TAP2 - PAT2

PROGRAMME TO STIMULATE KNOWLEDGE TRANSFER IN AREAS OF STRATEGIC IMPORTANCE

Stretchable & Washable Electronics for Embedding in Textiles

SWEET

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PROGRAMME TO STIMULATE KNOWLEDGE TRANSFER IN AREAS OF STRATEGIC IMPORTANCE

TAP2

FINAL REPORT

STRETCHABLE & WASHABLE ELECTRONICS FOR EMBEDDING IN TEXTILES

SWEET

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1 RESUME

1.1 Contexte

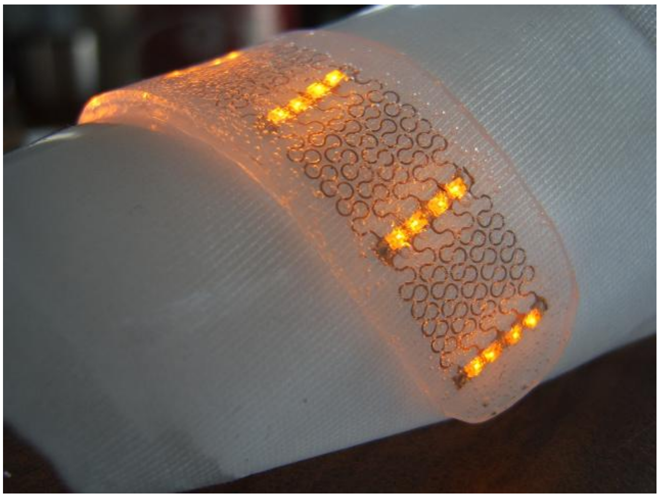
Dans notre société de consommation, les individus sont amenés à transporter de plus en plus de systèmes électroniques au cours de leurs activités. Pour ce faire, une solution confortable serait d'intégrer ces appareils dans les vêtements des utilisateurs. A l'heure actuelle, il existe divers modules standards d'électronique textile, mais leur intégration est fastidieuse pour principalement deux raisons:

- Le circuit ne peut être déformé avec le textile que de façon limitée (cas par exemple des circuits souples qui ne sont pas étirables);
- Le vêtement ne peut être lavé de manière classique sans retirer au préalable l'électronique.

Un des principaux facteurs empêchant la percée massive de l'électronique textile dans l'industrie est le manque de techniques d'intégration des circuits électroniques complexes aux textiles. S'il était possible de fabriquer des circuits électroniques ayant certaines des caractéristiques des textiles (souples, étirables, lavables), on pourrait atteindre un degré très élevé d'intégration, ouvrant ainsi la voie à un grand nombre d'applications.

1.2 Objectifs

C'est précisément le but de ce projet que de mettre au point une plateforme technologique pour le developpement de circuits électroniques étirables, lavables et intégrables aux textiles. En effet, au début du projet, une technologie embryonnaire était disponible au sein du consortium pour la fabrication de circuits électroniques élastiques et étanches. Cette technologie est basée sur l'incorporation de circuits électroniques dans des matériaux élastiques tels que les silicones ou les polyuréthanes et sur l'utilisation de méandres de cuivre pour les interconnexions électriques entre les composants.



Les objectifs suivants ont été formulés pour ce projet:

- Poursuite du développement de la technologie de circuits électroniques étirables, lavables et intégrables aux textiles;
- Développement de nouveaux polymères et de capteurs à base de polymères, intégrables à l'électronique lavable et étirable;
- Développement de technologies de caractérisation et de modification de surfaces afin de parvenir à une bonne adhérence entre les différentes couches;
- Développement de technologies pour l'intégration à un vêtement d'un système électronique modulaire complet comprenant des capteurs, ceci incluant le développement de technologies pour l'interconnexion des modules par des éléments tels que des fibres textiles conductrices;
- Mise en place de tests approfondis, en particulier pour vérifier la tenue au lavage des technologies développées (test d'étanchéité et de fiabilité);
- Conception et réalisation de deux démonstrateurs, comme preuve qu'il est possible de produire des circuits intégrés textiles fonctionnels et lavables.

1.3 Conclusions

Les principaux résultats et les conclusions du projet sont les suivants:

- Deux technologies ont été développées. La fiabilité et l'étanchéité, nécessaires pour l'intégration dans les textiles lavables, ont été optimisées par un traitement plasma d'oxygène, ce qui améliore l'adhérence des couches de silicone, et par l'utilisation de promoteurs d'adhésion qui permettent une tenue mécanique globale des circuits et de leur composants.
- Des capteurs d'humidité ont été mis au point à base de polyaniline en vue d'être intégrés au circuit électronique étirable, pour, par exemple, surveiller la présence d'humidité pendant l'utilisation du circuit (ex: sueur) ou après lavage (ex: test d'étanchéité).
- L'intégration de l'électronique étirable au textile se fait en deux étapes: le substrat textile est traité par sérigraphie d'une fine couche de silicone puis est collé au circuit préalablement scellé lui aussi dans du caoutchouc silicone. L'adhérence est assez élevée pour résister à plusieurs lavages.
- Deux techniques d'interconnexion des modules électroniques ont été développées: une des technologies assure la connexion électrique par des fibres textiles conductrices. Pour une meilleure connexion, la fibre est cousue à une pastille de cuivre sur le module. La deuxième technique d'interconnexion consiste au soudage de fils conventionnels sur cette même pastille de cuivre, combiné à des broderies pour maintenir les fils sur le substrat textile.
- Des essais approfondis sur des échantillons-tests ont été exécutés afin de vérifier l'étanchéité et la tenue au lavage. Ces tests ont été effectués avec une machine à laver domestique standard et avec des cycles de lavage en machine

professionnelle à chargement par le haut. Les tests ont montré que le facteur limitant pour la fiabilité ne vient ni de la pénétration de l'eau, ni de la présence de savon, mais bien des contraintes mécaniques incontrôlées survenant à chaque cycle de lavage (pliage, froissement, étirage, pressage). Lors de ces cycles, l'échantillon à tester était mélangé à d'autres textiles et à une charge, sans sac de protection individuel. En outre, il a été prouvé que le processus de séchage en machine limite le nombre de cycles de lavage que les circuits-tests pourraient supporter sans faillir. Le point faible des circuits se trouve au niveau des soudures des composants et des interconnexions qui sont rigides par rapport au substrat étirable. Suite à ces observations, les règles de conception des circuits ont été adaptées de façon à les renforcer localement aux endroits les plus soumis à des contraintes mécaniques. Les premiers résultats indiquent une amélioration drastique de la robustesse.

- Un certain nombre de démonstrateurs fonctionnels ont été conçus et fabriqués en utilisant les technologies développées. La plupart d'entre eux (affichage à LED étirable, module d'alimentation inductif) ont effectivement été réalisés dans la technologie des circuits étirables et intégrés dans un substrat textile. Pour d'autres démonstrateurs (capteur d'humidité à base de polyaniline, capteur de respiration par accéléromètres) les circuits électroniques ont été développés et approuvés sur circuit flexible, mais le temps était insuffisant pour la réalisation finale dans la technologie des circuits étirables et intégrés au textile. Néanmoins, il ne devrait pas y avoir de problème si cela devait être fait après la fin du projet car la même technologie d'intégration peut être utilisée.

1.4 Apport du projet dans un contexte d'appui scientifique au transfert des connaissances et à l'innovation

Le projet Belspo SWEET a eu, pendant et après le projet, un impact considérable sur les activités de recherche des différents groupes participants. Le projet a permis de créer une coopération avec des partenaires industriels, d'industrialiser des technologies de textiles intelligents et d'arriver à des applications plus proches de la réalité. Dans cette perspective, les activités et faits suivants doivent être mentionnés:

- Un brevet américain a été accordé à l'Université de Gand pour sa technologie de circuit étirable, qui forme la base pour les circuits lavables, tel que développés dans SWEET. De plus, sept demandes de brevets, portant sur l'amélioration technologique de la technologie brevetée, ont été présentées et sont actuellement en cours.
- Près de trente articles scientifiques, liés aux activités de SWEET, ont été publiés, dont dix dans la SCI (Web of Science), cités par des revues, et vingt lors de conférences internationales.

- Le projet a donné lieu à cinq doctorats, prouvant son haut niveau scientifique.
- SWEET est à la base d'un certain nombre de projets, permettant la poursuite des travaux sur le sujet. A titre d'exemple, jusqu'à présent, trois projets financés par la CE sur les textiles intelligents ont commencé, dans lequel au moins un partenaire SWEET participe.
- Un comité de suivi comprenant onze membres, provenant essentiellement de l'industrie, a été actif pendant toute la durée du projet. Son rôle était de diriger les activités des groupes de R&D, afin d'assurer la pertinence industrielle des travaux de recherche et de garantir le transfert des résultats de recherche obtenus dans un environnement industriel.
- En conséquence de cette interaction avec les utilisateurs industriels, l'Université de Gand se penche actuellement sur les voies d'industrialisation de sa technologie de circuits étirables. Les activités à mentionner à cet égard sont les suivantes:
    - L'installation planifiée d'une ligne de prototypage de petite taille, qui sera capable de produire des circuits sur substrat étirables jusqu'à 300 mm x 400 mm. Par conséquent, un investissement 300 k€ a été fait par le groupe de recherche concerné.
    - Une coopération bilatérale comprenant des partenaires industriels belges, et des membres du comité de suivi de SWEET, a été mise en place afin de vérifier les possibilités de transfert des différentes étapes de production des circuits étirables à un environnement industriel. Cette coopération implique en effet l'échange d'échantillons et le partage des développements technologiques pratiques.
    - Une coopération bilatérale entre l'Université de Gand et Centexbel Gand a permis une forte amélioration de la fiabilité et de la résistance au lavage grâce à des améliorations aux niveaux du design et de la technologie. Le résultat se rapproche à présent des normes industrielles pour les besoins de lavage des vêtements et textiles.

La réalisation industrielle de textiles intelligents contenant de l'électronique fortement intégrée et des éléments sensibles, tel que proposés et développés dans le projet SWEET, ne peut être menée à bien par une seule entreprise. Pour un tel produit toute une chaîne d'entités industrielles spécialisées est nécessaire: fabricants de PCB (circuits imprimés), sociétés d'assemblage de composants, industrie textile et l'utilisateur final, qui est à l'origine de l'idée et de la conception du produit. Tenter d'établir une telle chaîne est un défi que le consortium a désiré relever et des efforts sont en cours pour réaliser cette vision. Il est certain que si un tel effort peut être conclu correctement, un important marché s'ouvre pour les produits basés sur les technologies de SWEET. Cela a été mentionné par plusieurs membres de l'industrie textile du comité de suivi de SWEET, qui sont désireux d'utiliser la technologie pour leurs produits, mais pour l'instant ne voient pas de moyen direct pour concrétiser cet effort au niveau industriel.

1.5 Mots clefs

Textile intelligent, circuit étirable, senseur, capteur polymère, lavable, étanche, capteur de respiration, habit électronique.

2 SAMENVATTING

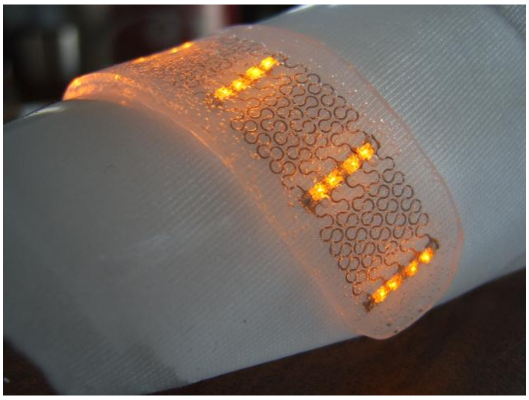
2.1 Context

In het huidige tijdperk van de "ambient intelligence" draagt de burger met zich meer en meer elektronische systemen mee tijdens allerlei activiteiten op allerlei plaatsen. Een voor de hand liggende manier om het groeiende aantal elektronische apparaten met een groeiende complexiteit op een comfortabele manier te dragen is om ze te integreren in de kleding van de gebruiker. Vandaag is de elektronica in deze "smart textiles" bijgevoegd als standaard beschikbare modules. Het is duidelijk dat dit niet ideaal is voor integratie in textiel, en dit om twee redenen:

- Het circuit kan niet of slechts in beperkte mate vervormen met het textiel (kan bij voorbeeld niet uitrekken);
- Het kledingstuk kan niet worden gereinigd/gewassen op een conventionele manier, zonder eerst de elektronica te verwijderen.

Een gebrek aan technologie voor een werkelijke integratie van de textiel-compatibele elektronica met hoge functionaliteit is een van de factoren die een massale doorbraak van "intelligent textiel" producten op dit moment verhindert. Indien men elektronische circuits zou kunnen produceren die op dezelfde wijze vervormen als textiel (bijvoorbeeld met een zekere uitrekbaarheid) en als deze circuits bovendien wasbaar zouden zijn, dan zou men een zeer hoge mate van integratie hebben bereikt, en aldus de weg geopend hebben naar een groot aantal toepassingen.

2.2 Doelstellingen



Het was precies het doel van dit project om een technologieplatform te ontwikkelen voor uitrekbare en wasbare elektronische schakelingen en voor de integratie van dit soort schakelingen in textiel. Bij het begin van het project was binnen het consortium een embryonale technologie beschikbaar voor de fabricage van elastische elektronische schakelingen. Deze technologie is gebaseerd op het gebruik van meandervormige Cu geleiders als interconnectie, en op inbedding van het circuit in elastische materialen zoals siliconen of polyurethanen. Deze inbedding biedt dus ook het potentieel op blootstelling aan vocht en water en voor wasbaarheid.

De volgende projectdoelstellingen werden geformuleerd:

- Verdere ontwikkeling van de elastische circuittechnologie en de aanpassing ervan voor textielintegratie en wasbaarheid;
- Ontwikkeling van nieuwe polymeren en polymeer gebaseerde sensoren, om te worden geïntegreerd met de wasbare elektronica;
- Ontwikkeling van oppervlaktekarakteriserings- en -modificatietechnologieën om een goede hechting tussen de verschillende lagen te bereiken;
- Ontwikkeling van technologieën voor de integratie van een compleet elektronica- en sensorsysteem in een kledingstuk, met inbegrip van de ontwikkeling van technologieën voor de elektrische connectie van ingebedde elektronica met textronics elementen zoals bv. geleidende textielvezels;
- Uitgebreide testen, met name van wasbaarheid van de ontwikkelde technologieën;
- Ontwerp en realisatie van twee demonstrators, waaruit de mogelijkheid blijkt om functionele wasbare en textiel geïntegreerde schakelingen te produceren.

2.3 Besluiten

De belangrijkste technische resultaten en conclusies uit het project zijn de volgende:

- Twee technologieën voor elastische circuits werden verder ontwikkeld. Betrouwbaarheid en hermeticiteit, die nodig zijn voor integratie in textiel en voor wasbaarheid, werden geoptimaliseerd, ten eerste met behulp van zuurstofplasma behandeling die de hechting van siliconelagen verbetert, en ten tweede door het gebruik van chemische hechtverbeteraars, die ook een verbetering van de hechting van siliconen op andere relevante materialen zoals elektronische componenten, soldeer, enz. bewerkstelligen.
- Polyaniline gebaseerde gas- en vochtigheidssensoren zijn ontwikkeld, die kunnen worden geïntegreerd met de uitrekbare circuits, en die bij voorbeeld dienen om het indringen van water of vocht (bv. zweet) in het circuit tijdens het gebruik of het wassen van het textiel te volgen.
- Een technologie voor de integratie van een rekbaar circuit in een textielsubstraat werd ontwikkeld, gebruik makend van zeefdrukken van siliconen op het textiel, gevolgd door het bonden van een in silicone ingebedde elektronicamodule op het silicone op het textiel. De hechting was hoog genoeg om wascycli te overleven.
- Twee technologieën voor interconnectie van elektronische modules, geïntegreerd in textiel werden ontwikkeld: in één technologie wordt de interconnectie verzekerd door geleidende textielvezels, en de beste verbinding met de elektronica wordt bereikt door het stikken van de vezels doorheen een Cu pad op de elektronicamodule. In een tweede technologie wordt de interconnectie verwezenlijkt door solderen van conventionele elektrische draden op Cu pads op de module, in

combinatie met borduren van de draden op het textielsubstraat.

- Uitgebreide waterpenetratie- en wasbaarheidstesten werden uitgevoerd op speciale monsters, waarbij zowel huishoudelijke als professionele wastesten werden geprogrammeerd. De tests toonden aan dat noch de indringing van water, noch de aanwezigheid van zeep de beperkende factor voor de betrouwbaarheid was. De ongecontroleerde mechanische stress op de ingebedde elektronica (vouwen, verfrommelen, uitrekken), die tijdens elke wasbeurt optreedt, het gewicht van ander textiel in de wastrommel, het niet gebruiken van een beschermend zakje tijdens het wassen, en het proces van droogzwieren bleken het aantal wasbeurten te beperken waaraan de testcircuits konden onderworpen worden zonder te falen. Het zwakke punt in de circuits, dat het gevoeligst is aan faling, is de plaats waar de contacten van de (vaste) componenten of gesoldeerde draad zijn aangesloten op de rekbare Cu geleider. Circuit ontwerpregels werden aangepast, rekening houdend met deze observaties, en plaatselijke verstevigingen (bescherming van deze zwakke punten) werden voorzien. De eerste resultaten wijzen op een drastische verbetering van betrouwbaarheid en robuustheid in opeenvolgende wasbeurten.
- Een aantal functionele demonstrators, gebruik makend van de ontwikkelde technologieën, werden ontworpen en gefabriceerd. Een aantal (uittrekbaar LED-display, inductieve bekrachtigingsmodule) werden effectief gerealiseerd in rekbaar circuit technologie en ingebed in een textielsubstraat. Voor andere demonstrators (polyaniline gebaseerde vochtsensor, accelerometrie gebaseerde ademhalingssensor) werden de elektronische circuits ontwikkeld en de functionaliteit bewezen, maar de tijd was te kort voor de uiteindelijke realisatie in rekbaar circuit technologie en textiel integratie. Omdat dezelfde integratietechnologie als voor de andere genoemde demonstrators kan worden gebruikt, worden geen problemen verwacht om deze integratie effectief uit te voeren.

2.4 Bijdrage van het project in een context van wetenschappelijke ondersteuning aan transfer van kennis en innovatie

Het Belspo-SWEET-project heeft een aanzienlijke impact gehad op de onderzoeksactiviteiten, tijdens en na het project, van de verschillende deelnemende groepen. Het project heeft samenwerking geïnitieerd met industriële partners over dit onderwerp, en bracht de industrialisatie van “slimme textiel”-technologieën en toepassingen dichter bij de werkelijkheid. In dit perspectief moeten volgende activiteiten en feiten worden vermeld:

- Een Amerikaans octrooi werd verleend aan de Universiteit Gent voor zijn rekbare circuit technologie, die de basis vormt voor de wasbare circuits, zoals ontwikkeld in SWEET. Zeven octrooiaanvragen, met betrekking tot technologische verbetering voor de gepatenteerde basistechnologie, zijn ingediend en zijn op dit moment in onderzoek.

- Bijna 30 wetenschappelijke artikelen, gerelateerd aan de activiteiten in SWEET, zijn gepubliceerd, waarvan 10 in SCI (Web of Science) geciteerde peer-reviewed tijdschriften en 20 op internationale conferenties.
- Het project resulteerde in 5 doctoraten, wat het hoge wetenschappelijke niveau ervan bewijst.
- SWEET is de basis geweest voor een aantal follow-up projecten, waardoor verder op het onderwerp kan gewerkt worden. Zo zijn tot nu toe 3 EG gefinancierde projecten op “smart textiles” begonnen, met telkens ten minste 1 deelnemende SWEET partner.
- Een follow-up Comité met 11 leden, voornamelijk uit de industrie, is tijdens het hele project actief geweest. Hun rol was om de activiteiten van de R&D-groepen te sturen om zodoende de industriële relevantie van het onderzoek te verzekeren en aldus te zorgen voor het potentieel voor overdracht naar een industriële omgeving van de verkregen onderzoeksresultaten.
- Als gevolg van deze interactie met industriële gebruikers is de Universiteit Gent momenteel routes naar de industrialisering van zijn uittrekbaar circuit technologie aan het verkennen. Activiteiten, in dit verband het vermelden waard, zijn:
    - De geplande installatie van een kleine prototype lijn, in staat om sample hoeveelheden van rekbare circuits te produceren op 300 mm x 400 mm substraten. Hiertoe is een 300 keuro investering gedaan door de betrokken onderzoeksgroep.
    - Bilaterale samenwerking met Belgische industriële partners, waaronder ook leden van de SWEET follow-up Comité, om het potentieel na te gaan voor de overdracht van de verschillende stappen in het productieproces voor uitrekbare circuits naar een industriële omgeving. Deze samenwerking omvat effectieve uitwisseling van monsters en praktische gedeelde technologische ontwikkelingen.
    - Verdere bilaterale samenwerking tussen de Universiteit Gent en Centexbel Gent, in het kader waarvan de betrouwbaarheid en de wasbaarheid ondertussen nog sterk verbeterd is door middel van ontwikkelingen in technologie en design, en de industriële normen voor de wasbaarheid van kleding en textiel benaderd worden.

De industriële realisatie van “smart textiles” met sterk geïntegreerde elektronica en sensor componenten, zoals voorgesteld en ontwikkeld in SWEET, kan niet worden gedaan door één enkel bedrijf. Voor een dergelijk product is een hele keten van gespecialiseerde industriële bedrijven noodzakelijk: PCB (Printed Circuit Board) fabrikanten, bedrijven voor elektronische componentassemblage, textielindustrie, en de uiteindelijke eindgebruiker, die het idee en het ontwerp van het product heeft geïnitieerd. Het wordt gezien als een uitdaging voor het consortium om te proberen een dergelijke waardeketen op te zetten, inspanningen worden momenteel gedaan om deze visie te realiseren. Het is zeker dat indien een dergelijke inspanning met succes kan worden afgerond, zich een belangrijke markt voor SWEET technologie gebaseerde producten zal openen. Dit is ook gesuggereerd door verschillende leden uit de textielindustrie van het SWEET follow-up Comité. Ze zijn vragende partij om de technologie in hun producten gebruiken, maar zien momenteel het industrieel pad niet om dit te realiseren.

2.5 Trefwoorden

Smart textiles, uittrekbaar circuit, polymeer sensor, wasbaarheid, ademhalingssensor, draagbare elektronica.

3 SUMMARY

3.1 Context

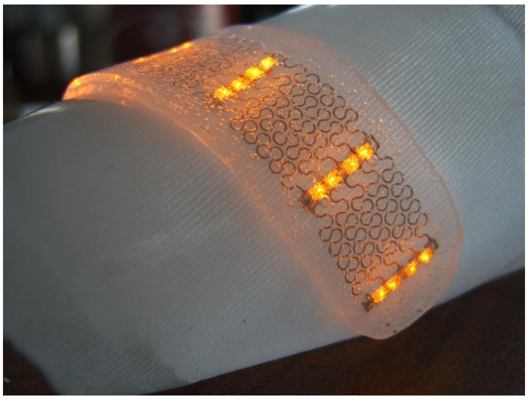
In the current era of "ambient intelligence" the citizen carries along more and more electronic systems during all kinds of activities at all kinds of places. An obvious way to comfortably carry along the growing number of electronic devices with growing complexity is to integrate them in the textile garments of user. Today the electronics in these "smart textiles" are attached as standard available modules. It is clear that this is not ideal for integration in textile for two reasons:

- The circuit cannot or only in a limited way deform with the textile (e.g. cannot stretch);
- The garment cannot be cleaned/washed in a conventional way without first removing the electronics.

A lack of technology for real integration of textile compatible electronics with high functionality is one of the factors which prevent a massive breakthrough of "intelligent textile" products at the moment. If one could fabricate electronics circuits which deform the same way as textile does (e.g. which are stretchable to some extent) and moreover which are washable, one would have achieved a very high degree of integration, thus opening the way to a large number of applications.

3.2 Objectives

It was precisely the aim of this project to develop a technology platform for stretchable and washable electronic circuits and for integration of this type of circuits in textile. Indeed at the start of the project an embryonic technology was available within the consortium for the fabrication of elastic electronic circuits. This technology is based on the use of meander shaped Cu conductors as interconnections, and embedding of the circuit in elastic materials such as silicones or polyurethanes. This embedding thus also creates the potential for exposure to humidity and water and for washability.



