAs). Strategies to enable multi-layer designs that incorporate VIAs are being developed within the SINTEC project. Design opportunities include both additive and subtractive methodologies. Prior art includes mechanical machining or using a laser to connect several levels of patterned circuitry separated and encapsulated by PDMS [14].

Conclusions

It is evident that wearable electronics products offer a myriad of opportunities for commercial and professional use. It will be necessary for these products to be stretchable to a considerable degree which in turn will require an adjusted production strategy for the commercial manufacturing of the products. Rigid printed circuit board manufacturing is a mature technology and many of its modules may be used to produce stretchable electronic products, but complemented with additional and novel production steps. A concept production line has been presented including steps for substrate deposition, inspection, interconnect deposition, component placement, curing and sealing. The SINTEC project has performed initial proof-of-concept studies of the main production technologies and presented a demonstrator in the form of a stretchable wireless sensor patch. The implementation of the tested technologies is being implemented with commercial production machines and will be presented in more detail in the future.

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