The following project objectives were formulated:

- Further development of the stretchable circuit technology and adaptation for textile integration and washability;

- Development of new polymers and polymer based sensors, to be integrated with the washable electronics;
- Development of surface characterisation and modification technologies in order to achieve proper adhesion between different layers;
- Development of technologies for integration of a complete electronics and sensor system into a garment, including development of technologies for electrical connection of embedded electronics with textronics elements like e.g. conductive textile fibres;
- Extensive testing, especially of washability of the developed technologies;
- Design and realisation of two demonstrators, proving the possibility to produce functional washable and textile integrated circuits.

3.3 Conclusions

The main technical results and conclusions from the project are the following:

- Two technologies for stretchable circuits were further developed. Reliability and hermeticity, necessary for integration in textiles and for washability, were optimised using oxygen plasma treatment which improves the adhesion strength of silicone layers, when dry-bonded to each other and secondly using chemical adhesion promoters, which moreover also improves the adhesion strength of silicone to other relevant materials like electronic components, solder, etc.
- Polyaniline based gas and humidity sensors were developed, which can be integrated with the stretchable circuits, and which can e.g. serve to monitor water or other humidity (e.g. sweat) ingress during use or washing of the smart textile.
- A technology for integration of a stretchable circuit in a textile substrate was developed, using screen printing of silicone on the textile, followed by bonding of a silicone embedded electronics module to the silicone on the textile. The achieved bonding strength was high enough to survive washing.
- Two technologies for the interconnection of electronic modules, integrated in textiles were developed: in one technology the interconnection is secured by conducting textile fibres, and the best connection to the electronics module is achieved by stitching of the conducting fibre through a Cu pad on the electronics module. In a second technology the interconnection is achieved by soldering conventional electrical wires to Cu pads on the module, combined with embroidery of the wires to the textile substrate.
- Extensive water penetration and washability tests were executed on dedicated test samples, performing standard domestic as well as professional washing cycles in top loading washing machine. The tests showed that nor the water penetration nor the presence of soap was the limiting factor for the reliability. The uncontrolled

mechanical stress on the embedded electronics (folding, crumpling, stretching), occurring during each washing cycle, and especially the presence of the weight of other textiles, the absence of a protective washing bag, and the process of tumble drying proved to limit the number of washing cycles to which the test circuits could be submitted without failing. The weak point in the circuits, prone to failure, is the place where the contacts of the (rigid) components or the soldered interconnection wire are connected to the stretchable Cu conductor. Circuit design rules were adapted according to these observations, and local stiffeners (protecting these weak points) applied. First results indicate a drastic reliability and robustness improvement under consecutive washing cycles.

- A number of functional demonstrators, using the technologies developed, were designed and fabricated. A number of them (stretchable LED display, inductive powering module) were effectively realised in stretchable circuit technology and embedded in a textile substrate. For other demonstrators (polyaniline based humidity sensor, accelerometry based breathing sensor) the electronic circuits were developed and the functionality proven, but time was too short for final realisation in stretchable circuit technology and textile integration, but as the same integration technology as for the other mentioned demonstrators can be used, no problems are expected to effectively do this after the official end of the project.

3.4 Contribution of the project in a context of scientific support to transfer of knowledge and innovation

The Belspo-SWEET project has had a considerable impact on the research activities, during and after the project, of the different participating groups. The project initiated co-operation with industrial partners on the subject, and brought industrialisation of smart textile technologies and applications closer to reality. In this perspective following activities and facts should be mentioned:

- A US patent was granted to Ghent University for its stretchable circuit technology, which forms the base for the washable circuits, as developed in SWEET. Seven more patent applications, covering technological improvement for the patented base technology, have been submitted and are currently pending.
- Almost 30 scientific papers, related to the activities in SWEET, have been published, of which 10 in SCI (Web of Science) cited peer reviewed journals and 20 at international conferences.
- The project resulted in 5 PhD’s, proving its high scientific level.
- SWEET has been the base for a number of follow-up projects, allowing further work on the subject. As an example, until now 3 EC funded projects on smart textiles have started, in which at least 1 SWEET partner is participating.
- A follow-up Committee with 11 members, mainly from industry, has been active

during the whole of the project. Their role was to steer the activities of the R&D groups, in order to insure the industrial relevance of the research work and thus securing the potential for transfer to an industrial environment of the obtained research results.

- As a result of this interaction with industrial users Ghent University is currently exploring routes to industrialisation of its stretchable circuits technology. Activities, worth mentioning in this respect are:
    - The planned installation of a small prototype line, able to produce sample quantities of stretchable circuits on 300 mm x 400 mm substrate. Therefore a 300 keuro investment has been done by the involved research group.
    - Bilateral co-operation with Belgian industrial partners, among which also members of the SWEET follow-up committee, in order to verify the potential for transfer of the different production steps for stretchable circuits to an industrial environment. This co-operation effectively involves exchange of samples and practical shared technological developments.
    - Further bilateral co-operation between Ghent University and Centexbel Ghent, in the frame of which reliability and washability is further strongly improving through advancements in technology and design, and now approaches the achievement of industrial standards for washability requirements of garments and textiles.

The industrial realisation of smart textiles with highly integrated electronics and sensor components, as proposed and developed in SWEET, cannot be done by a single company. For such a product a whole chain of specialised industrial entities is necessary: PCB (Printed Circuit Board) manufacturers, component assembly companies, textile industry, and the final end user, who has generated the idea and the design of the product. It is seen as a challenge for the consortium to try to establish such a value chain, and efforts are underway to realise this vision. It is for sure that if such an effort can be concluded successfully, an important market opens for SWEET technology based products. This has been mentioned by several members from textile industry of the SWEET follow-up Committee, who are eager to use the technology in their products, but currently do not see the industrial path to realise this.

3.5 Keywords

Smart textiles, stretchable circuits, polymer sensor, washability, breathing sensor, wearable electronics.

4 RESEARCH CONTEXT AND OBJECTIVES

In the current era of “ambient intelligence” the citizen carries along more and more electronic systems during all kinds of activities at all kinds of places. These electronic systems fulfil more and more complex functions. As an example “wearable computing” has become an important research domain. The limitation on user comfort and mobility of this increasing number of “portable” electronic systems must be kept to a minimum. Ideally these systems are quasi invisible and non-noticeable to the user. Therefore the increasing functionality must be combined with an increasing compactness, portability and decreasing weight. Preferentially the electronic circuit must take the shape of the object onto or into which it is integrated.

An obvious way to compile these portable electronic systems to one aggregate and to carry along the system in a comfortable way, is to integrate it in textile. Indeed textile is very versatile in construction and usage, and offers a platform for introduction of innovative technology, which is widely accepted by potential users. In this way portable electronics is transformed into wearable electronics with a low threshold for use. Therefore in recent years a lot of work on intelligent textile and embedding of electronics in textile is reported. Depending on the degree of integration following categories can be distinguished:

- Embedded electronics: existing electronic devices, circuits and components (e.g. portable phone, mp3-player, sensors,…) are built in into the textile (e.g. by integration in buttons, pockets, etc.).
- Textronics: certain passive electronic functions are realised in textile, e.g. connections by electrical or optical fibres, keyboards, textile antennas and electrodes, sensors.
- Fibertronics: realization of active components (transistors, sensors, etc.) with textile fibres.

At this moment “fibertronics” is still in its infancy and a lot of basic research is still required in this domain before achieving actual products. Furthermore the spectrum of components in textronics is too limited. As soon as a certain degree of functionality is required, one reverts to “traditional” electronics, which is then built in into the garments. All current commercial or pre-competitive products are of this type. The developments in the field of smart textiles can be divided into three main application categories: (1) consumer suits (mainly the integration of a mobile phone and/or a music player), (2) protective suits and (3) medical suits, intended for ambulatory monitoring. There are numerous prototypes and (semi)commercial products, e.g.:

- Developments in EC funded IST projects Wealthy, MyHeart, ConText, PlaceIt.
- The Mamagoose suit, intended for the prevention of SIDS (Sudden Infant Death Syndrome) and the WTSS, a training suit for special forces or firemen, able of monitoring movement, position, heart and respiration rate, both developed by the Belgian company Verhaert.
- The Lifeshirt from Vivometrics, intended for sports and health care applications. Respiration, ECG, blood pressure, position and movement can be monitored by attaching existing, removable sensors to a shirt.
- The ICD+ suit, developed by Philips and Levi's. A mobile phone and an MP3 player are integrated in a jacket.
- The Solar JKT Jacket of Zegna Sport (spring 2008) with 2 silicon-based integrated (rigid) solar cells, size 9 cm x 5.5 cm each, delivering 1.5 W max. in full sunlight, using technology from SOLARC Innovative Solarprodukte GmbH (Berlin, Germany) and in co-operation with Interactive Wear (Starnberg near Munich, Germany, a spin-off from Infineon (founded 2005) and a major European player in the field of intelligent textile (http://www.interactive-wear.de).

The pictures above show some examples of realised products. From left to right one sees the O'Neill Hub (snowboard jacket), MP3Blue (2005, MP3 playing jacket) and "Know Where Jacket" (2006, GPS/Galileo Demo Jacket) from Interactive Wear.

Today the electronics in "smart textiles" are attached as standard available modules or, when dedicated modules are preferred, are realized on traditional interconnection substrates, i.e. normally rigid Printed Circuit Boards (PCB's) or mechanically flexible substrates at the most. It is clear that this is not ideal for integration in textile for two reasons:

- The circuit cannot or only in a limited way deform with the textile (e.g. cannot stretch);
- The garment cannot be cleaned/washed in a conventional way without first removing the electronics.

A lack of technology for real integration of textile compatible electronics with high functionality is one of the factors which prevent a massive breakthrough of "intelligent textile" products at the moment. If one could fabricate electronics circuits which deform the same way as textile does (e.g. which are stretchable to some extent) and moreover which are washable, one has achieved a very high degree of integration, thus opening the way to a large number of applications. It was precisely the aim of this project to develop a technology platform for stretchable and washable electronic circuits and for integration of this type of circuits in textile.

Additional insights have been gained from discussions within the SFIT (Smart Fabrics and Interactive Textiles) cluster of EC funded projects. Main points to be remembered from these discussions include:

- An intelligent textile product can be successful only if one takes full advantage of the large area the textile offers. It does not make sense to integrate an mp3 player in textile; consumers rather wear the player around their neck. Putting the player in a textile pocket does not offer enough added value. In this respect wearable signage (LEDS distributed over a textile surface) and distributed sensors (e.g. movement sensors on different body parts) seem to offer interesting applications.
- Extensive research on physiological sensors in textile format for EEG or EMG has revealed the limited use of these types of sensors because of movement artefacts. Reliable sensing requires the sensors to be attached to the skin, which considerably decreases the advantages, offered by textile integration of the electronics which handles the sensor signals.
- Almost all projects so far concentrate on "professional" applications: medical textile, sensors in fire brigade suits, etc. Reason is the maintenance and washability issue: this professional gear is normally sold by a company who also offers a contract for maintenance. No fire fighter will wash his own uniform. The company who has delivered the garment has the necessary knowledge on how to clean/maintain it. If one wants to develop consumer products it is absolutely necessary that the consumer can clean the product by him- or herself. Therefore washability of intelligent textile is an absolutely necessary condition for being able to enter the consumer market.

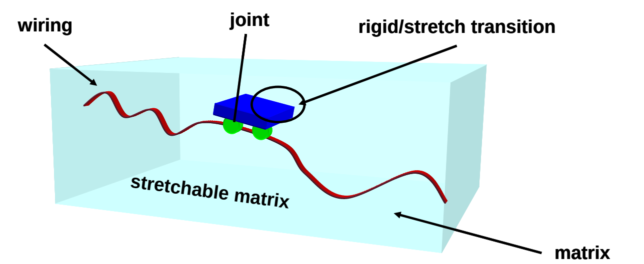
Experts, involved in EC funded projects on intelligent textiles, identify development of washability of intelligent textile as truly basic research. In 2008 these experts did not expect that the problem of washability would be solved within the next 5 years. In this respect it is clear that SWEET was much more ambitious: SWEET wanted to demonstrate a certain degree of washability by the end of the project (2010). It can be said that important steps towards reaching this goals have been set, but the work is not complete.

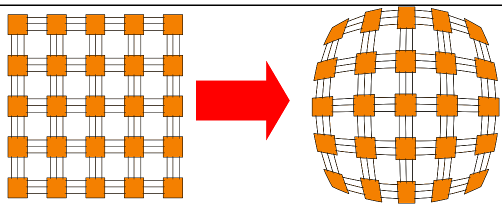
It was the intention of the SWEET project to perform work in the direction of highly integrated electronics in textile. ***SWEET aimed at the development of a technology platform for stretchable and washable electronic circuits and for embedding technologies of these circuits in textiles.***

Technology developments were driven by 2 demonstrators which were be selected, with the advice of the follow-up Committee.

5 METHODOLOGY AND CONSORTIUM

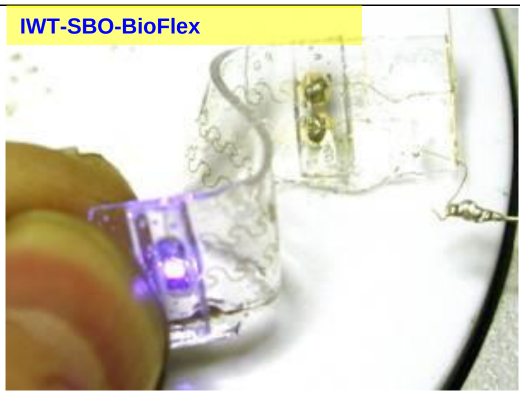
As described in the previous paragraph one of the main challenges of this project was to fabricate stretchable and washable electronic circuits. Stretchable electronics is a very innovative technology. At the start of the project the technology was under development at only a few R&D institutes in the world, mainly at some renowned institutes in the USA (Princeton University, Lawrence Livermore National Laboratories, Johns Hopkins University Hospital). In elastic circuits the components form small rigid or ultimately (e.g. ultrathin chips) flexible islands, which are connected with stretchable wiring. This principle is shown in the figure below.





Rigid/flexible components connected by stretchable wiring allowing arbitrary deformation of the circuit

The essence of stretchable circuits is thus the fabrication of stretchable electrical interconnections. These stretchable conductors can be achieved in a number of ways. Because metals have by far the best conductivity and are cheap compared to nano-materials, conducting polymers and filled polymers, they seem to be the best choice, provided they can be applied in a suitable shape. At the start of the project UGent was developing a cost effective technology for stretchable wiring, based on meander shaped metal wires, embedded in a stretchable carrier, and using an MID (Moulded Interconnect Device) technology. Details of this technology and further versions of are described in section 6.1.1. The very first demonstrator, available from UGent, is shown in the picture below. It is a single LED, with two meander-shaped stretchable interconnects (consisting of plated Au in this case).



In this technologies silicone (PDMS – poly-dimethyl siloxane) is used as the stretchable material. In projects, preceding SWEET (IWT-SBO-"BioFlex" and EC-IST-IP-"STELLA" ("Stretchable Electronics for Large Area Applications")) however no special attention was paid to integration in textiles. UGent had proven the feasibility of interconnections with a stretchability of 50% and more. Also the possibility of component embedding in the stretchable matrix had been demonstrated.

At the start of the project it was clear that a very promising embryonic technology for the manufacturing of stretchable electronic circuits was available in the SWEET consortium; however a lot of additional work was required to achieve intelligent textile, based on this technology. In SWEET the following methodology and work package structure was implemented for achieving the goal of a competitive and exploitable intelligent textile technology:

- Work package 1: In the beginning of the project suitable demonstrators were defined and specified. The plan was to develop 2 demonstrators with an increasing degree of complexity and risk:
    - The first demonstrator: a universal intelligent textile building block without textronics components or polymer based sensors (purely based on the MID technology as explained above). A wireless power supply building block was chosen.
    - The second demonstrator: a fully functional unit, including textronics elements and selected electro-active polymer sensors, developed in SWEET.

- Work package 2: Based on the demonstrator specifications, the necessary technology building blocks were developed:
    - MID stretchable electronics circuit technology was further developed and transformed into a version, suitable for textile integration.
    - Electro-active polymers were developed for sensing functions and sensing devices, using these polymers were fabricated.
    - Technology for metal and polymer surface modification and characterization in order to optimize metal/polymer and polymer/ polymer adhesion were developed.
    - Technology for embedding of the MID stretchable electronic circuits in textile and for interconnection of the MID circuits with textronics components was developed.

Although the technology developments were driven by the specific demonstrators of WP1, the aim was to develop a broad technology platform, allowing many other intelligent textile applications.

- Work package 3: Based on the specifications of WP1 and technology developments of WP2 the demonstrators were be designed.

- Work package 4: Demonstrators were realised and tested.

- Work package 0: Management with following separate activities:
    - Administrative management
    - Follow-up Committee organization
    - Valorisation
    - Dissemination

To perform this work a competent and well balanced consortium has been formed:

- UGent/CMST is a substrate and assembly technology provider and was responsible for further development of MID stretchable electronic circuit technology, partly for the development of interconnection technology electronics – textronics and washability evaluation. UGent/CMST was also responsible for the project coordination.
- KULeuven/MICAS is specialized in electronic system design in the field of medical/biomedical applications including power supply and wireless communication hardware; MICAS was responsible for the design, fabrication and testing of the demonstrators.
- Centexbel is a Collective Research Centre on textile and was the main responsible for development of the technology for integration of the stretchable electronic circuits in textiles, including the interconnection with existing textronics components. The two divisions of Centexbel (Gent and Verviers) with their own specificities were implied in the project. Centexbel also served as the link between SWEET and potential users within the Belgian textile industry.
- UCL/PCPM is a materials specialist, especially on polymer materials fabrication and surface science. PCPM was responsible firstly for the development of new electro-active polymers, especially for their use as sensing materials, and secondly for the work concerning characterization and modification of polymer and metal interface surfaces.

6 TECHNICAL REPORT

6.1 Technology development

6.1.1 Stretchable electronic circuits

Regarding Task 2.1, different technologies for stretchable electronic circuits have been developed at UGent. This activity was carried out, not only in the frame of the SWEET project, but also in the frame of IWT-SBO-BioFlex and EC-FP6-IP-STELLA. The stretchable electronics technology uses standard SMD electronic components, typically being non-stretchable. They are grouped in non-stretchable functional islands which are interconnected by 2-D spring-shaped copper connections. This principle is shown in Fig. 1.

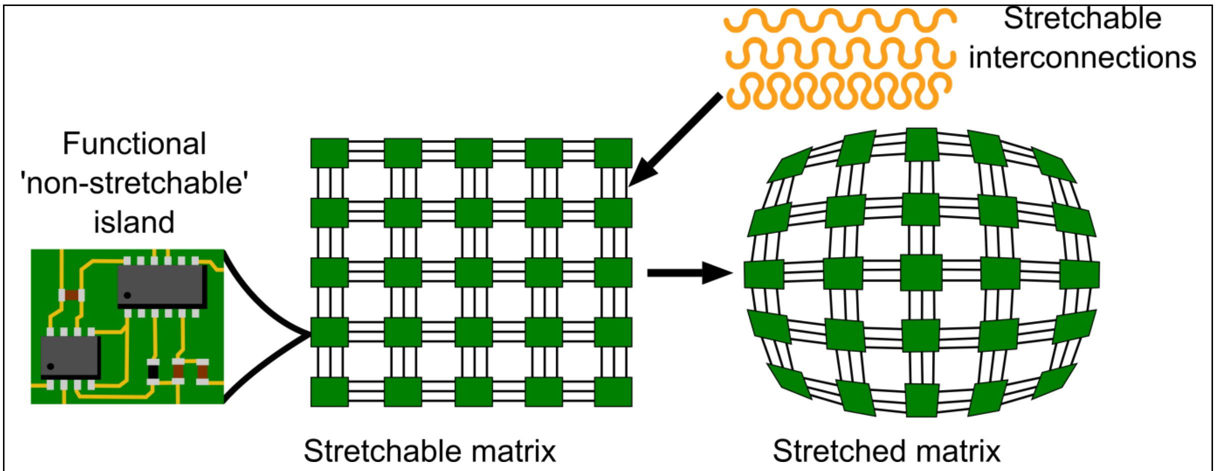


Fig. 1: Design principle of stretchable circuits

According to the initial planning it was the intention to fabricate stretchable circuits using meander shaped plated metals as the conductor. Plated metals included Au and Cu. By the start of the SWEET project, additional technologies were under development at UGent in the frame of other projects on stretchable circuits, which are preferable to the plated metal technology for a number of reasons, cost and feasibility being the main ones. The key features of these technologies are:

- Use of meander shaped interconnections as stretchable interconnects;
- Use of a rigid or flexible sacrificial substrate, removed at the end of the process;
- Use of moulding technology yielding completely embedded circuits, with potential for washability;
- Attempt to develop processes close to industrial printed circuit manufacturing (e.g. use of conventional leadfree solder assembly process (250-260 deg C)).

These processes are further co-developed in SWEET and other running projects on stretchable circuits. In general they are called SMI = "Stretchable Mould Interconnect" technologies. These SMI technologies are used to encapsulate the electronics and to protect them from water during washing. The process flow of the 2 versions of SMI technology, used by UGent in SWEET are shown below:

- The "peelable substrate technology" (Fig. 2): starts from a Cu sheet, laminated on a sacrificial substrate, using wax.
- The "laser structuring technology" (Fig. 3): starts from a standard flex, laminated on a ceramic substrate and uses laser structuring of the meanders. This technology is used for fast prototyping, but is less suitable for industrialisation (because of the residue removal step).

The process flow of the "peelable substrate technology", developed by UGent is shown below in Fig. 2:

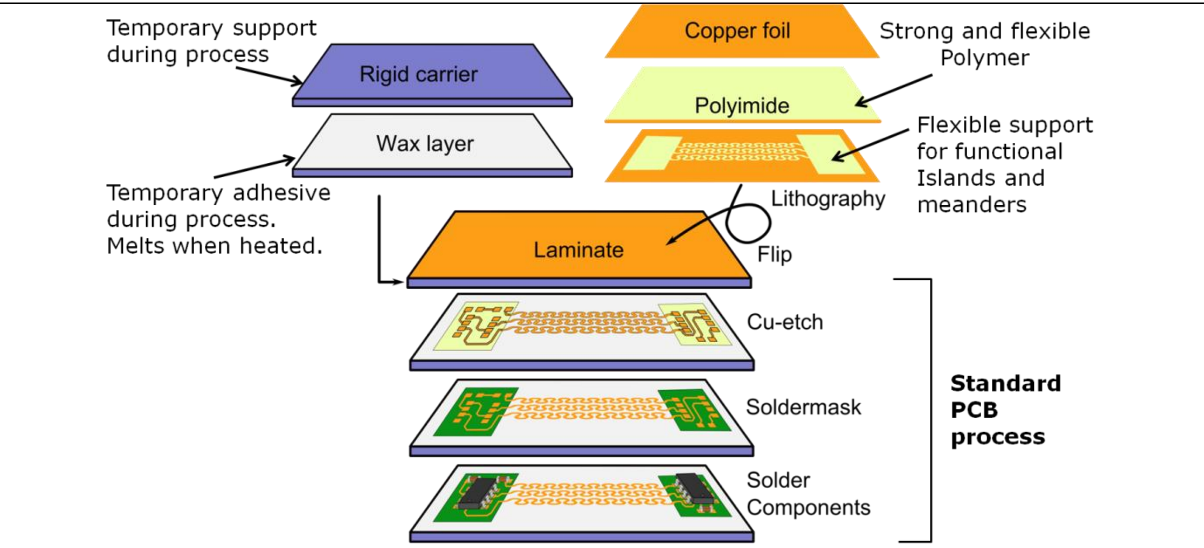


Fig. 2: Peelable substrate technology

The technology starts from a copper foil on which a layer of photo definable polyimide is spun. By lithography the polyimide is patterned to create non-stretchable, but flexible islands. The polyimide is also used to support the copper meanders in order to give them additional strength. After patterning, the substrate is turned with the plain copper side upwards and laminated with wax on a rigid carrier. The carrier is only temporary and will be removed just before embedding the circuit. At this stage of the process, the substrate looks like a standard, rigid PCB. The following steps are the same steps used in PCB manufacturing: patterning the copper by lithography and spray-etching; screen printing soldermask; mounting components and reflow soldering. At this point the circuit can be tested and if necessary (and possible) repaired.

Another way of producing the stretchable electronic circuits is by use of the "laser structuring technology". The process flow is shown in Fig. 3.

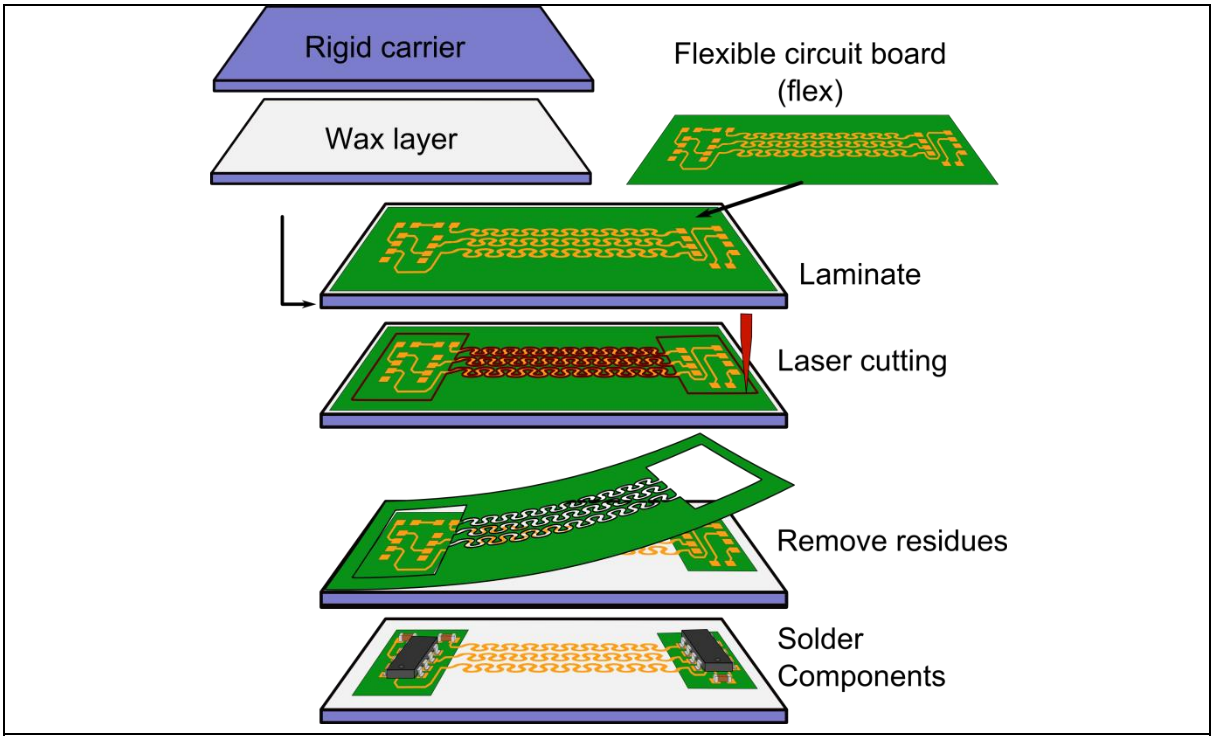


Fig. 3: Laser structuring technology

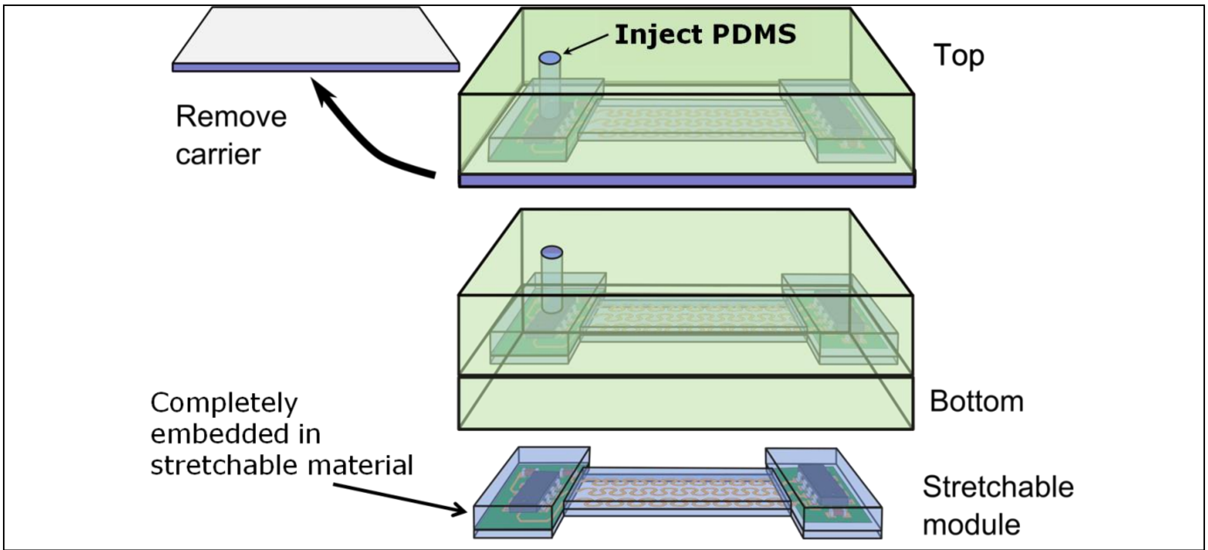


Fig. 4: Molding

The "laser structuring technology" starts from a standard flexible circuit board (polyimide + copper pattern) which is laminated with wax on a rigid carrier. The meanders and polyimide islands are structured in one step by laser cutting. The rest of the process steps are the same as for the peelable technology (solder components and molding). This technology is used for fast prototyping, but is less suitable for industrialization (because of the residue removal step). From the moment that there are a lot of meanders, the laser cutting becomes also more time consuming and it's harder to remove the residues (done by hand). However the technology is very useful and fast for small and simple test structures.

In the next steps the circuit is embedded by liquid injection molding (see Fig. 4). First the upper part is moulded and cured. Then the wax is heated to peel of the temporary rigid carrier. In the last step the bottom part is molded. After the described process we end up with a stretchable and completely encapsulated electronic circuit. This embedded electronic module will be integrated with textile.

6.1.2 Organic flexible/stretchable conductor and sensor development

The development of electro-conductive polymers

The flexible and stretchable electronics paradigm would not have been properly tackled without introducing at least one organic electro-active material in the project. Polyaniline (PANI) was chosen among various electro-conductive polymers (PEDOT-PSS, polypyrole, poly-alkylthiophene) for its versatile properties and possible utilizations. Firstly, it can be simply used as an organic electrical conductor when highly doped with protons. Secondly, it can be used in any pH-linked sensor when proton doping is properly interfaced with a sensitizer (enzyme, etc.).

<u>Polyaniline as a conductor</u>

Different polyaniline synthetic routes were explored, including chemical oxidative reaction and electro-polymerization. In the first one, aniline was oxidized into polyaniline by ammonium persulfate - $(NH_4)_2S_2O_8$ - in acidic aqueous condition. In a first attempt, the chemical oxidative reaction was successfully tested on golden meanders circuits manufactured by UGent partner on a polydimethylsiloxane (PDMS) substrate. The resulting devices were characterized using both Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) and scanning electron microscopy (SEM), as depicted in the following section. Electrical shunting between independent meander tracks was verified. Once it was realized that the electrical failure of the meanders was mostly due to a mechanical disruption in the meanders/connection pads interface, the electrical shunting with PANI in this specific region would favour the overall conductive behaviour of the ensemble. For solving this problem, electro-polymerization could be used to specifically coat the metallic meanders bonded to the connection pads. Because PANI also deposits onto hydrophobic surfaces, some polymerized aniline would coat both gold and PDMS, ensuring in this way the electrical contact in the case of a mechanical failure. The possibility of employing this methodology and the most promising route were defined by UCL and UGent partners. The electrochemical synthesis of PANI directly at the interface should be compatible with the current procedure of embedding metallic tracks applied by UGent.

<u>Polyaniline as a sensor</u>

Polyaniline was also investigated to produce humidity and gas sensors. Humidity sensing was first demonstrated by coating the gold meanders developed at UGent with PANI. The idea consisted in short-circuiting the gold tracks with the conducting polymer, and in such a configuration the PANI coating could act as a resistive sensor. This simple configuration was tested and the impedance changes between several independent meanders tracks, bridged by PANI, were electrically characterized. Humidity could be easily detected by monitoring impedance decreases of such a device.

As an improvement of the potentiality in developing sensors with PANI as the sensitive agent, a small assembly of gas sensors was then demonstrated by coating gold electrodes produced in printed circuit board (PCB) substrates. These were used as resistive sensors and their response to the environment was demonstrated by sensing different gases such as isopropanol, base (NH_3), acid (HCl) and humidity changes (Fig. 5). High sensitivity and good reproducibility were obtained with these electrodes. As in the case of a PCB substrate, a very reproducible change in the impedance as a function of the surrounding humidity was also obtained for the sensor fabricated on the PDMS stretchable substrate. The advantage is that the size of the sensors can be easily downscaled to the micrometer scale.

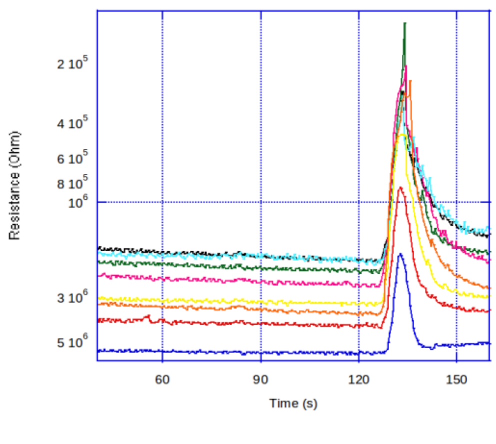


Fig. 5: Humidity sensing on a 8 sensors array

Other more specific gas sensors where also produced such as electrochemical sensors based on a three electrodes system (reference, counter and PANI working electrodes) embedded in an electrolytic gel (Fig. 6).

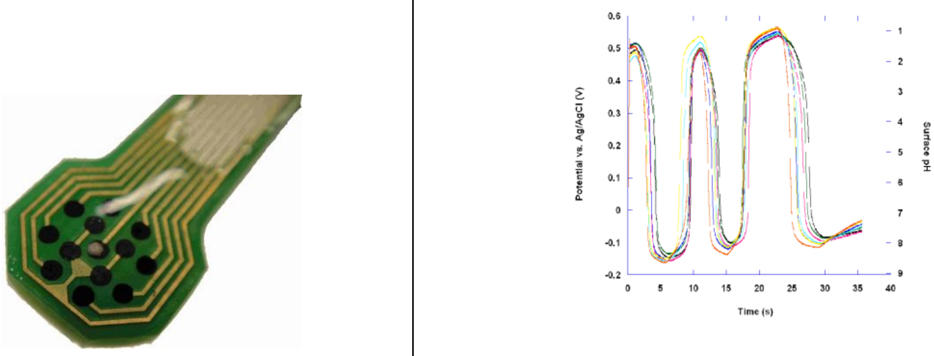


Fig. 6: Acid (HCl) and base (NH3) gas sensing with a 8 sensors array electrochemical cell

By then, it had become clearer that the humidity sensors could be properly adapted for the monitoring of electronic circuit environments when embedded in washable clothing.

During this last year, a considerable effort was then furnished in order to build a fully integrable humidity sensor in the sweet demonstrator. For that purpose, it was found more convenient and cheaper to fully integrate the sensing probe to its driving electronic circuit on a flexible substrate. This driving electronic unit was also adapted to KUL partners needs concerning data exchange protocols (mainly through ADC-SPI exchange) (Fig. 7).

Fig. 7: Schematic and prototype of the SWEET humidity sensor

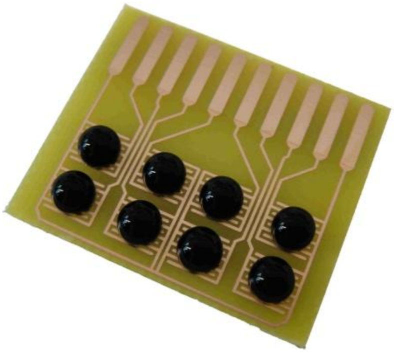


Fig. 8: Drop effect by surface tension contrast patterning

As copper does not allow to electrochemically deposit polyaniline, a proper water based colloidal polyaniline suspension was developed. The latter allows an easy and precise covering of the interdigited sensors by using surface tension contrast patterning (Fig. 8).

The entire device was fully characterized and tested many times for its reproducibility.
Its complete embedding in Sylgard 184 silicone showed no particular side-effects on the humidity sensing capabilities.

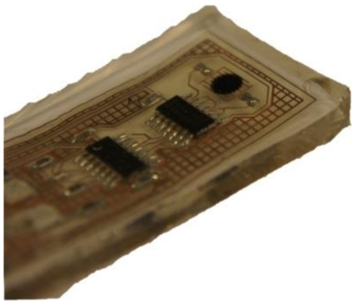


Fig. 9: Example of silicone embedded humidity sensor

This device is now currently used to test many silicone embedding processes. Indeed, in the future, the flexible electronics circuits could either be completely embedded in a pre-cured silicone preparation (complete sealing) or trapped between two soldered silicone sheets (either by gluing or by plasma bonding). It is clear that depending on the process water leakages or diffusions will happen differently in time and intensity.

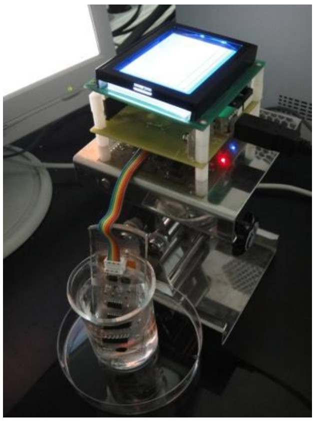


Fig. 10: Picture showing an ongoing experiment of humidity sensing

This electronic circuit has been sent to UGent partners in order to insert it in the final SWEET demonstrator.

6.1.3 Surface treatment and modification

Improvement of metal-polymer and polymer-polymer adhesion

Many studies were undertaken in order to resolve the many challenges that silicone implies in the metal-polymer and polymer-polymer adhesion. These results can be found in scientific articles referenced on section 7.1.

The most important result concerned the characterization of PDMS plasma treatment. The adhesion of poly(dimethylsiloxane) (PDMS) rubber can be largely improved by oxygen plasma surface treatment. The thickness of the subsequent silica-like surface layer was characterized by performing transmission electron microscopy imagery on microtome slices of welded plasma treated surfaces. The specific double layer contrast was considered as equal to twice the thickness of the silica-like layer. The thickness measurements combined with strain-induced elastic buckling instability analysis gave an estimate of the elastic modulus of the silica-like layer equal to 1.5 GPa.

Use of Dow Corning adhesion promoters

To prevent the electronic circuit from several influences of the textile washing process, (Humidity, Chemical load, mechanical load) a high degree of encapsulation is necessary. Therefore a good adhesion between the silicone and the other materials (polyimide, soldermask, Cu, silicone,...) is needed. A good adhesion is also important for the reliability of the end product. The use of plasma treatment and adhesion promoters (1200 OS primer from Dow Corning) where investigated.

The most important test results obtained by UGent are discussed below.

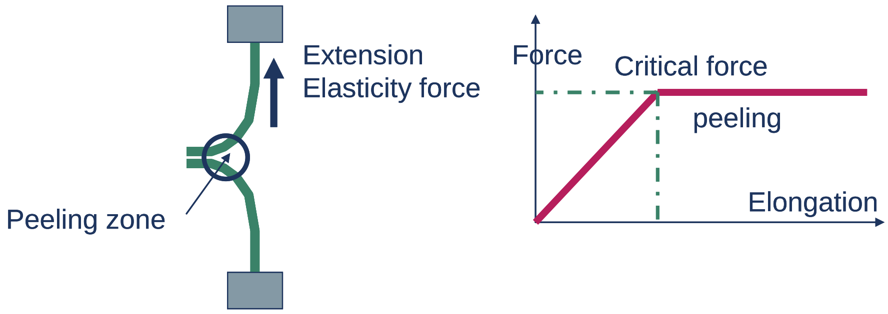


Fig. 11: Methodology of the peeling test

To test the adhesion, a standard peeling test is not possible, as at least one of the layers is elastic. Therefore we developed a test which can handle samples with an elastic layer.

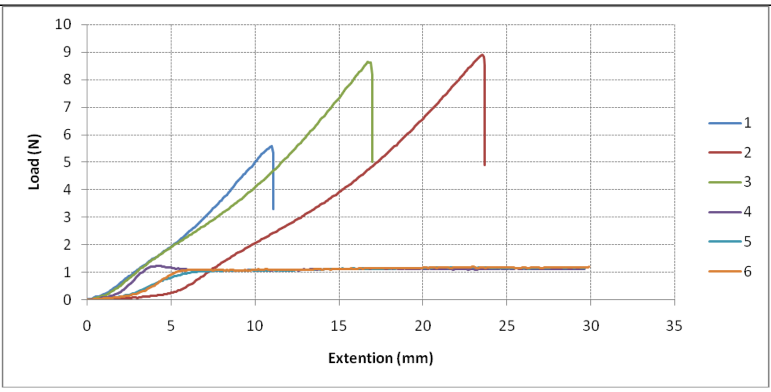
Adhesion is a force between two elements, proportional to the length of the adhesion line, and to a parameter G which depends only on the surface of the two elements. If a sample has a width W, then the adhesion force is ADH = G x W. Testing the adhesion is measuring G.

Fig. 12: Sample under test

The test uses a puling system INSTRON 5543, which can measure the force and the elongation. The sample has two layers, which have a width W. Those two layers are partially in adhesion together. At the beginning of the pulling test, the elongation E induces a force F, which is F = Y* E (Y can be the young modulus, or a composite of two young modulus). If F < ADH, then there is only elongation. If F = ADH, then there is peeling off of the two layers, and then elongation E is due to the peeling off and not anymore due to elongation. If the sample is homogeneous, the force F is then constantly equal to ADH. It appears on the graph that in a first stage the force is proportional to the elongation, and when the force reaches a critical level the force is constant. To ease comparison, we set up a standard that the entire sample should be 1 cm wide and the elastic layer should be 1 mm thick.

The described peeltest methodology was used to test the adhesion between the following layers:

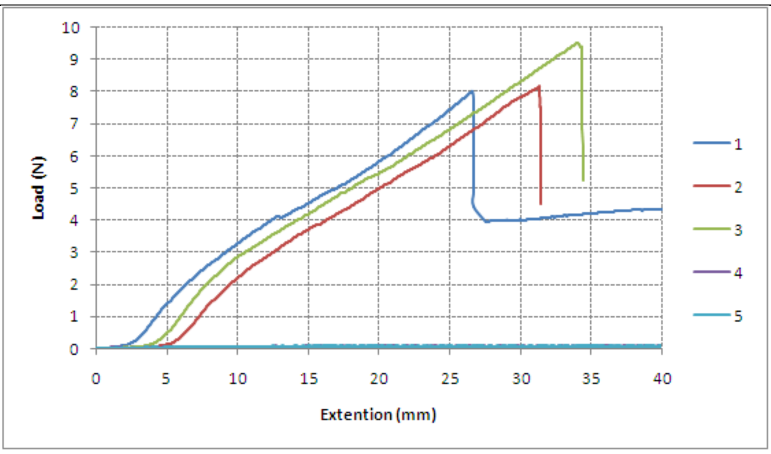
- Sylgard 186 silicone – copper (wet silicone casted on copper) (Fig. 13)
- Sylgard 186 silicone – polyimide (wet silicone casted on polyimide) (Fig. 14)
- Sylgard 186 silicone – soldermask (wet silicone casted on polyimide with soldermask) (Fig. 15)
- Sylgard 186 silicone – soldertin (wet silicone casted on layer of soldertin) (Fig. 16)
- Sylgard 186 silicone cured – Sylgard 186 cured (plasmabonding) (Fig. 17)
- Sylgard 186 silicone cured – Sylgard 186 wet (wet silicone casted on cured silicone) (Fig. 18)



Test samples 1, 2 and 3 are with 1200 OS primer, resulting in a very good adhesion with the µetched copper. There is no peeling and the Sylgard 186 strip breaks at a load off about 8.7 N.

Test samples 4, 5 and 6 are without primer. Peel off occurs at about 1.1 N, showing that the adhesion without primer isn't good.

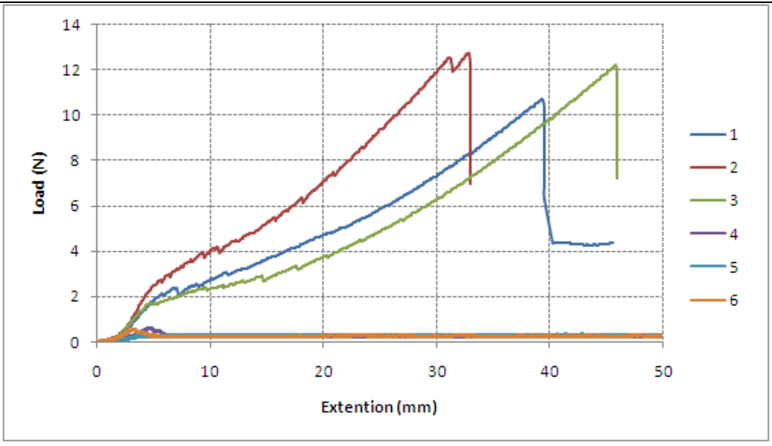
Fig. 13: Comparison adhesion Sylgard 186/µetched copper with and without 1200 OS primer



Test samples 1, 2 and 3 are with 1200 OS primer, resulting in a very good adhesion with the polyimide. There is no peeling and the Sylgard 186 strip breaks at a load off about 8 N - 9.5 N.

Test samples 4 and 5 are without primer. Peel off occurs directly, showing that there is no adhesion without primer.

Fig. 14: Comparison adhesion Sylgard 186/polyimide with and without 1200 OS primer



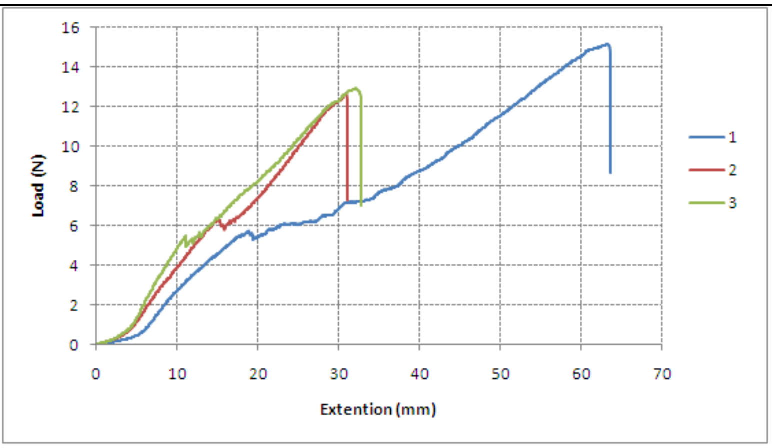
Test samples 1, 2 and 3 are with 1200 OS primer, resulting in a very good adhesion with the soldermask. There is no peeling and the Sylgard 186 strip breaks at a load off about 10 N – 12 N.

Test samples 4, 5 and 6 are without primer. Peel off occurs at about 0.3 N, showing that there is almost no adhesion without primer.

Fig. 15: Comparison adhesion Sylgard 186/soldermask with and without 1200 OS primer

It must been noticed that the adhesion promoter is in fact used twice here due to the process flow of the peelable technology. At first the primer is applied on the wax layer of the carrier. Onto this, the first wet silicone layer is applied and cured. After peel-off, the primer is used a second time before we apply the second wet silicone layer.

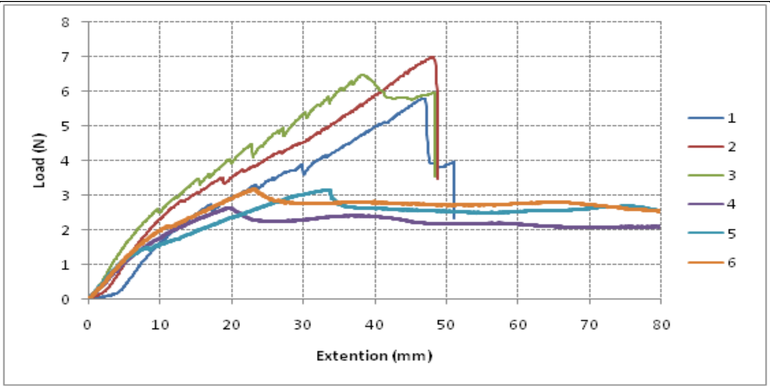
When the adhesion promoter was applied directly on the cured silicone layer + casting a second wet silicone layer, no adhesion improvement was noticed.



Test samples 1, 2 and 3 are with 1200 OS primer, resulting in a very good adhesion with the soldertin. There is no peeling and the Sylgard 186 strip breaks at a load off about 12 N – 15 N.

Fig. 16: Adhesion Sylgard 186/soldertin with 1200 OS primer

We can conclude that the adhesion promoter performs good adhesion between the PDMS and the copper, polyimide, solder mask and solder tin. Because de promoter is used two times in the moulding process, it also performs a good adhesion between the molded top and bottom PDMS layer.



Test samples 1, 2 and 3 are with 1200 OS primer, resulting in a very good adhesion with the other casted silicone layer. The strip breaks at a load of about 6.4 N.

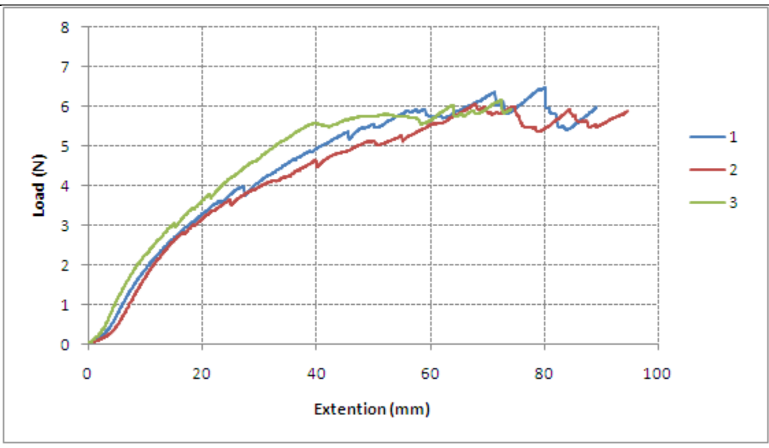
Test samples 4, 5 and 6 are without primer. Peel off occurs at about 2.5 N, showing that there is a certain adhesion without primer (but not sufficient).

Fig. 17: Adhesion Sylgard 186 cured/Sylgard186 wet

The use of plasma results in a sufficient bonding between two cured 186 layers. It's important to notice that these adhesion tests for plasma bonding where done at the moment that we thought of using the Sylgard 186 for molding and for screen printing on textile.

As mentioned in section 6.1.4, we used the 9600 and 9601 textile silicones for screen printing and gluing. This means that new adhesion tests are needed to evaluate the bonding between 186 and the textile silicones 9600 and 9601.

Dummy molded samples were glued to a textile and subjected to several washing cycles without delamination. We concluded that the adhesion is strong enough for the washing in a standard washing machine.



Peeling starts at about 5.5 N, showing that the plasma treatment results in a sufficient adhesion. Without plasma treatment there is no adhesion.

Fig. 18: Adhesion Sylgard 186 cured/Sylgard 186 cured with vacuum plasma treatment (drybonding)

An alternative procedure was proposed by Centexbel based on experience and literature to improve the adhesion between metal conductors (Cu or Au) and silicone rubber. Often a layer of mercaptosilane is deposited onto the metal but this material is prone to polymerization and has a low reactivity leading to a rather limited improvement in adhesion. Considering the type of silicone precursors used, Centexbel suggested a procedure to deposit a vinyl-terminated monolayer on top of the Au or Cu metal which is reactive towards the cross-linker and Pt-catalyst commonly used in room-temperature curing silicones. In this way, the silicone rubber becomes chemically bonded to the metal surface during the curing process.

6.1.4 Integration of electronics in textiles

After embedding, the electronic modules need to be integrated with the textile. As a first possibility UGent proposed the following process flow:

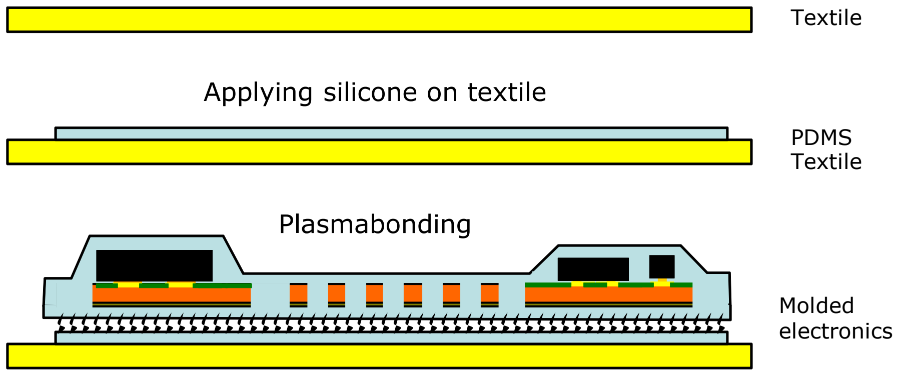


Fig. 19: Laser structuring technology

A thin layer of silicone is applied on the textile on the spots where the embedded electronic modules have to come. After applying the silicone is cured. In the next step the cured silicone layer on textile and the bottom layer of the molded part are activated by plasma and pressed together to form an irreversible bonding. At UGent this plasma-activation was done in a vacuum plasma chamber. However when one looks to industrialization the vacuum plasma activation of (several) spots on a "large" textile is not an option. One should look then to atmospheric, corona or ozone plasma. Centexbel has the possibilities to use corona and ozone.

UGent first tested the possibility of casting silicone on textile. An aluminum plate is used to cast the desired pattern onto the textile (Fig. 20). This casting technique was used to produce the test vehicles for stitch tests (Fig. 21).

Fig. 20: Casting silicone on textile

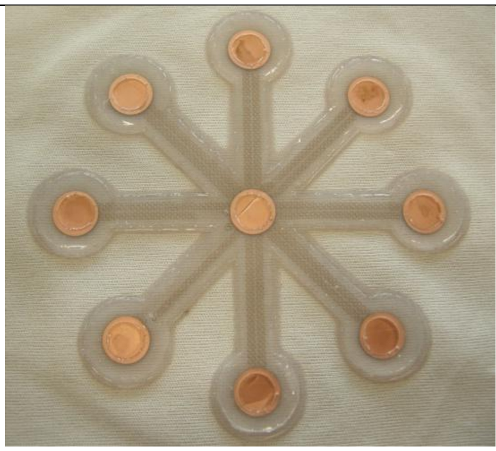


Fig. 21: Stitch test sample

At this stage in the project Sylgard 186 was used for casting. Sylgard 184 was also tested but its viscosity seemed to be too low to have a layer on top of the textile. Sylgard 186 has a higher viscosity which made it possible to have a layer on the textile. Nerveless we noticed silicone penetration through the textile which was visible on the back.

Casting is a well suited technique for applying simple patterns, like the star, on the textile. However if more complex patterns are needed, casting is not always possible. This is illustrated in Fig. 22.

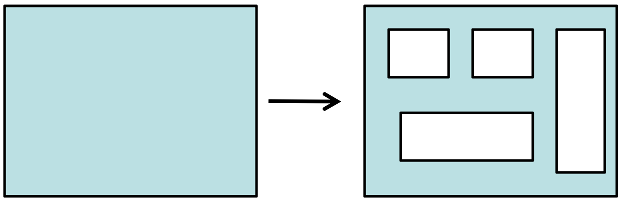


Fig. 22: Minimizing silicone surface for maximum breathability

We're looking for a minimization of the silicone surface, to make the end result as breathable as possible. This will also lead to a lighter and more flexible/stretchable product. In order to achieve this higher comfort a technique like screen-printing is needed to define the silicone pattern on textile. Not only the screen-printed part needs to have these openings in the silicone, also the molded part should have these openings. Therefore UGent optimized the molding step and more complex mold designs were made to create these openings.

Centexbel did several screen-print tests with the Sylgard 184 and 186 silicones (see below). The main conclusion was that also with screen-printing too much silicone penetrated through the textile. Therefore UGent searched for other silicones with higher viscosity. The Dow Corning 9600 and 9601 Textile Printing Ink were selected. Table 1 shows the much higher viscosity in comparison with the Sylgard 184 and

186. The Dow Corning 9600 and 9601 Textile Printing Ink were evaluated at Centexbel.

	Viscosity (centipoise)
9601	280000
9600	490000
184	4575
186	66700

Table 1

These tests have shown that there lays a thin silicone layer on top of the textile and that there is no penetration through the textile. However the printed layer is not as flat as the result obtained by casting Sylgard 186 on textile. Because of that it was not possible to obtain a good adhesion between the screen printed 9600 or 9601 and the molded 186 modules by means of plasma bonding.

Instead of using plasma bonding we used the textile printing inks as a kind of gluing layer. The printing inks are a lot more “sticky” in their wet, uncured state after the screen printing than the 186 silicone. Therefore they were well suited to glue the stretchable electronic modules on the textile. Several adhesion tests have shown that the adhesion is sufficient to survive several washing cycles without delamination.

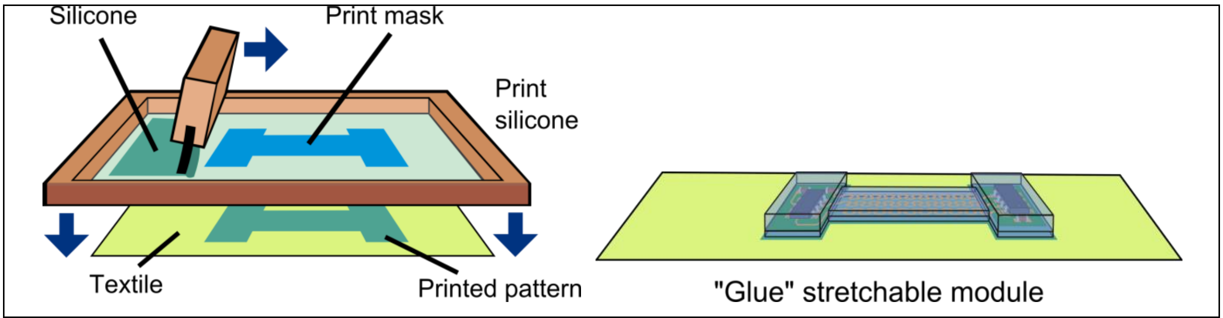


Fig. 23: Textile integration

This final process of the textile integration is illustrated in Fig. 23. A dedicated screen, which matches the bottom surface of the molded electronic module, is used to print the silicone gluing layer on the textile. Next the module is placed with light pressure on the wet printed silicone layer. After placement the silicone is cured to obtain an irreversible bonding between the textile and the module.

Textile substrate selection.

Mainly for integration of electronics in textiles but also for interconnection of electronics and textronics (cfr. infra), Centexbel was contributing from a material and testing point of view. Several searches were performed to find suitable materials or products and test methods. Several basic textile substrates were selected based on the requirements and provided to the partners. In the area of bonding & encapsulation of circuits, several searches were performed on suppliers of flexible/stretchable sealing compounds and adhesives for textiles, both as a liquid and as a film.

As the final goal is the incorporation of electronic circuits into textiles, the choice of the textile substrate and its properties is important and should be representative for the end applications. The primary requirement of the textile substrate is stretchability which should be at least of the same order as the stretchable circuit. Stretchability in textiles can be achieved in several ways, namely by using an elastic textile structure (non-woven < woven < knitted) and/or by using an elastic material (e.g. elastane). For this reason both knitted and woven textile (both with and without elastane) samples were procured. Further the textile material should be electrically insulating and representative of clothing materials. Therefore polyester (PES) and cotton (CO) based textiles were selected by Centexbel and made available to the partners.

Choice of bonding and encapsulation materials

Regarding bonding and encapsulation of the circuit onto a textile, Centexbel has searched the market for suitable bonding and encapsulation materials but this has proven non-trivial: plenty of compounds exist for the encapsulation of electronics ("potting compounds") and also for coating of textiles a wide range of materials are available but formulations which suit both applications were not found on the market. Nevertheless several companies (BASF, Dow Corning, CHT and Cytec Surface Specialties) expressed their interest in this emerging field so it can be expected that more specific materials will emerge in the near future.

Centexbel has selected (liquid) formulations for textile coating (silicones, polyurethanes and acrylates) which best fit the encapsulation requirements i.e. electrically insulating, flexible/stretchable and impermeable to water and preferably also gases (oxygen, water vapour).

An interesting alternative to the liquid coating formulations could be the use of thermoplastic films and foils and the process of lamination to either bond the circuit to the textile or to encapsulate it. Several thermoplastic flexible and stretchable films were selected and obtained from Epurex.

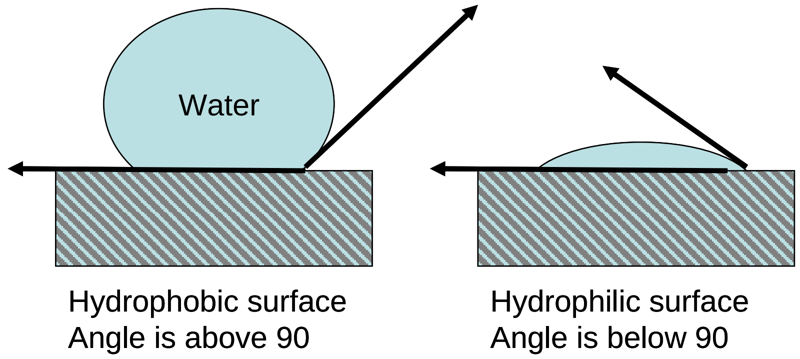


Fig. 24: Left: Hydrophobic PDMS surfaces; Right: Hydrophilic PDMS surfaces

Two cured layers of PDMS can easily be bonded if their surfaces are activated by plasma. Cured layers of PDMS are hydrophobic, with a contact angle of 135 degrees (see Fig. 24). Their surfaces are composed of PDMS chains which are hydrophilic. Without any treatment, PDMS has a surface which adheres to almost nothing. Plasma treatment of cured PDMS surfaces transforms them into hydrophilic surfaces, for which angles is less than 15 degrees.

PDMS plasma treated surfaces are covered with hydrophilic radical chains. Those chains depend on the type of plasma treatment. If those chains are put in contact together, a chemical bond is formed. This is plasma bonding. (see Fig. 25).

Parameters of the plasma should be optimized: if the plasma treatment is too weak there is no bonding as the surface is not activated. If the plasma treatment is too strong, the surfaces are over-activated, and a layer of glass is formed, which prevents also any bonding. We have optimized the plasma treatment for 3 kinds of PDMS (DowCorning Sylgard 184, Sylgard 186 and Silastic MDX 4210). Optimised parameters for plasma bonding are listed in Table 2. A plasma oven Diener Pico, 40 KHz, was used for this development

The smoother the surface is, the stronger the adhesion force is. The next step is to optimize those parameters and to use atmospheric plasma bonding, more suitable for textile industry.

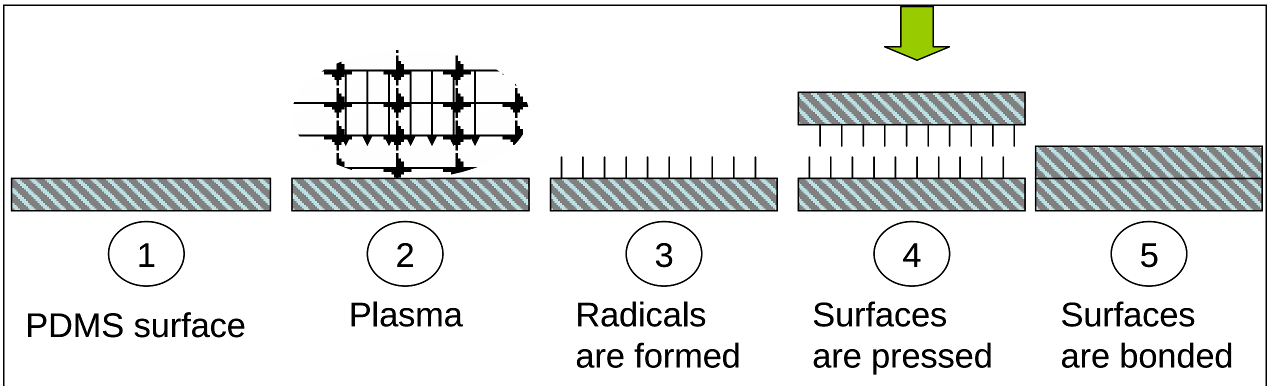


Fig. 25: Plasma bonding of two cured layer of PDMS

Silicone type	Gas	Power	Time
Sylgard 184	Air, 20 mbar	190 Watt	24 s
Sylgard 186	Air, 20 mbar	190 Watt	72 s
MDX4210	Air, 20 mbar	190 Watt	140 s

Table 2: Optimised parameters for plasma treatment of PDMS surfaces

Screen printing method

For performing the screen printing tests, a Johannes Zimmer (mini MDI 482) apparatus is used (Fig. 26).

Fig. 26: Illustration of screen printing method used. The basic screen mask consists of 4 rectangular shapes (8x1 cm); the picture show the bar as it is moving over the screen. The silicone is also visible.

For optimising the screen printing process, the typical parameters available are: the mesh properties (thickness, opening size and density), bar (thickness, surface structure (flat or serrated)), magnetic force on the bar, speed of the bar.

First, depositions were performed on a PET foil using a mesh with 50 lines/cm. By varying the type of silicone and changing the screen printing parameters within the reasonable possible limits, coating thicknesses ranging from 30 to 140 µm could be obtained. The parameter that appeared to have the strongest influence on the thickness is the magnetic force exerted on the bar during coating: the larger the force on the bar, the thinner the coating.

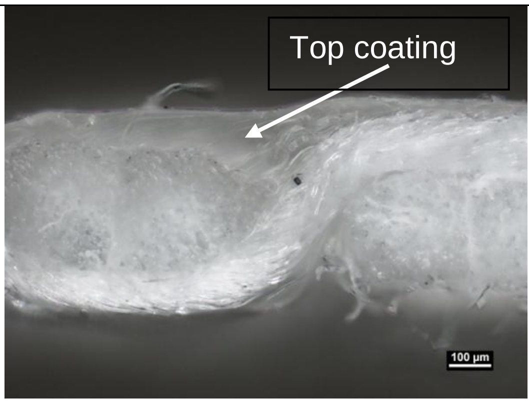
Using a rougher mesh (with less lines/cm and made of thicker wires) resulted in thicker coatings.

Penetration of the silicone

The first screen printing tests showed that there is a strong penetration into the fabrics that were used. Of course, the type of substrate that was used (both knitted and woven fabrics) had a strong influence on the penetration but in general the penetration degree was considered too high.

One possible solution that was investigated was a heat treatment immediately after deposition of the silicone. This heat treatment consisted of 10 minutes at 100°C in an oven. For some substrates (e.g. a knitted Lycra fabric) there was no positive effect of the heat treatment (even a slight tendency to have more penetration) but for others the penetration could be substantially reduced as shown on the pictures below.

(a)



(b)

Fig. 27: Cross section of cotton fabric coated with silicone (type DC186 from Dow Corning): (a) curing at room temperature; (b) first curing in oven, then at room temperature. The right image shows how a layer of silicone is formed on top of the fabric; the left image shows that practically all silicone penetrates into the fabric structure.

Fig. 27 shows that with only curing at room temperature, all silicone penetrates into the fabric structure. The heat treatment in the oven clearly prevents this and a layer of silicone is formed on top of the fabric. Of course, no uniform layer is formed and the existing “holes” because of the weave pattern are filled so that the thickness varies from more than 100 µm to about 10 µm. For comparison: with the same settings we found on the PET foil a thickness of (87±5) µm.

Hence, for some substrates a heat treatment immediately after deposition can be a good solution.

Breathability tests

Another important parameter of textile with stretchable electronic should be comfort and especially breathability which is the ability of a textile to transfer water vapour from skin to outside. One of the most current standards to measure breathability is ISO 11092 which is based on a device called “skin model” (see Fig. 28). The principle relies on a sweating guarded hot plate (see Fig. 29) with a temperature of 35°C simulating a sweating skin. A textile sample of 30x30 cm² is placed on the sweating plate. The device measures the heat caused by water evaporation going through the sample. As most of the samples used in this project have a size smaller than the required 30x30 cm², a frame has been designed to allow for measuring them (see Fig. 30).

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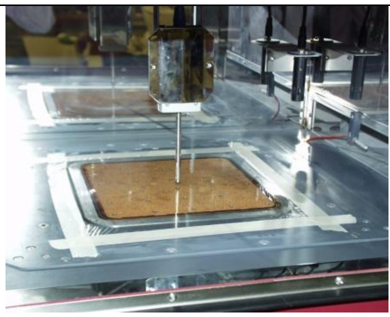
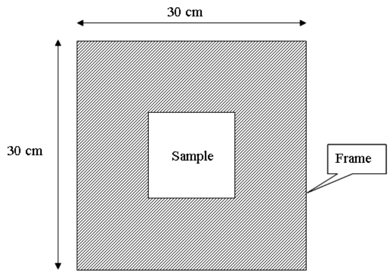
<td></td>
<td>
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<tr>
<td>Fig. 28: Skin model</td>
<td>Fig. 29: Measuring unit</td>
<td>Fig. 30: Device for measuring smaller samples</td>
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Sample of PDMS with a size of 10x10 cm² and thickness of 0.5 mm has been tested and a water vapour resistance (actually the inverse of breathability) of 142 Pa·m²/W was obtained which represents a very low breathability, much lower than what is required to ensure adequate comfort.

Nevertheless it was interesting to characterize more accurately the breathability of PDMS used in stretchable electronic. That is the reason why a method based on standard ASTM E96 – part E was selected because it has a better sensibility than the skin model in the range of lower water vapour transmission.

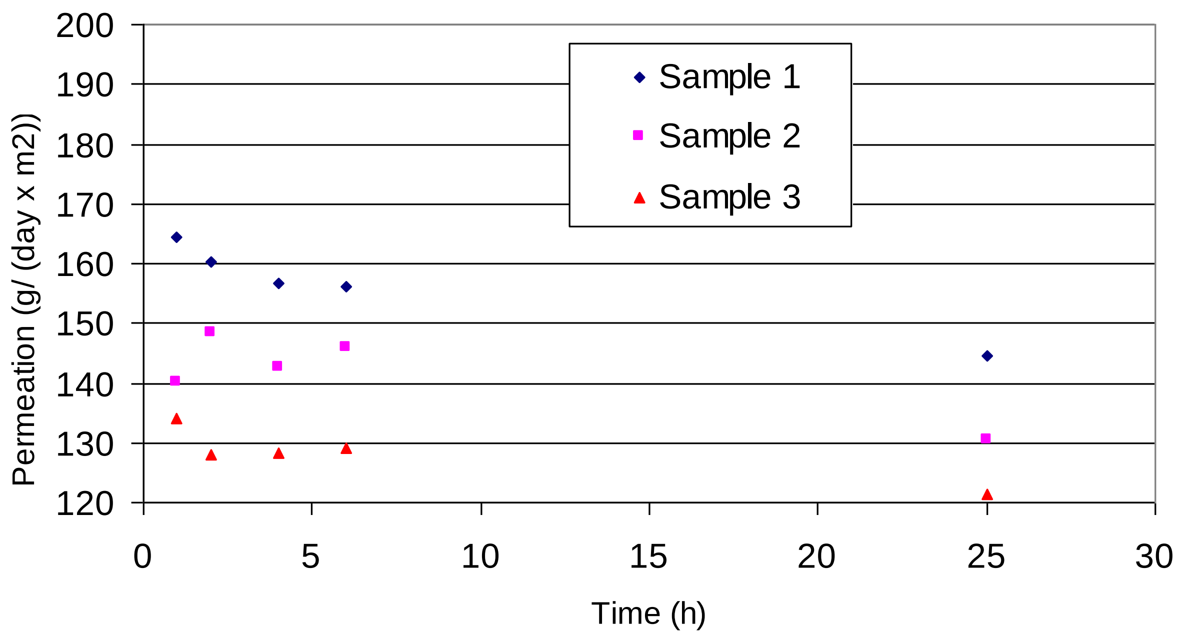


Fig. 31: Breathability measurement result on a silicone sheet using the standard ASTM E96– part E

An example of a result obtained on a silicone sheet (similar to the one in which the electronics are embedded) is shown in Fig. 31. Measurements were performed on three samples to average out the result. The result was an average breathability of ca. 150 g/(day x m^2). For reference: this is much smaller as for commercial products like Sympatex: (ca. 2500 g/(m^2xday)) or Goretex (ca. 3000-4000 g/(m^2xday)).

Conclusion: *it is clear that breathability should come from minimising the area of silicone needed, rather than to rely on the breathability of the silicone itself.*

6.1.5 Interconnection of electronics and textronics

In the sections *Stretchable electronic circuits (6.1.1)* and *Integration of electronics in textiles (6.1.4)*, we described how the electronics are completely encapsulated and integrated with the textile. In this section we describe how these integrated electronic modules can be interconnected with textronics (textile sensors, antennas) and with other electronic modules. A concept for this type of interconnection has been proposed by UGent. The concept comprises following steps:

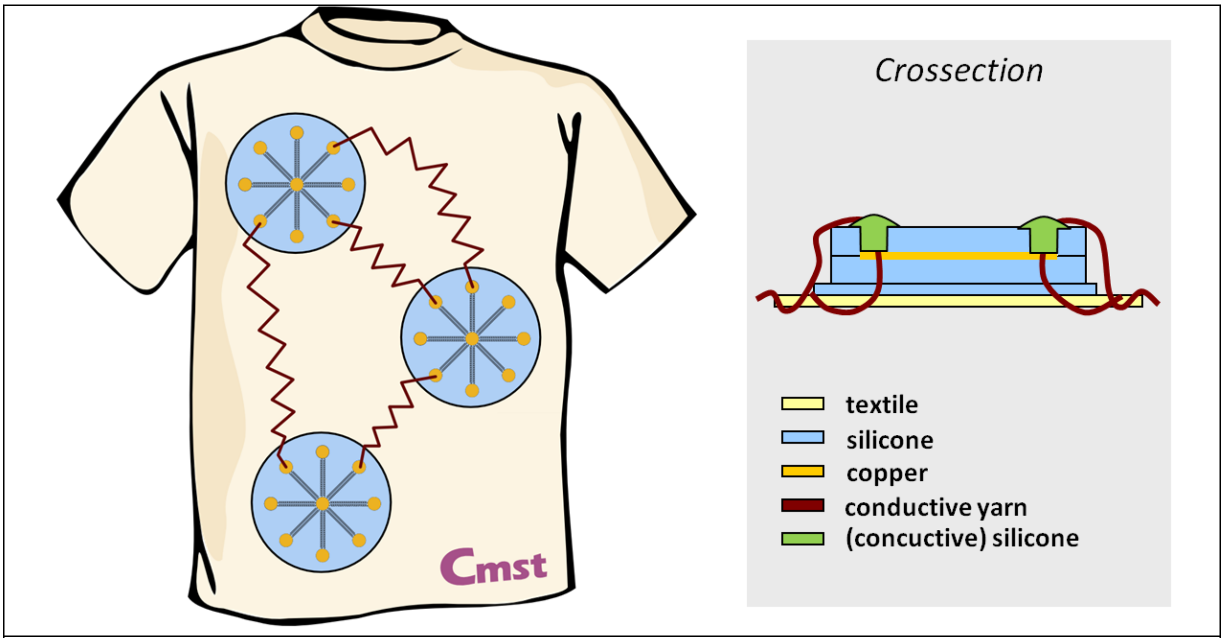


Fig. 32: Stretchable electronic circuits (circular parts), interconnected with conductive yarn

- The moulded stretchable electronic circuit should have openings in the silicone to access copper pads which will be used for interconnection. This was accomplished by designing the mould in such a way that the copper pads are free of silicone after the moulding.
- Start from moulded electronic modules on one hand and a piece of textile on the other hand.
- Deposit silicone on those spots on the textile where the moulded electronic modules have to come. Application can be done using casting, doctor blading, screen printing, or similar techniques. Screen printing has proven to be the best solution.
- Bond the moulded electronic modules to the textile. Here the screen printed silicone layer acts as a gluing layer.
- Interconnect the electronics parts with a conductor. The interconnection is made at the open copper pads. Interconnection can be done with a conductive yarn by sewing through the copper pads or by soldering a thin copper wire which is integrated in the textile.
- Seal the interconnections with (conductive) silicone to protect the contact pads from water and to increase reliability.

This concept is shown in Fig. 32 in the case that the interconnection is made by sewing a conductive yarn through the pad.

Interconnection by sewing

Regarding interconnection of electronics and textronics, Centexbel developed solutions based on sewing. As a preliminary test sewing was performed on a simple silicone layer. This reveals to be possible only if the right silicone thickness is selected. If silicone is too thick, it can be broken by the needle. If silicone is too thin, the space between two adjacent holes in a stitch can crack. Naturally this last case is a worst case because silicone is never used alone and is always associated with a fabric which plays the role of a strengthening agent.

The next step was to work with all the components used in flexible and stretchable circuits namely silicone, copper, textile fabrics and conductive yarns. The tests were performed with different configurations:

- Silicone: different thickness
- Copper: different thickness: 18 μm and 35 μm
- Conductive yarns: two types:
  - Stainless steel multifilaments
  - R-stat (polyamide multifilaments coated with silver)
- Silicone + copper: laminated and not laminated
- Distance between two adjacent holes in a stitch: various distances.

For the textile layer, a knitted fabric was selected because this is naturally flexible and stretchable and it is precisely the property we want to give to the final product. We used both laminated and not laminated copper + silicone to show how lamination can enhance and make easier the sewing process. The electrical connections were made by sewing conductive yarns several times between two adjacent holes. The different layers (copper + silicone + knitted fabric) were assembled by sewing them together with a simple insulated PES yarn.

To make all those tests, it has been necessary to use isopropyl alcohol (IPA). By this way the silicone becomes sufficiently slipping and it is much easier to use the sewing machine. A more practical way to obtain this result was found later on in the project.

The results of the sewing tests on separated elements can be summarised as follows:

- Copper + silicone: “laminated” better than “not laminated”
- Copper: thick (35 μm) better than thin (18 μm)
- Silicone: thick (1 mm) better than thin (0.5 mm)
- Yarn: r-stat (polyamide coated with silver) better than stainless steel
- Sewing: slipping silicone (with isopropyl alcohol) better than not slipping silicone (dry)

As a conclusion those tests have allowed to select a set of conditions that makes possible to sew conductive yarns in stretchable circuits. If conditions are not optimised, some problems can occur like broken silicone or crack between two adjacent holes in a stitch. Also the optimised distance between two holes is about 4 mm. The electrical resistance of connection between the copper layer and conductive yarn is less than 1 Ohm which is quite good for the aimed applications.

The same tests were carried out also with polyimide. Polyimide is flexible but not stretchable and is in flexible printed circuits. Sewing in polyimide has also given good results. Even better results were obtained with simple insulated PES yarn than with conductive yarns. This simply proves (as will be shown later) that the right conductive yarn selection was of special importance to obtain the best results.

The next tests have been performed on a single connection pad made by UGent (Fig. 33). This connection pad is made of a flex (Polyimide + copper) which is embedded in 186 silicone. An opening is provided to the copper. The embedded pad is glued to the textile.

Two types of conductive yarns have been used exactly as in the previously described tests. The first results of sewing tests on the test vehicle were a bit disappointing. The problem seems to be caused by the conductive yarn type. As a matter of fact the yarn twisting of r-stat is not sufficient for sewing. Because of this, cohesion between filaments is not sufficient. This can lead to problems (for example: entanglements) during the sewing process. As sewing with a normal insulated PES yarn gives much less problem, we were confident that selecting the right yarn type will be the solution.

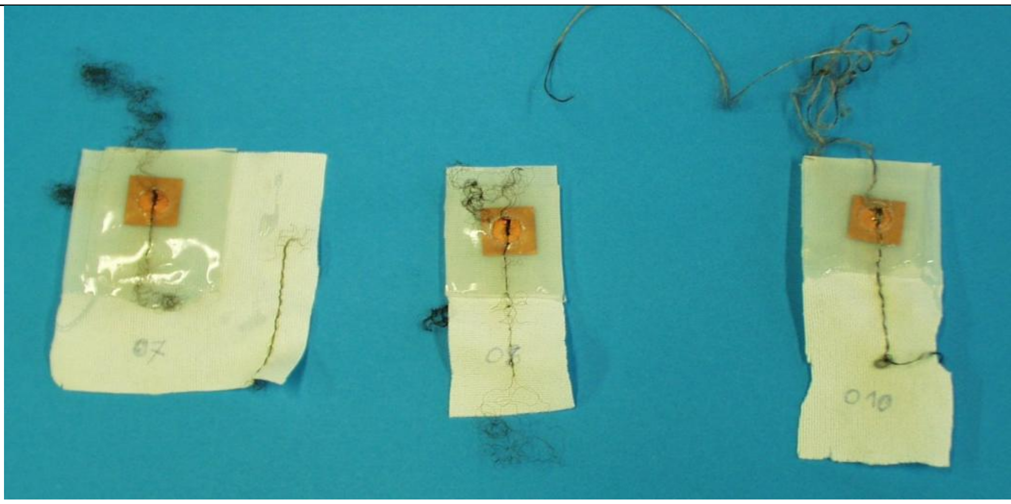


Fig. 33: Preliminary sewing tests on single connection pad

Conductive yarn selection

Several conductive yarns were selected for use to interconnect the circuit with the textronics substrate by sewing. Finally the best conductive yarn proved to be Shieldex© 235 f34 dtex 2 ply. Shieldex© is also a polyamide yarn coated with silver which is moreover a twisted yarn (S500/Z400). Thanks to twisting it is possible to obtain very clean sewing with that yarn. Resistivity is about 120 Ω/m which is quite good for aimed applications. First tests were made with Shieldex© in combination with PES yarn. It was also the opportunity to replace IPA by a film like a sheet of paper to allow the foot of the sewing machine to slip easily on the silicone. This method proved to be more practical and efficient that with IPA. The sheet of paper is removed after sewing. It is very important that connection pads are not covered with the sheet of paper because it is difficult to remove the paper on the pad and this makes the connection less reliable.

Sewing on test vehicle

Final sewing tests were made on a dedicated test sample realised by UGent. The copper patterning was done using the laser prototyping technology. The samples are produced in accordance with the process flow, as described above. A general view of the test circuit can be seen on the left, a detail (the center pad) on the right of Fig. 34. Function of the pads is to provide a contact surface onto which stitching can be done. Diameter of the star-formed structure is about 100 mm, circular stitching pads are about 4 mm in diameter. The detail photograph also clearly shows the meander shaped interconnections, allowing stretching. In this way the center pad is connected to each of the 8 “satellite” pads. After stitching this provide an easy way to check continuity of the interconnections, also under stretch in one of the main directions. This test vehicle is glued on a knitted fabric with a high stitch density. This high density is necessary to avoid that silicone go through the fabric but at the same time reduces the stretchability.

Fig. 34: Electronic interconnection structures, integrated on textile

The result after stitching by Centexbel is shown in Fig. 35. The Shieldex© yarn was sewn forward and backward on both sides of silicone laminated on textile. This corresponds to four parallel yarns decreasing resistivity by a factor four which is still a better result. Zig zag sewing allows to prevent to reduce too much stretchability of knitted fabrics.

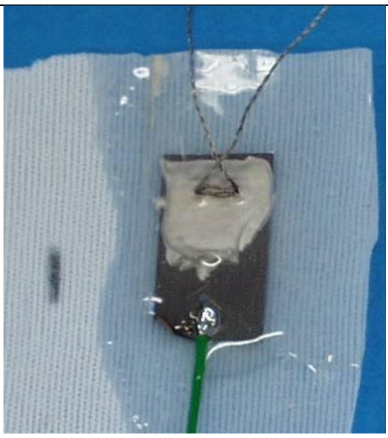
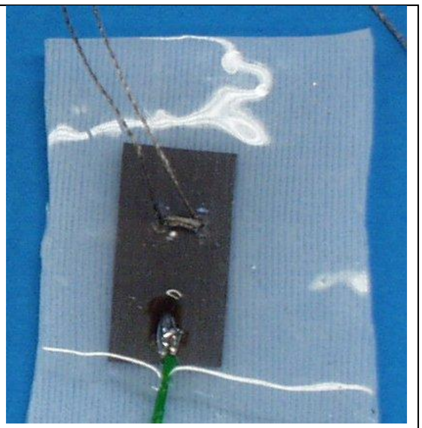
Fig. 35: Stitched contacts

Fig. 36: Embroidery tests

Different types of embroidery have been tested as shown in Fig. 36 in order to reduce electrical resistance of textile connections. On the figure it can be seen that practically only zigzag sewing is possible on the silicone. It can be seen also that in some cases, paper used to make easier sewing is difficult to remove. Moreover electrical tests revealed that practically no decrease of electrical resistance occurs with embroidery and thus the best solution is to keep zigzag sewing which is more convenient.

Sewing and gluing

After that Centexbel investigated with UGent how it was possible to combine sewing and gluing. Gluing is interesting because it can strengthen the connection and protect it against corrosion. The main question is to know whether sewing can be made after gluing. If this was possible the process could be simplified. So Centexbel received from UGent three connection pads. The hole made in the silicone layer to access copper was filled with three kind of conductive glue (two silicones loaded with silver and one with carbon black). Sewing in conductive glue was easy and produced reliable connection with low resistivity. The next step was to decide if it is necessary to make a hole in silicone to connect conductive yarn with copper. So again Centexbel received from UGent three samples with conductive glue on the copper pad and lamination of a silicone layer on the pad (without hole). Two kinds of conductive glues were used (one with silver and the other with carbon black). The third sample had no glue at all. So the process of this last sample was very simple. (see Fig. 37)

<table>
<tr><td></td><td></td><td></td></tr>
<tr><td>Silicone + Ag:
1.9 Ω</td><td>Silicone + carbon black:
3.0 Ω ... 1K Ω
(not reliable)</td><td>No glue:
12.9 Ω ... infinite
(not reliable)</td></tr>
<tr><td colspan="3">Fig. 37: Stitch test samples</td></tr>
</table>

Mechanical tests

After sewing a Shieldex© yarn on the pad, electrical resistance was measured. This measurement showed that electrical contact was not reliable when the pad is mechanically stressed except when silver glue is used. In order to prove that gluing with silver silicone is really reliable, a system was realised to repetitively apply mechanical stress on a connection pad (see Fig. 38).

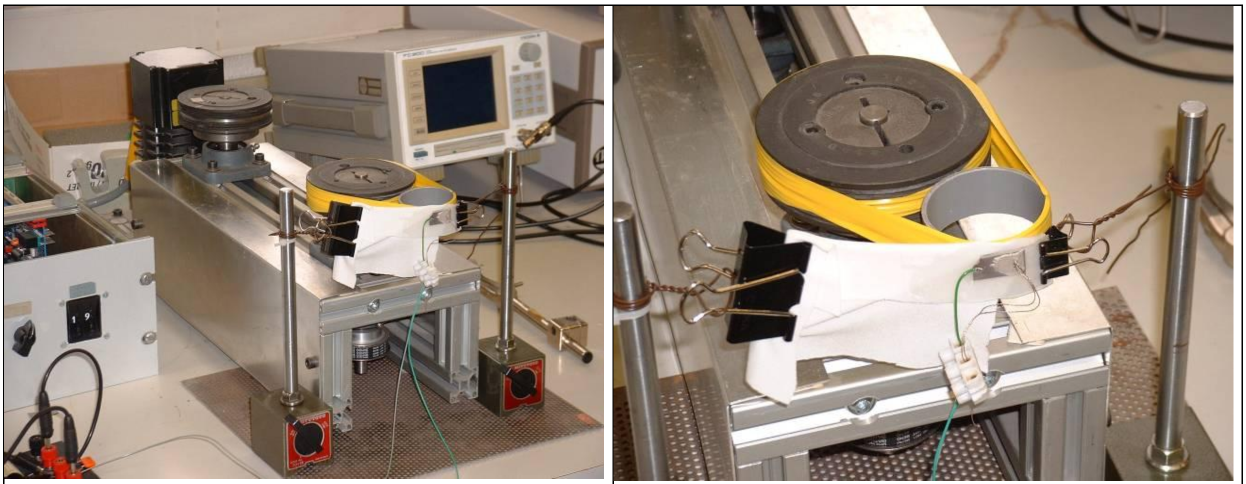


Fig. 38: Test system for applying repetitive mechanical stress

After 22000 stresses on the pad, contact was always reliable and electrical resistance was as small as it was when the test began. So we can conclude that sewing and gluing with silver loaded silicone is very reliable. Unfortunately it is not possible to avoid making a hole in the silicone layer to access copper because the connection without glue was not reliable at all.

Subsequently the mechanical system has been improved as can be seen on Fig. 39. This system allows for extension cycles with variable amplitude and frequency. The mechanical tests performed with it have confirmed the previous results.

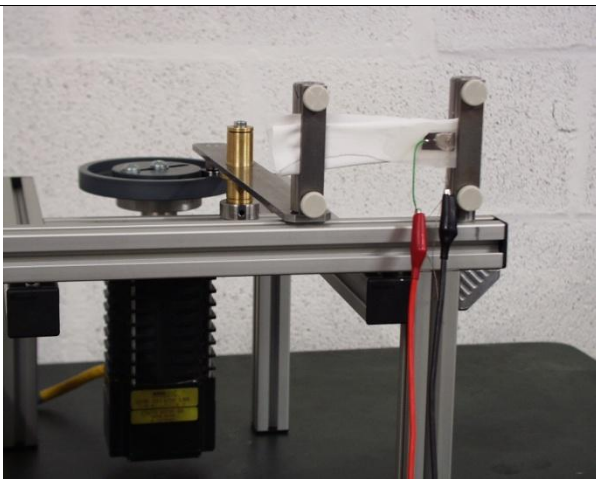


Fig. 39: Improved mechanical system

Concerning the interconnecting electronics with textronics, Centexbel has also performed an extensive market search on suitable conductive rubbers (silicones) and conductive yarns. The conductive silicones can be used to cover the meander-shaped conductors for improving reliability and to seal the gaps of the connector pads where connection to the textile is made.

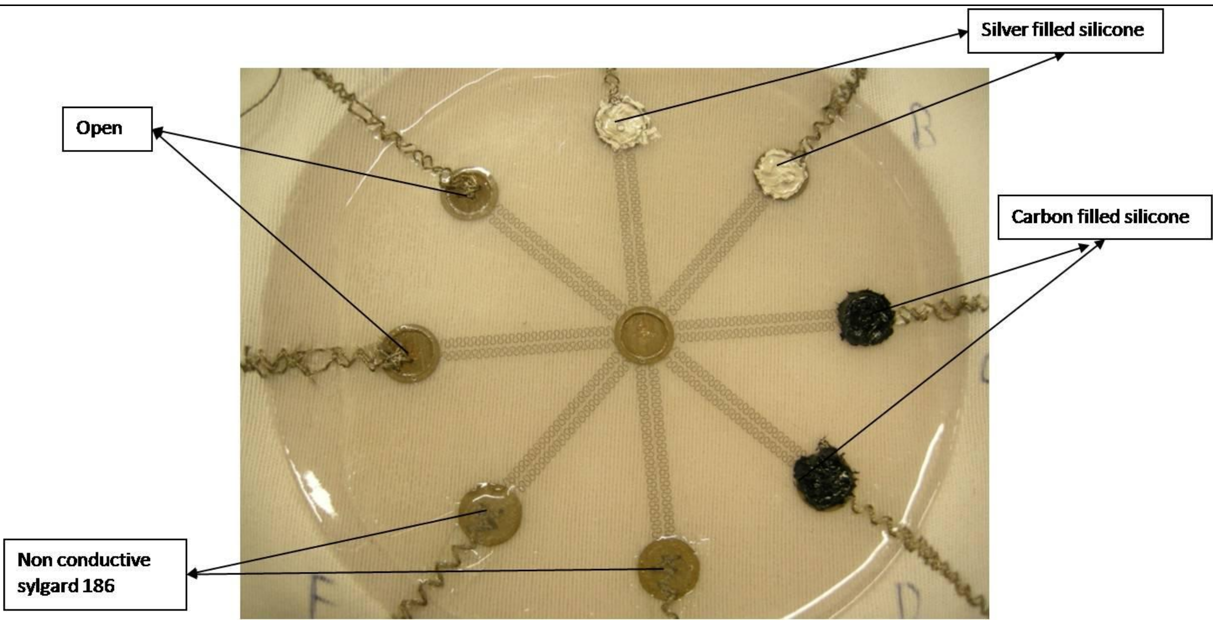
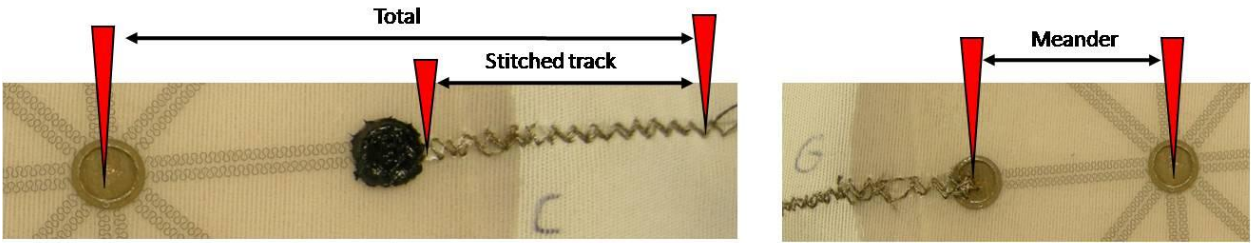


Fig. 40: Sealed contact pads

We also learned that it is better to make the interconnection first and then seal it with (conductive) silicone. In this way the interconnection is more reliable because there is more contact between the copper pad and the conductive yarn. This was also tested on the test sample with the star pattern. The result after sealing (by UGent) with different silicones is shown in Fig. 40.

For each contact pad the resistance was measured (see table below; Fig. 41):

PAD	Total [Ω]	Meander [Ω]	Stitched track [Ω]	Connection [Ω]
A (silver filled)	4.2	0.8	3.8 (4.2 cm)	-0.4
B (silver filled)	4.6	0.8	3.9 (4.5 cm)	-0.1
C (carbon filled)	4.4	0.8	3.6 (4.0 cm)	0
D (carbon filled)	4.8	0.8	4.1 (4.6 cm)	-0.1
E (sylgard 186)	5.3	0.8	4.4 (5.0 cm)	-0.1
F (sylgard 186)	5.1	0.8	4.2 (4.5 cm)	0.1
G (broken)	--------	---------	--------	--------
H (open pad)	4.3	0.8	3.5 (4.0 cm)	0



Connection = Total – Meander – Stitched track

Fig. 41: Probe points

Finally we can draw a few conclusions:

- Interconnection between stretchable electronics and textile by sewing proved to be very satisfactory.
- Conductive yarn type is of high importance. A sufficient twisting is necessary to avoid problems during the sewing process. “Shieldex© 235 f34 dtex 2 ply” satisfies this specification.
- To sew on silicone a practical means is to use a film like a sheet of paper to allow the foot of the sewing machine to slip easily. However paper on the connection pad should be avoided.
- It’s hard to measure on stitched tracks with probes => not a perfect measurement, but good enough to make conclusions on resistivity.
- The stitched tracks have the biggest resistivity (~ 0.9 Ohm/cm).
- Stitched contact is very good and has a low resistance.
- Kind of sealant has no effect on the resistivity of the contact.
- Stitched contact is determined by the stitch, not by the (conductive) sealant.
- The sealant acts as a protection for the sewn connections.
- At this point non conductive silicone seems to be the best choice because it’s cheaper and easier to apply (less viscous than the conductive ones).

Long distance connection with Ohmatex ribbons

Another solution for long distance interconnection is the ribbons manufactured by Ohmatex. Those ribbons are stretchable fabrics with enamelled silver filaments inserted in them. Resistivity is 15.5 Ω/m which can be decreased by using several filaments in parallel. The problem was to find a way to make an opening to access the conductive filaments and to remove the insulating varnish. Centexbel and UGent searched their separate ways for a solution with a CO_2 laser. Specifications of Centexbel’s laser are: maximum power: 20 W (pulse width modulation), beam diameter: 1 or 2 mm, wavelength: 10.6 μm. The problem was that for removing the insulating varnish the laser power has to be maximum. However if the power is too high the ribbon burns (Fig. 42). A first solution was to use nitrogen to prevent burning but unfortunately this didn't solve completely the problem (Fig. 43). Better results were obtained when the ribbon was wetted but even at maximum power the varnish was not completely removed (Fig. 44).

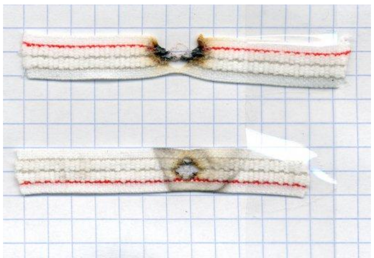
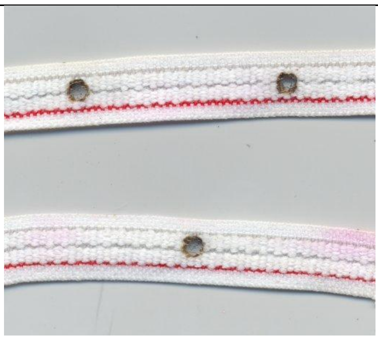
		

Fig. 42: Laser at full power	Fig. 43: Laser with nitrogen	Fig. 44: Wetted ribbon

Interconnection with snap fasteners

A other simple way to connect flexible electronics to textronics is based on snap fasteners (see Fig. 45). This type of connection is designed especially to be integrated in textile. The snap fasteners are sewn on textile substrate with a conductive Shieldex© yarn. The second part of the snap fastener that mates on the first one is connected to a flexible circuit by gluing with silicone.

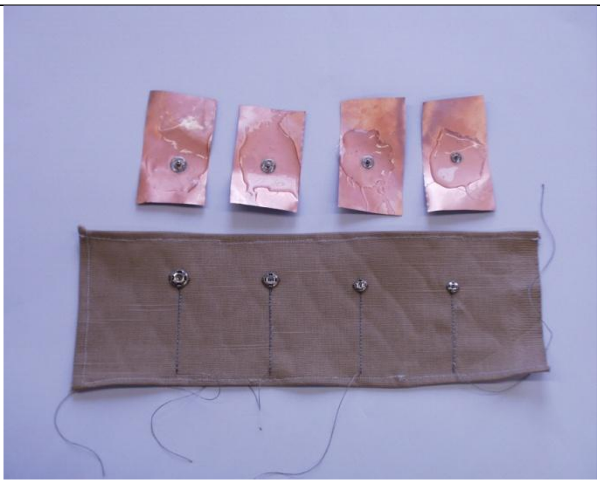


Fig. 45: Interconnection by snap fasteners

This system allows for interconnections with low electrical resistance. Another advantage is the possibility to easily plug and unplug a flexible circuit to or from a textile substrate with textronics for example for maintenance operations or repair.

Coated stitches

To avoid electrical leakage between parallel conductive yarns embroidered on a textile substrate caused for example by sweat moisture, it has been necessary to protect those yarns with insulating coating. Some tests were carried out to demonstrate the efficiency of the proposed solution. First a knitted fabric is embroidered with 4 conductive yarns (Shieldex©) as shown on Fig. 46 and afterward those yarns are covered with a PDMS coating. For testing the fabric is placed on a hydrophilic polyester knitted fabric moistened with a salted solution simulating sweat (Fig. 47). The electrical leakage is measured with an ohmmeter. After some time the electrical resistance remains infinite and thus this test proved the efficiency of the coating to prevent electrical leakage between conductive yarns.

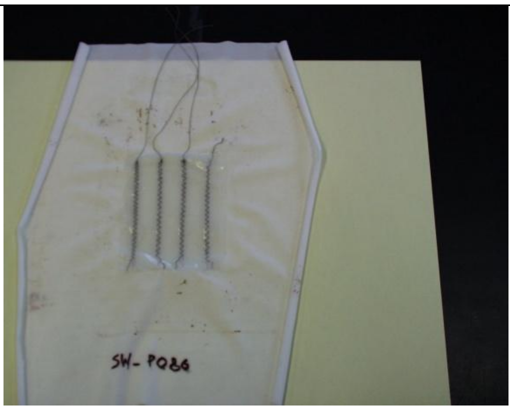


Fig. 46: Knitted fabric with embroidered conductive yarns

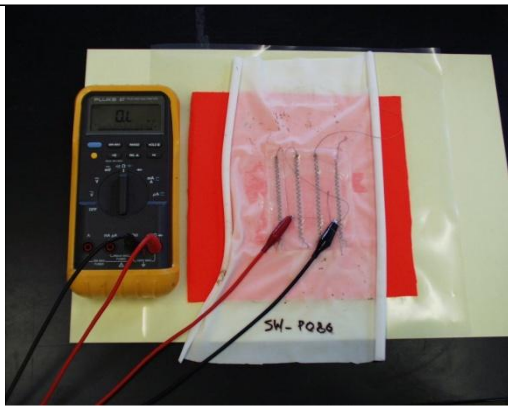


Fig. 47: Testing device for electrical leakage

Interconnection by soldering

For some types of interconnection the resistivity of the sewn tracks can be too high. If we have an interconnection for the power over a distance of 1 meter for example. In this case each track would have a resistance of 90 Ohm. At 10 mA this would give already a voltage drop of 0.9 V on each track.

In these cases where we need a lower resistivity we can use standard (insulated) copper wires that are attached to or integrated in the textile. The interconnection is then made by soldering the wire onto the copper pad. The sealing of the holes can be done in the same way as with the sewn contacts described before.

UGent made an electronic design to illustrate and to test this principle. The test design has functional islands that can be separated from each other (see Fig. 48 and Fig. 49). Each island can function independently and has four LED’s that are blinking two by two. The electronic design on each island is an a-stable multivibrator circuit to obtain the oscillation for blinking the LED’s. The circuit can be powered by soldering electric wires on the open connector pads. The openings in the silicone have different shapes for placing the electric wire.

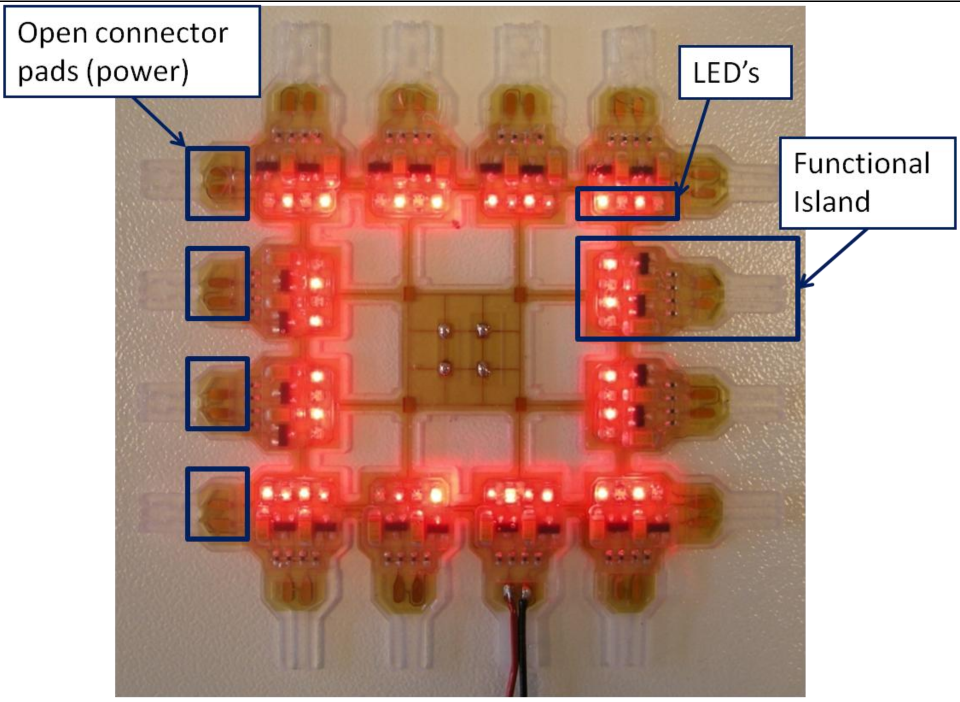


Fig. 48: Blinking led test sample for testing solder interconnections

The modules are glued on a textile using the screen printing technique. After placement the electric wires are attached to the textile by stitching. Next the interconnection is made by soldering the wires onto the pads. The module with the corner shape has two places for interconnecting the power. On one side the power arrives and the other side is used to interconnect another module. Once the soldering is done and the interconnection is proved to be good, the openings are sealed with silicone to protect the interconnection. The end result is shown in Fig. 50. Fig. 51 shows a module after soldering and before sealing.

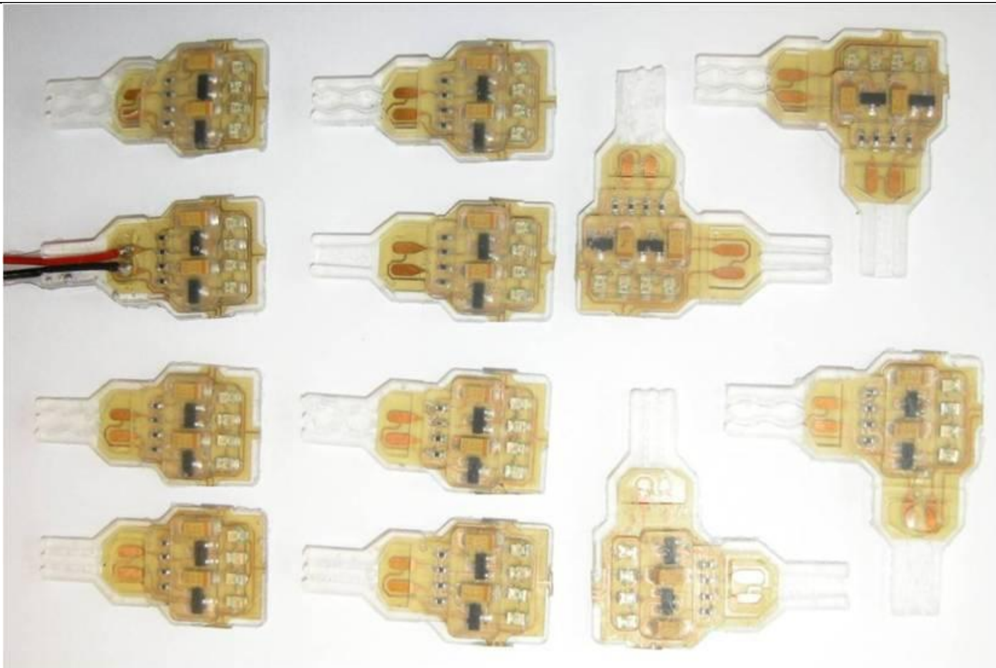


Fig. 49: Separated blinking led modules

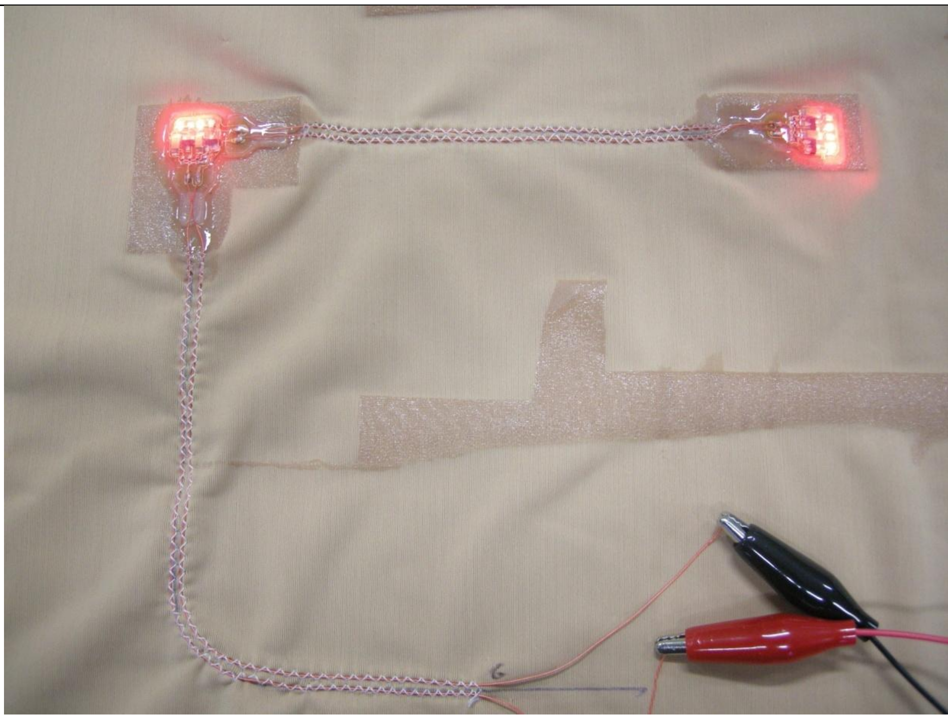


Fig. 50: Interconnected blinking LED modules

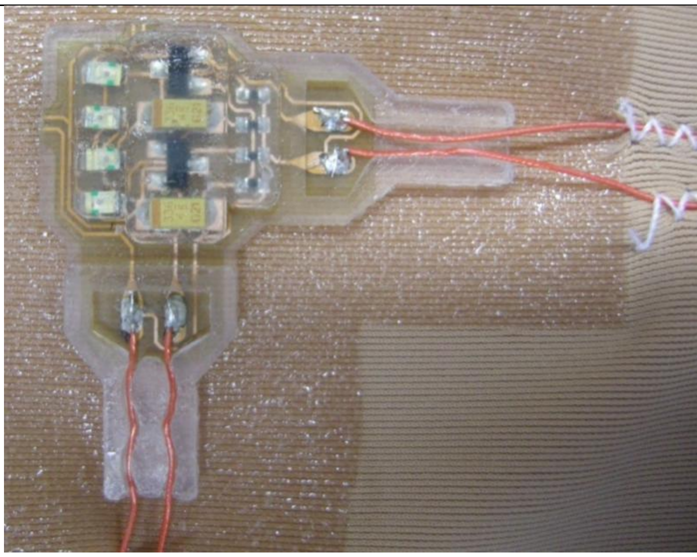


Fig. 51: Soldered interconnection

The interconnected blinking led samples were also used in washing tests. The results are described in 6.1.6 Washability**.**

6.1.6 Washability

Washability requirements

Centexbel has selected representative washability requirements and corresponding test methods to evaluate the samples and has proposed several other tests to assess general durability (weathering, bending/crumpling etc.). For evaluating the overall durability and reliability of encapsulated stretchable circuits bonded to textiles there are, of course, no existing standards available yet.

As a general rule in textile industry, clothing textiles should be able to endure at least 30 washing cycles to be commercially viable. However, specific requirements depend on the targeted application.

For the drying procedure Centexbel proposed to use tumble drying but depending on the reliability of the circuit that can be attained after washing, less severe drying methods such as drying on a line, could be preferable.

The washing tests performed within SWEET were performed step-by-step. A synthesis of the tests is given below.

During the SWEET project UGent did basic research concerning washability of the embedded electronics. When electronic circuits are integrated in textile in an irreversible way, the electronics should be well protected in order to wash or clean the garment. The unique process of embedding stretchable electronics in a polymer like PDMS opens the potential for washability.

Because there are no real standards for testing washability of electronic circuits, Centexbel selected for water-based cleaning the ISO 6330:2000 standard, procedure 6A. This standard is representative for domestic washing conditions. More specifically, procedure 6A was selected because it seems to be a good compromise between cleaning requirements and the technical challenges for the development of embedded, stretchable electronics. The details of procedure 6A are:

- The use of a front-loading washing machine (type A) which is most common in Europe (90%).
- A washing test at 40°C.
- Normal agitation during heating, washing and rinsing.
- Standard detergents (IEC or ECE which are slightly alkaline (pH ~ 10)).

It can be stated that there are two major challenges to obtain washability: water resistance and resistance to mechanical stress. The encapsulant should protect the electronics from the water during the washing process. This water resistance is determined by different factors like temperature, soap and washing time. Next to water resistant, the encapsulated electronics should also be reliable enough to survive the physical deformations during the cleaning process. It can be stated that there are two major challenges to obtain washability (Fig. 52).

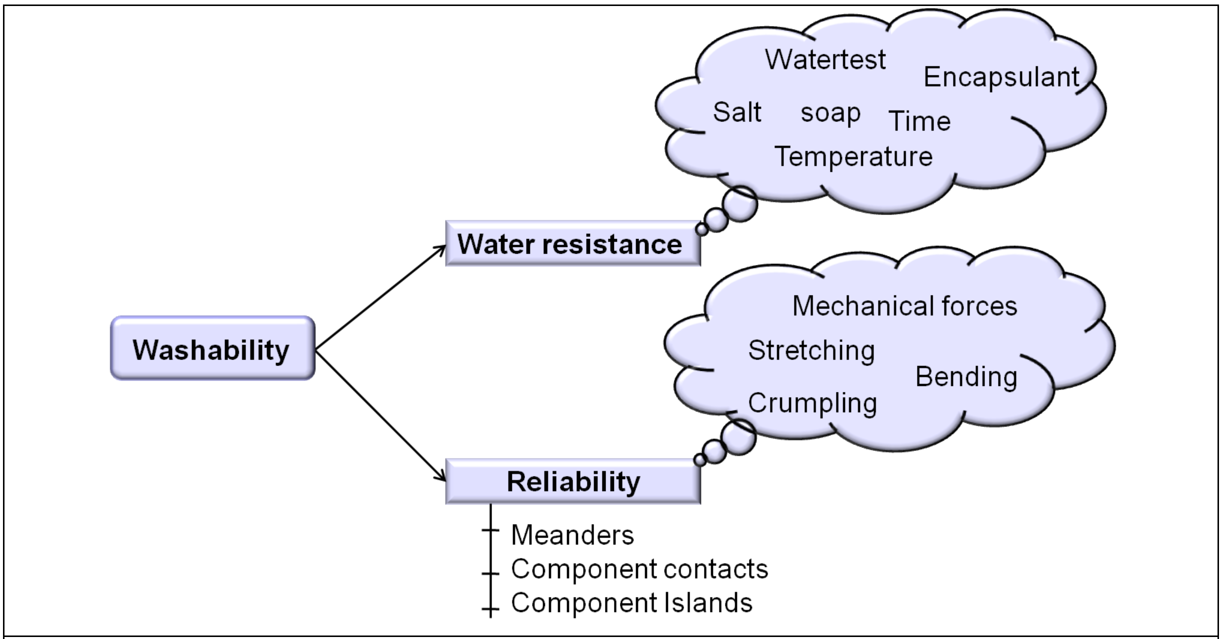


Fig. 52: Washability

Water resistance

The encapsulant should protect the electronics from the water during the washing process. This water resistance is determent by different factors as shown in the figure. Next to water resistant, the encapsulated electronics should also be reliable enough to survive the physical deformations during the washing process.

To test and to understand the effect of water, soap and temperature on the embedded electronics, UGent developed a test structure as shown in Fig. 53. Two copper tracks are closely spaced with a pitch of 200 µm (100 µm width, 100 µm spacing). Total length of the track is about 1 meter. The test structure is made on a standard flex (copper laminated on polyimide) and is then completely embedded. A voltage is applied on the two tracks and the leakage current between them is measured. When water can diffuse through the silicone, the leakage current will increase due to the conductivity of the water. A sample under test is shown in Fig. 54. The leakage current is measured with a Keithley 237 High voltage source measure unit. A dedicated Labwindows program was written for real time monitoring of the leakage current and to log the data in an excel file.

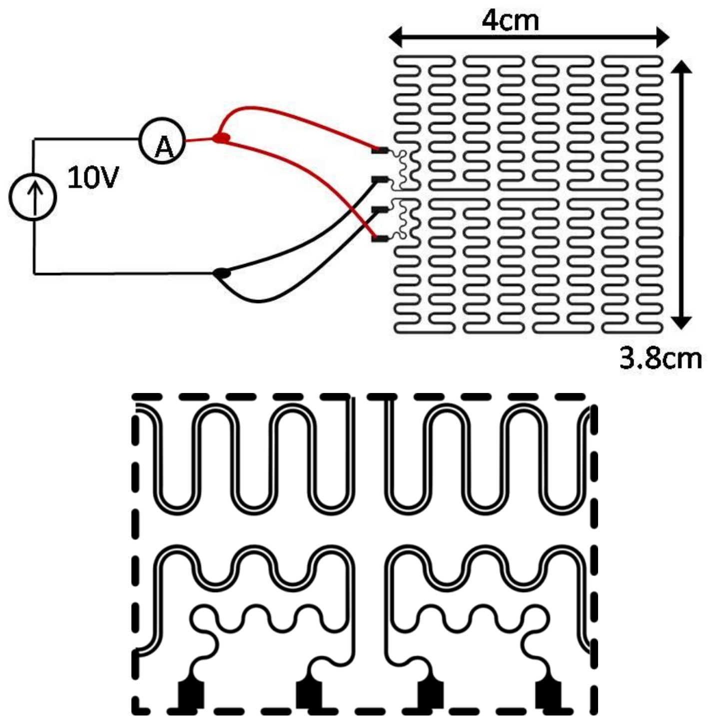


Fig. 53: Test structure for watertest

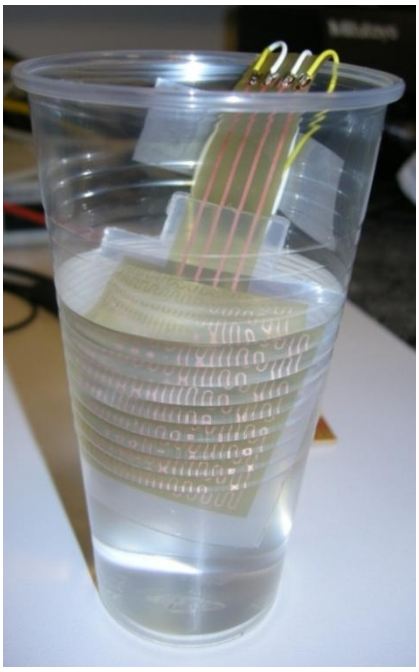


Fig. 54: Sample under test

The results will be discussed now. The flex with test structure was embedded in PDMS Sylgard 186 (Dow Corning). The thickness of each silicone layer is 1 mm. The 1200 OS adhesion promoter is used to have a good adhesion between the flex and the silicone. The sample is placed in a beaker with normal tap water at room temperature. A constant voltage of 10 V is applied between the parallel copper tracks. Then the leakage current is monitored over a period of 6 days to see if there is an effect of the water. The leakage current is logged every 15 minutes. Test results are plotted in Fig. 55. The leakage current (in Amps) is plotted over time (numbered, every 15 minutes).

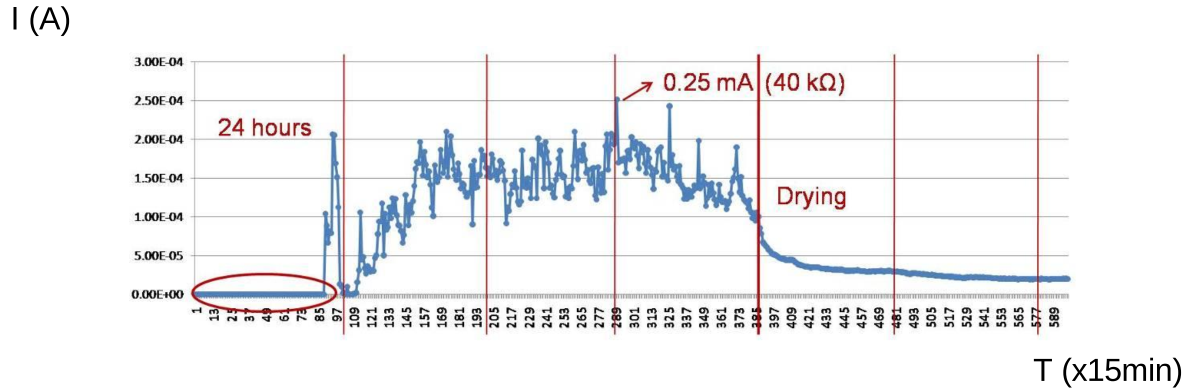


Fig. 55: Leakage current I (A) in function of time T (x15min)

There is no significant increase in leakage current during the first 21 hours. After this period there is a leakage pad between the parallel tracks which results in an increase of leakage current. This leakage current is fluctuating over time. After a period of 4 days the water was poured out of the beaker and the sample was dried at room temperature. The leakage current decreases when the sample is drying. From this preliminary measurement result we can conclude that there is definitely an effect of the water over a longer period of time. However in the case of washing, the sample is only in the water during a period of about 2 hours. The data of the first period (oval in Fig. 55) is plotted in Fig. 56.

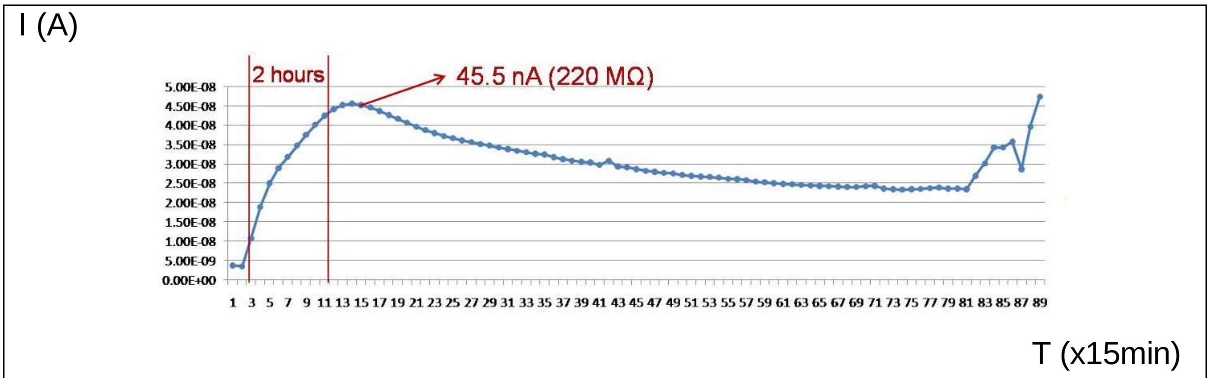


Fig. 56: Leakage current I (A) in function of time T (x15min)

One can see that there is not a high increase of leakage current during this period. The maximum leakage current is only 45.5 nA which means that the effect of the water can be ignored. There are more tests needed to verify this result and to further investigate the effect of water (and soap, temp,…). Nevertheless this is already a very promising result. It also has to be noticed that we are testing here a worst case scenario of very long, closely spaced copper tracks. In real circuits the straight tracks on the polyimide islands are shorter and the meanders are further spaced from each other. Besides that, the copper tracks are also covered with solder mask, providing an extra barrier for the water.

Reliability

Next to protecting the electronics from water, a good reliability is another challenge. The reliability of the meanders during cyclic stretching is still under investigation at UGent and was mainly done in the frame of the STELLA project. There, several test vehicles have been designed and realized in order to test the reliability of meander shaped copper conductors embedded in a polymer. Not only the reliability of the copper conductors itself but also the reliability of the transition between the rigid, flexible and stretchable parts has been investigated.

For SWEET, UGent has designed and produced different samples to investigate the reliability of a whole system when washing several times.

UGent executed first washing tests on a simple functional electronic circuit, consisting of 20 LED’s. The LED’s were chosen because (1) they are simple 2-lead SMD components and (2) it is very simple to check the functionality of the circuit. This circuit was fabricated using the SMI laser structuring method, described above and bonded to a textile substrate, by using atmospheric plasma bonding. Atmospheric plasma bonding was used instead of screen printing, because at that time de screen printing process wasn’t yet developed. The functional circuit is shown in Fig. 57. The circuit was submitted to two consecutive domestic washing cycles with following parameters:

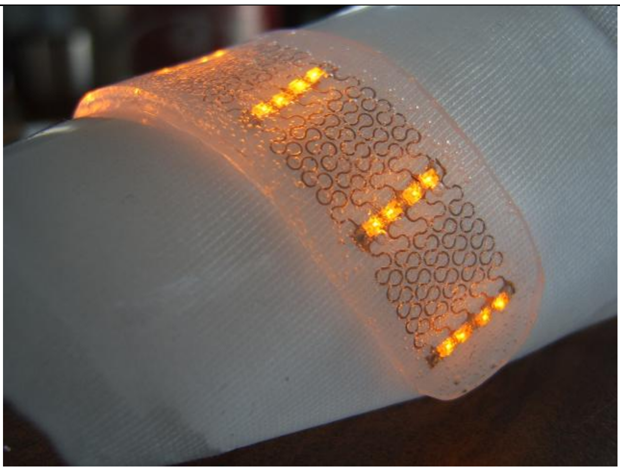


Fig. 57: Simple 20 LED stretchable circuit after 2 domestic washing cycles

Cycle 1:

- Washing machine: Miele Novotronic W820
- Soap: Persil Color Gel (15 ml, liquid)
- Cycle: short program (40 min, "mini wash", nevertheless including washing, rinsing, centrifugation)
- Sample placed in commercial common net for "delicate textile", no other garments in washing machine
- Centrifugation: 600 rpm max.
- Temp: 40°C max.

Cycle 2:

- Washing machine: Miele Novotronic W820
- Soap: Persil Color Gel (15 ml, liquid)
- Full washing cycle (washing, rinsing, centrifugation) together with other laundry
- Duration about 2 hours
- Tumbling speed: 900 rpm max.
- Temp: 40°C max.

After washing following observations were made:

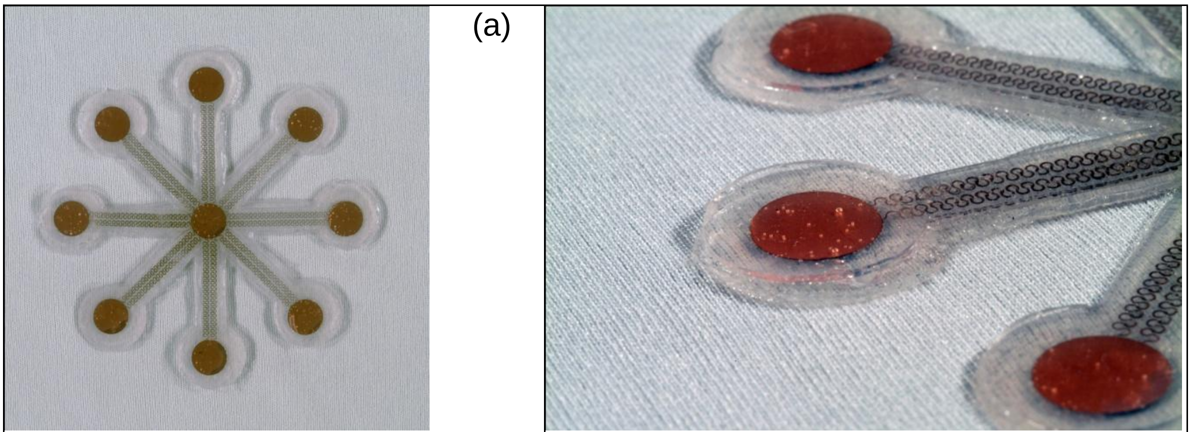
- All 20 LEDS were still functional.
- There was no delamination of the circuit from textile carrier.
- A non-embedded, non protected connector was detached in this test, an embedded connector did not show this failure. This shows the importance of complete embedding of the circuitry, avoiding any wires, connectors, etc. coming out of the protective envelope.

Although not scientific this test was encouraging, and leaded to more standard washing tests. It was also expected that washing cycles on circuits with larger components would be more challenging.

Washing tests of encapsulated conductors

Centexbel received from UGent some samples with a silicone print on them. The aim was to investigate the washing durability of the applied silicone layer. As one can see on the macro image (Fig. 58), no sign of delamination or damage occurs after one washing at 40°C. It was shown that the structures can take up 50 washing cycles.

Conclusion washing tests of encapsulated conductors: *these tests showed that the silicone used for encapsulation is very stable and that it does not delaminate from the textile surface. Hence, it is a good choice as encapsulant.*

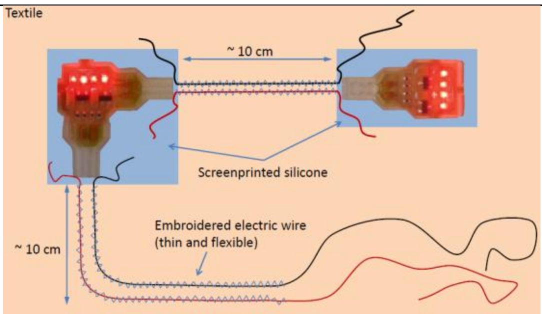


(a) (b)

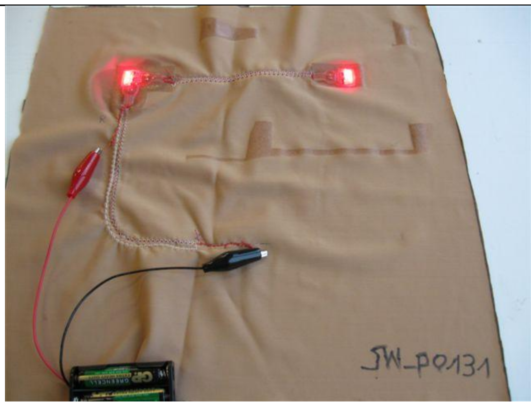
Fig. 58: Silicone pattern on knitted fabric (a- overview; b-detail). The picture is taken after one washing cycle. No damage or delamination occurred.

Immersion tests of encapsulated LEDs

A specific designed circuit with blinking LEDs was designed by UGent to assess the washability. Sketch and one of the realised samples are shown in Fig. 59. As substrate a knitted fabric (polyamide) was used.



(a)



(b)

Fig. 59: Textile with LEDs to investigate washability of silicone encapsulated electronics. (a) sketch; (b) functional real-life sample

Step 1 - immersion in water:
The sample was immersed in hard water at 60°C for 3 hours while soft stirring (ca. 25 rpm – amplitude ca. 2 cm) was done.
Result: after overnight drying, all LEDs were still working.

Step 2 - immersion in water and soap:
The same procedure as in Step 1 was followed but the soap used for standardised textile washing was added (ECE Soap), concentration: 2.5 g/l.
Result: after overnight drying, all LEDs were still working.

Gyro washing tests of encapsulated LEDs

Next step was to use the gyro wash method instead of the immersion. The term “gyro washing” refers to a simplified washing method, used for evaluation of e.g. color fastness of textile materials. The equipment consists of several separate vessels, per vessel only one sample was put in together with the water-soap mixture (800 ml hard water, 2 g ECE soap). The sample was positioned around a plastic tube that fitted in the vessel in order to limit the mechanical action on the sample. The vessels were swung around and kept at the washing temperature (60°C) via the “au-bain-marie” method. This washing was performed during 30 minutes.
Result: after overnight drying, all LEDs were still working.

Standardised domestic washing of encapsulated LEDs

Given the encouraging results obtained with the immersion and gyro washing, domestic washing was performed according to the standard ISO 6330 – method 5A. This means washing at 40°C, together with other items. Two more parameters were varied: (i) the samples were added to the washing load with or without a protective bag and (ii) the drying method was varied: open air or tumble drying. During tumble drying, the temperature goes up to max. 50°C.

The results:
In a *protective bag and with overnight drying*: one sample was tested, it was still functional after 5x repeating the washing & drying procedure. Then, test was stopped.
Without protective bag and with overnight drying: one sample was tested, it was still functional after 5x repeating the washing & drying procedure. After the 6th washing and drying cycle, the sample was no longer functioning.
In a *protective bag and with tumble drying:* one sample was tested, after the 2nd washing and drying cycle, the sample was no longer functioning.

Standardised industrial washing on encapsulated LEDs

Industrial washing was performed according to the standard "Textiles – Industrial washing and finishing procedures for testing of work wear" – ISO15797. Similar as for domestic washing, the temperature during washing is either 40°C or 65°C. However, compared to the domestic washing, the total load in the washing machine is larger, thus leading to stronger mechanical forces working on the sample and there is always tumble drying, maximum temperature up to 80°C. The sample was simply added to the rest of the washing load.

Results:
After 1x washing and drying at 40°C, both groups of LEDs were still functioning but it appeared that 1 group of LEDs had a loose contact. This was due to the nature of simple interconnects and has nothing to do with the encapsulated electronics itself. After 5x washing, both LED groups still worked.
Given the good results, a test was performed at 65°C. After 1x washing, one group of LEDs did not function anymore. Between the 2nd and 5th time of washing, also the other group of LEDs was affected: instead of blinking, the LEDs now burned continuously.

Conclusion washing tests of encapsulated LEDs: these tests showed that the group of LEDs, which represents a simple and robust structure, can be successfully encapsulated in silicone for washing. The results show that standard domestic (at 40°C) or industrial washing is possible for at least 5 cycles. Tumble drying seems to be harder than washing itself.
It was found that the LEDs stopped functioning because cracking occurred in the area where the silicone encapsulated electronics was connected with the external electrical wires.

Once the LED's where not functioning anymore, UGent examined the samples to detect the defect. At first we tested if the interconnections to power the modules where still OK. This was done by putting needles through the silicone to make contact with the pads. When powered up all the LED's where blinking again, which means the defect was at the interconnection. It was hard to detect the defect under microscope because the silicone blurs the image (see Fig. 60).

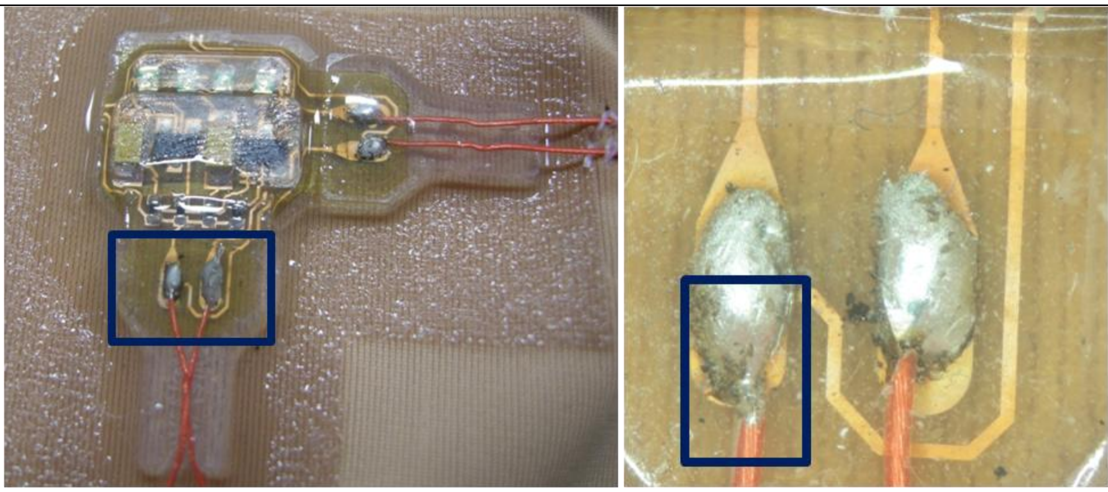


Fig. 60: Broken wire after washing

To have a better view of the broken wire an X-ray image was made. (see Fig. 61)

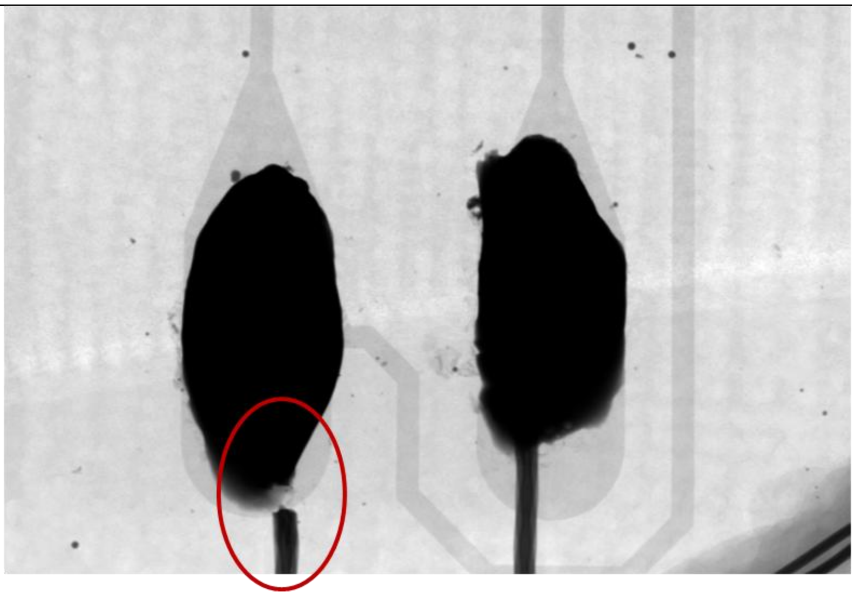


Fig. 61: X-ray of broken wire

This result teaches us that the electronic circuit is still functional after washing and that the failure arises at the interconnection. It is not the solder ball that comes off the copper pad, but the wire that breaks at the solder ball. This means that the forces on this weak spot should be lowered to prevent failure. This can be done by using a silicone with a higher hardness as a sealant or by creating a stiffer zone at the transition. Also a small SMD connector can be used to make a more reliable connection.

Standardised domestic washing of encapsulated resistors and ICs

To test the reliability of bigger SMD components UGent designed a dedicated test sample. The purpose of this test is to evaluate the solder contacts of SMD components on a flexible island when a moulded module is washed several times in a standard washing machine. In order to avoid problems with broken wire interconnections the sample was designed with measurement pads that can be accessed through openings in the silicone. The layout of the design is shown in Fig. 62.

Four different types of SMD components are tested: 0402, 0603, TSSOP28 and QFN32.

The 0402 and 0603 components are 0 Ohm resistors which are interconnected in series. Between every 5 resistors there is a measurement pad to detect opens in the chain. These pads are named P1 to P11.

The TSSOP28 and QFN32 components are dummy IC's. The pins of these IC's are internally interconnected in groups of 2 (indicated in blue in the symbol). A daisy chain with measurement pads is created to detect broken contacts.

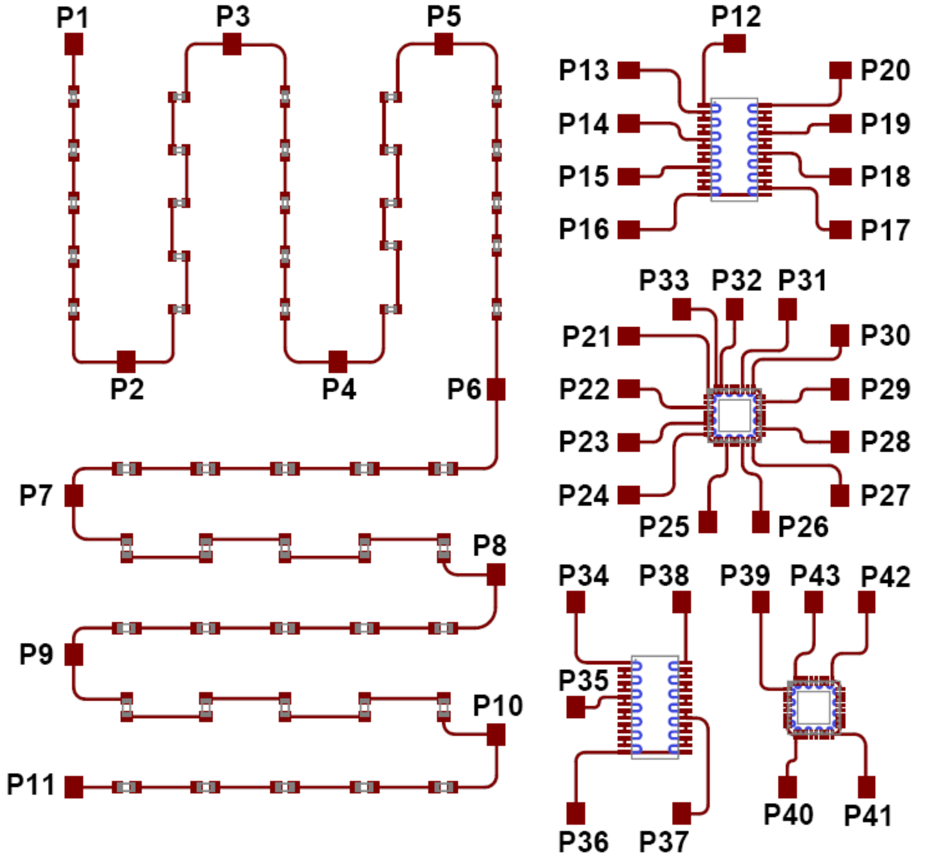


Fig. 62: Layout of wash test sample

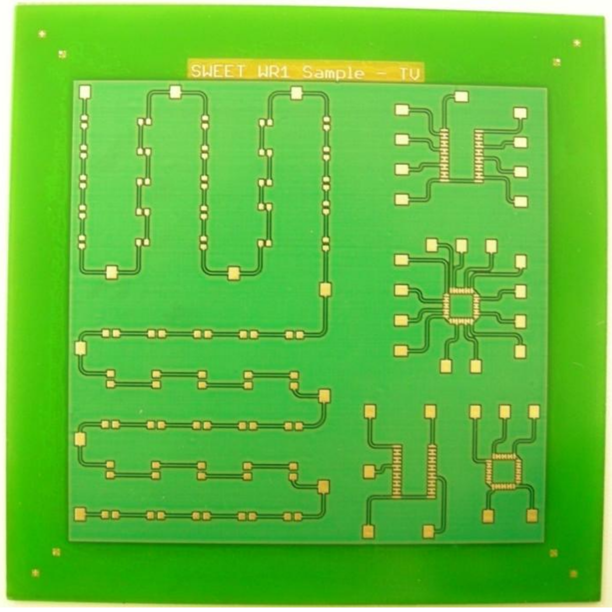


Fig. 63: Laminated flex

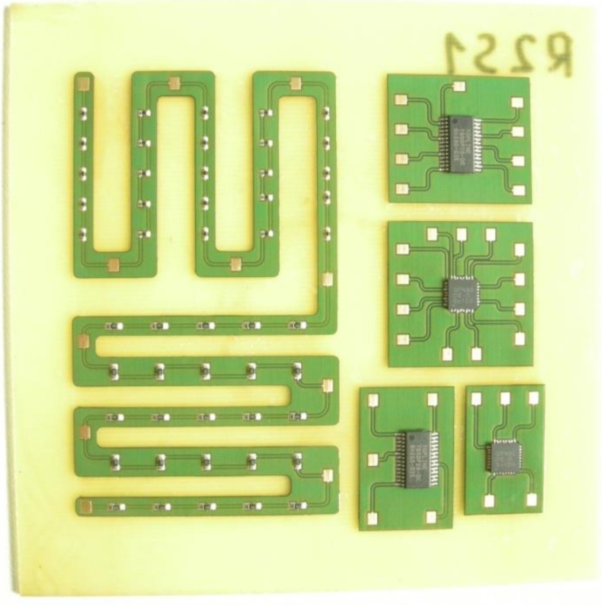


Fig. 64: Substrate after laser cutting and assembly

The samples where made using the laser cut technology described in section 6.1.1. A flex with the test pattern is laminated with wax on a rigid carrier board. This flex is laser cut to define flexible islands. The components are soldered with lead free solder in a vapour phase reflow oven. A picture of the sample before and after laser cutting is shown in Fig. 63 and Fig. 64.

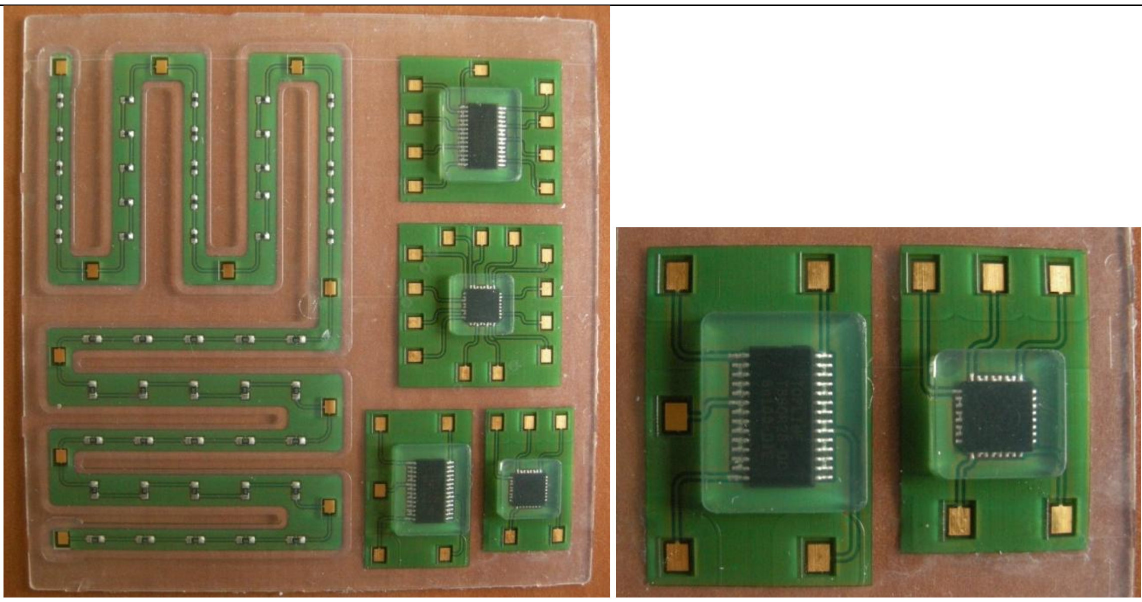


Fig. 65: Moulded test sample

The flexible islands with the test components are moulded in PDMS. Openings to the test pads are provided to measure the contact between washing cycles. (see Fig. 65)

Finally the moulded modules are attached to a stretchable textile. This was done at Centexbel by screen printing a thin silicone layer on the textile which is used to “glue” the modules onto the textile. A picture of the final test sample is shown in Fig. 66.

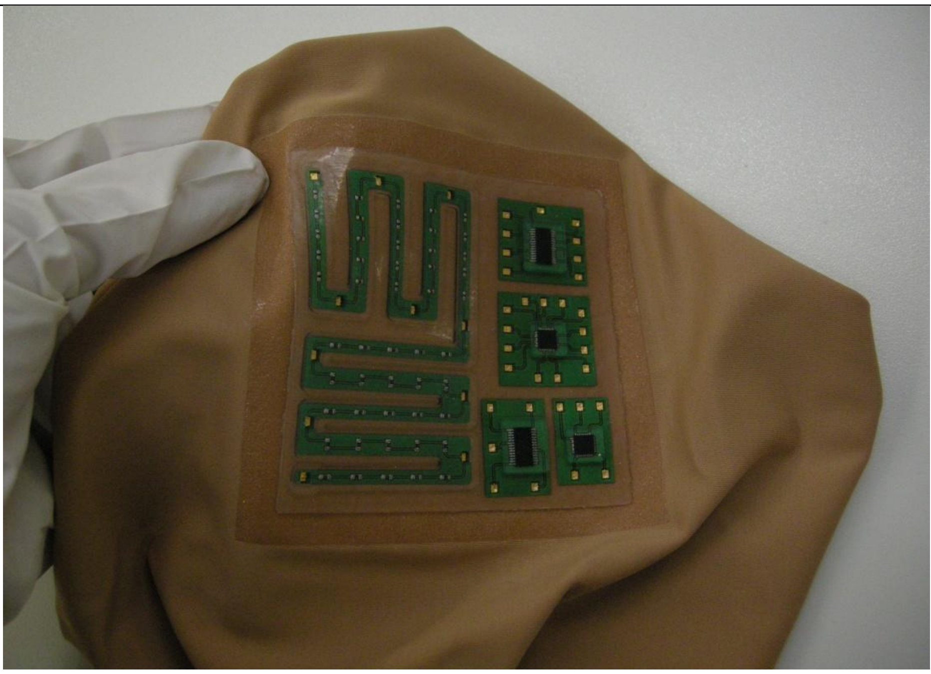


Fig. 66: Wash test sample on textile

The wash tests were performed at Centexbel. Measurements on the test pads were done between the washing cycles to detect broken contacts. The test methodology and results are described below.

On the test vehicle of Fig. 62, 5 different structures were put together: one long line of resistors (on the left side) and 4 ICs on the right side. Each external connection point has been numbered (from P1 to P43). There are a total of 37 points where the electrical connection is measured, each time between two consequent numbers. We distinguish between the connections in the long line of resistors (9 connections measured) and the 4 ICs (28 connections measured).

In undamaged state, there is a good electrical connection between subsequent numbers of a given component. Hence, this structure allows following up which connections got damaged by washing.

The silicone patches with integrated electronics were laminated via screen printing on both woven and knitted fabrics.

First, we look at the number of working connections after washing (referred to as “survivors”). An overview of the test results is given in the table below. The results are given for lamination of the structure on a woven and on a knitted fabric. For the latter, both domestic washing (40°C) and industrial washing (65°C) has been performed. All samples were tumble dried after washing, a severe step.

type of fabric	knitted						woven	
type of washing	industrial (65°C)			domestic (40°C)			domestic (40°C)	
sample tag	S1	S2	S3	S4	S5	S12	S8	S9
# survivors	11	20	7	11	22	21	20	23
average # survivors	**12,7**			**18,0**			**21,5**	
% of survivors	**34%**			**49%**			**58%**	

Table 3: Overview of "survivors", i.e. connections that remained functional after 1x washing. The table summarises the result for different types of fabric and washing methods.

In total 8 samples were washed, for each condition at least 2 samples were processed to get a hint of the reproducibility. One can see that there is quite a spread in the results, so these values should be interpreted with the necessary care. In spite of this, it seems fair to conclude that the industrial washing on knitted fabric leads to the worst results. The best result is obtained for the milder domestic washing and air drying of woven fabric. Even for this "best" result, less than 60% of the connections survive the washing and drying.

An important difference was noted between the results obtained on the resistor line in comparison with the 4 ICs. Indeed, for the resistor line all connections failed after the industrial washing. For domestic washing on the sample, only one survivor was found for samples S12 and S8, for the others none of the connections survived a single washing. Therefore, this structure is not further considered as it needs redesigning. We only considered the combination "domestic washing - woven fabric" for repeated washings.

The result of multiple washings is shown in the graph below. This graph shows that it is not the case that only during the first washing and drying the weak connections are broken and the rest continues on. The trend observed is that the number of broken connections increases with the number of washings, indicating a progressive destruction of the sample.

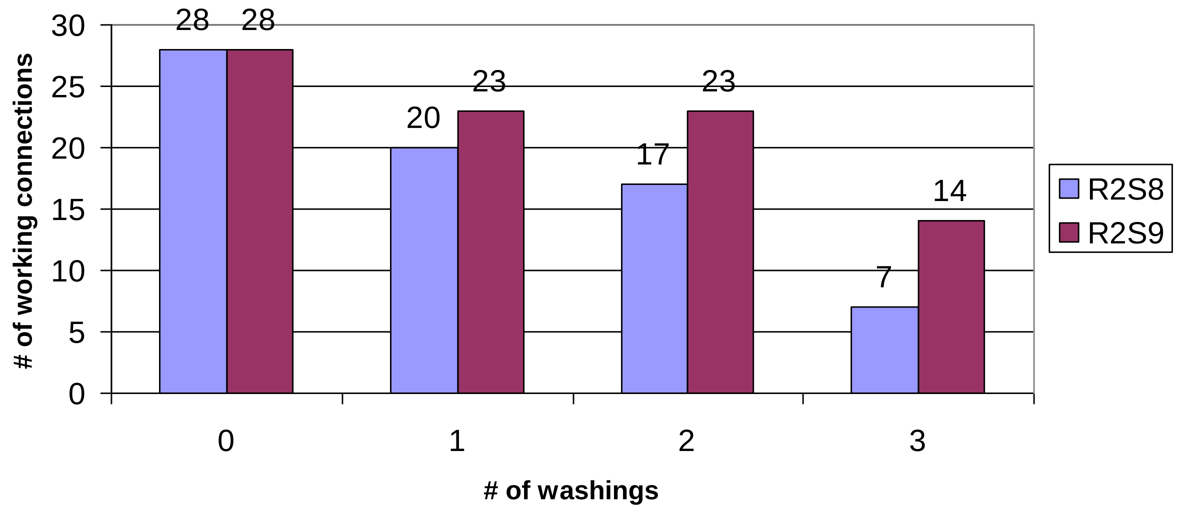


Fig. 67: Overview of repeated domestic washings of the woven fabric. Only the connections of the 4 ICs are taken into account.

UGent inspected the wash test samples to detect where the failure occurs. Between almost all the measurement pads in the chain with the 0 Ohm resistors conductivity was lost. The failure was found near the pads of the SMD resistors. A crack in the copper track leads to a loss in conductivity. The crack arises when the substrate bends too much during the washing (see Fig. 68). The SMD resistor together with the thicker part of the solder creates a rigid zone. Next to it, on the track, the solder is thinner. Because the solder is brittle and this zone tries to bend a crack propagates through the solder and the under laying copper track. In Fig. 69 one can also see that the (rigid) pad is also lifted from the polyimide when the sample is bending.

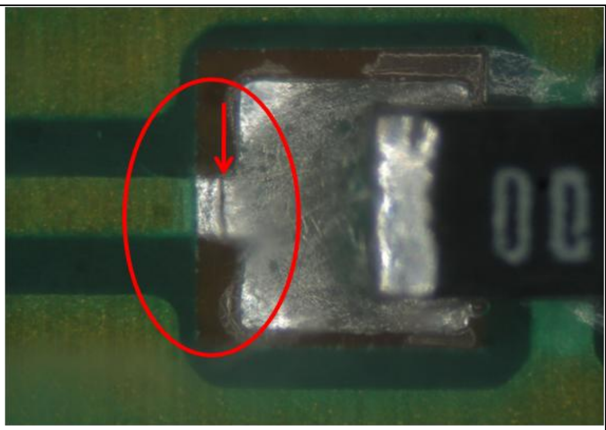


Fig. 68: Crack in solder and copper track

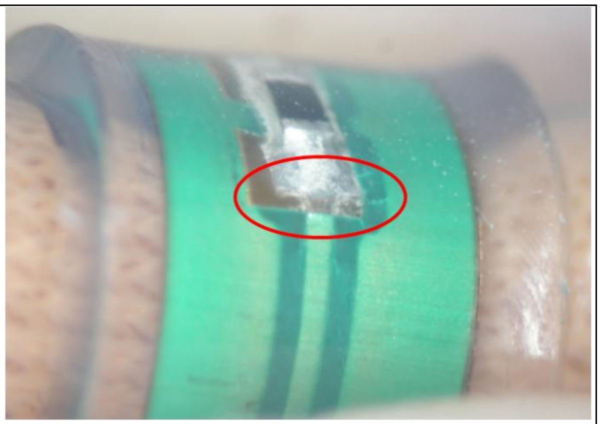


Fig. 69: Lifting of copper pad from polyimide

To overcome this problem a redesign of the pads can be the solution. The aim is to change the pad layout so that we don't have a fragile zone where a crack can be formed. In the first design the opening in the solder mask is bigger than the size of the copper pad (see Fig. 70). This is done to create some margin for aligning the solder mask. But because this opening is bigger the solder can also flow on the track (clearly visible in Fig. 68). This creates the fragile zone where the crack is formed. To solve this, the solder mask is reduced to the original pad size. The pad size itself is made larger in the new design (see Fig. 71). Now the opening in the solder mask is smaller than the area of the copper. The solder will not flow onto the thinner track any more. Also the width from the copper track to the pad changes gradually to distribute the stresses when bending. This improvement still needs to be tested.

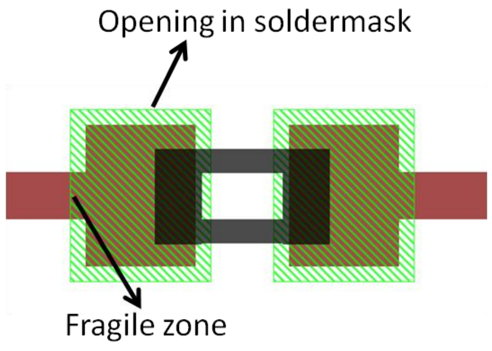


Fig. 70: First design

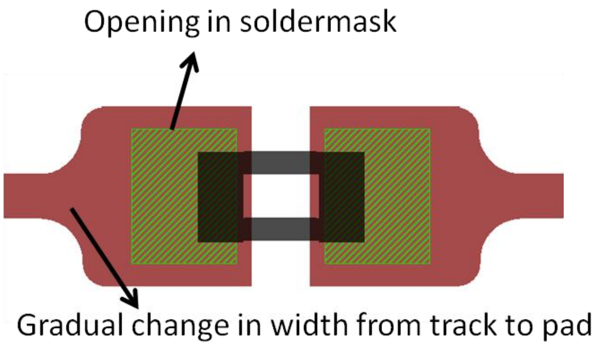


Fig. 71: Improved design

When we look to the interconnections of the TSSOP package another problem becomes visible (see Fig. 72). The leads are pulled from the flex starting at the corner of the package. At the moment the sample is bended there is too much force on the leads because the “big” rigid TSSOP package cannot bend.

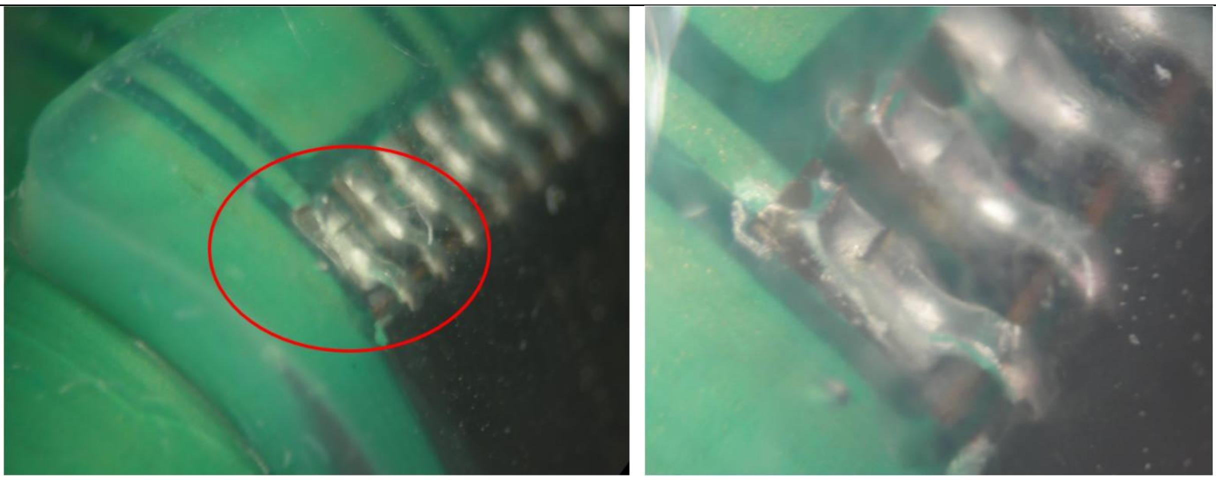


Fig. 72: Broken contacts at TSSOP leads

In an attempt to overcome this problem, the leads were locally reinforced with an underfill material that is usually used for underfilling BGA’s. Also the QFN packages had broken contacts and where reinforced with the underfill. This is shown in Fig. 73. This was done on a sample with the first design.

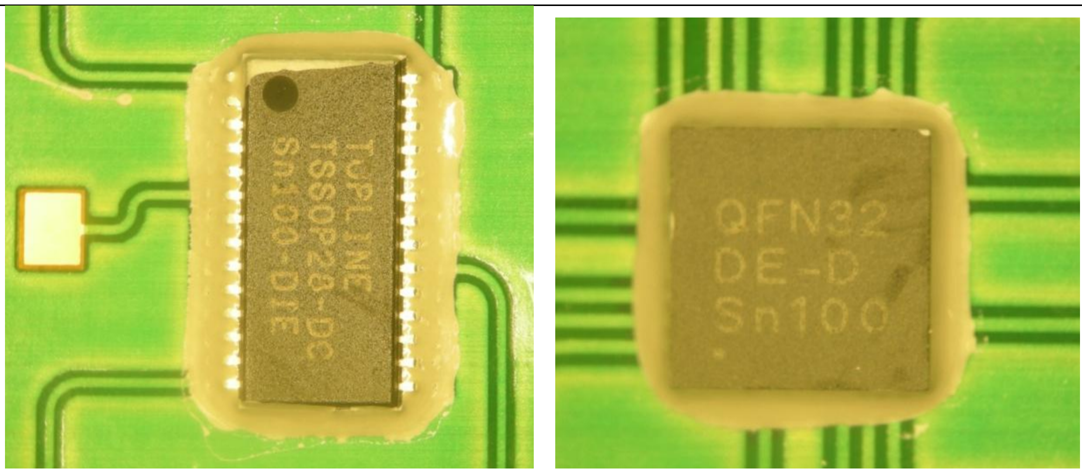


Fig. 73: TSSOP and QFN contacts reinforced with underfill

The test sample with the underfill was washed at Centexbel, but It appeared that the reinforcement was not strong enough to survive the stresses during the washing cycles. The only solution left seems to be a local reinforcement by making the board substrate stiffer. This can be done in two ways that are illustrated in Fig. 74 and Fig. 75.

The first idea is to attach a stiffener under the big components. This should support the contacts and replacing the bending to a more robust zone.
The second idea is to put the components on rigid interposer boards. But here attention should be paid on the contacts from rigid board to flex. Both ideas still need to be tested and evaluated.

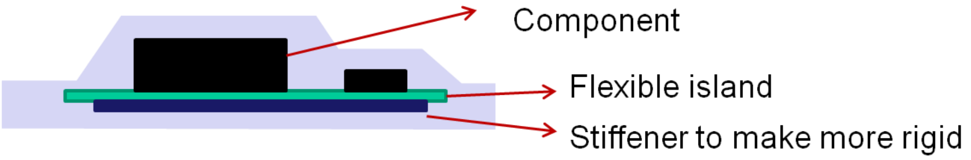


Fig. 74: Use of stiffeners

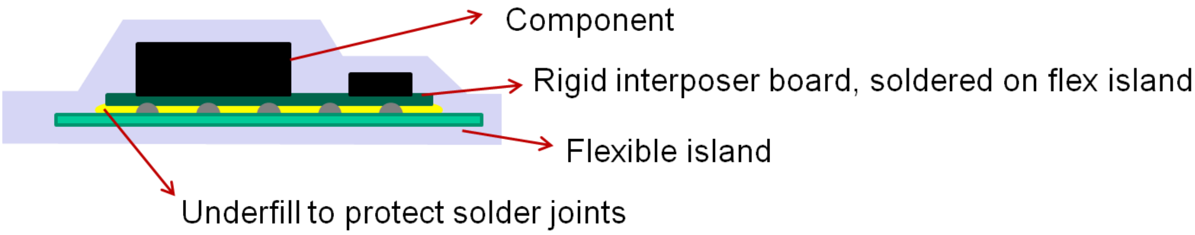


Fig. 75: Use of interposer boards

General conclusions washability:

Several washability tests on silicone embedded electronics on textile substrates were performed. Briefly summarised, the following main conclusions can be deduced:

- *The embedded electronics can withstand water and washing detergent very well, as tested by soaking the samples. A slight stirring has no negative effect.*
- *Real washing (domestic or industrial) involves mechanical action. The tests showed that the electrical contacts are gradually, i.e. the effect becomes worse per washing cycle, destroyed by this mechanical effect.*
- *Tumble drying involves severe mechanical action and, consequently, also has a severe impact on the samples.*
- *Samples on a woven structure are better suited to cope with washing than knitted structures.*
- *Best results for LEDs laminated onto textile were obtained when they are put on a woven substrate, domestically washed and dried in open air. In this case, five cycles could be reached.*

6.2 Demonstrators design

6.2.1 First demonstrator: a basic building block

The result of the first demonstrator is an evolution over three versions: The first (Fig. 76, left) proved the feasibility of an inductive powered flexible system. The second version (Fig. 76, right) added a microcontroller and a LED array. This was implemented on two separate islands interconnected by stretchable connectors. One island contains a flexible coil and conversion electronics, the second contains the microcontroller and the LED array showing a blinking pattern.

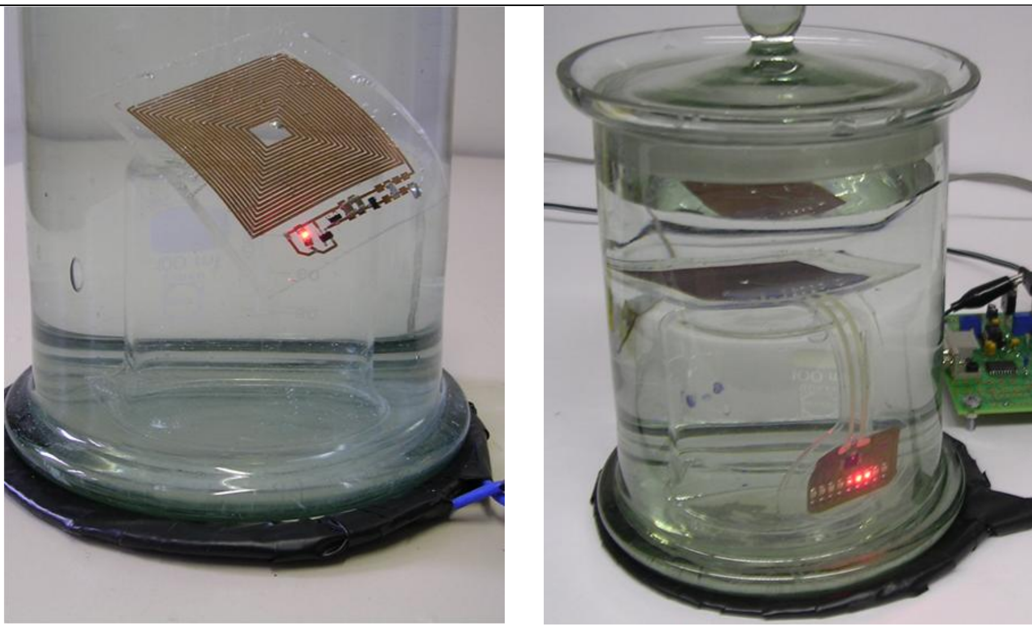


Fig. 76: First demonstrator Version 1 (left) and Version 2 (right) submerged and operating in normal tap water

Fig. 77: First demonstrator, Version 3. A coil is to be added to the connectors on the right, a battery to connectors on the left.

The third version adds functionalities such as backup battery power when the link is absent, a charger to charge this battery over the inductive link and RX/TX functionalities to make the LED-array user-controlled through a PC and the inductive link. The final implementation of V1.3 is shown in Fig. 77. In this implementation, only the four straight lines interconnecting both islands need to be replaced with the stretchable meandering of CMST-Gent. Only the final version is discussed into further detail since this contains also the functionalities of the earlier two.

The block level diagram of the system is depicted in Fig. 78. The diagram can be divided into two parts, connected by an inductive link module with a coupling factor k. The external part (left) consists of some data communication electronics and a dedicated class E amplifier to drive an AC current through the primary coil of the magnetic link. This part is further named “primary side”. The link can be considered as a coreless transformer with large magnetic leakages but which can support both power and bidirectional data transfer. Hence the coupling factor k will be small. The current flowing in the primary coil generates a magnetic field, which is partially picked up by the secondary coil and converted into a voltage. AC-DC voltage conversion and regulation is achieved by the block “Power regulation”. This transferred power can then be used to recharge the battery and bias a load (in this case, indirectly regulated through the microcontroller). In absence of the primary coil (supplying power to the system), the battery powers the load. Bidirectional data transmission is also possible through the inductive link and handled by the microcontroller. The collection of these blocks are further called “secondary side”, and some of these building blocks require further details and are discussed next.

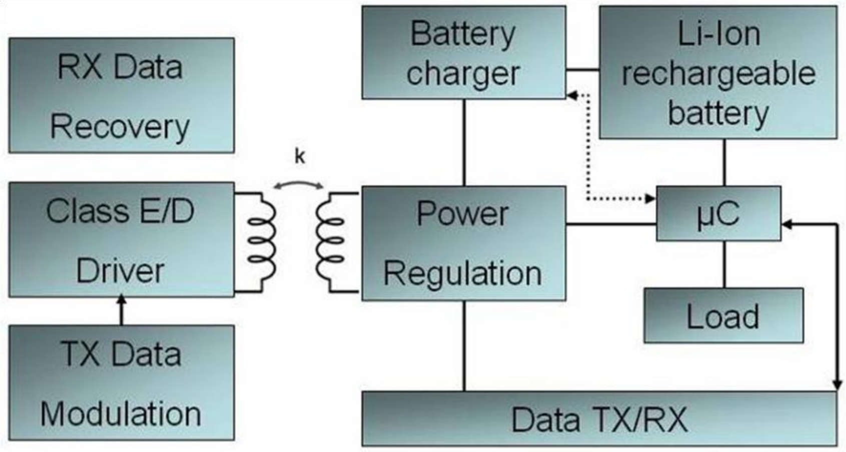


Fig. 78: System block level diagram of the first demonstrator

The choice of the charger controller is a trade-off between full programmability and extra features vs. small dimensions and circuit complexity. The LTC4054-4.2 was selected because:

- The charge current can be selected from 10 to 800 mA.
- The only external components are: one resistor and two stabilizing capacitors.
- It is available in a small 5-pin SOT23 footprint and is low cost.

The charging is planned overnight and battery power can be used during the rest of the day. The current to the battery is monitored through a shunt monitor (INA138) only inducing a minor voltage drop of about 10 mV. This signal and the battery voltage are sent to the microcontroller which uses these signals to determine and display the charge status on an array of 8 coloured LEDs. These LEDs form the actual load in this simplified system and will later be replaced by sensors in paragraph 6.2.2.

Not only does the microcontroller (PIC16F687) monitor and display the charge status of the battery, it also handles data transmission from and to the external unit. Bidirectional data transmission while charging allows adjusting implant parameters and retrieving information about the charge status. OOK modulation (On-Off Keying), for data transmission through the downlink, and absorption modulation, for the transmission through the uplink, were selected. The first is achieved on the primary side by AND-ing the data with the oscillator signal actuating the MOSFET switch. This data is demodulated at the secondary side by an envelope detector. The second is achieved by temporarily short-circuiting the coil on the secondary side to change the load. This signal can be picked up by the absorption modulation detector on the primary side.

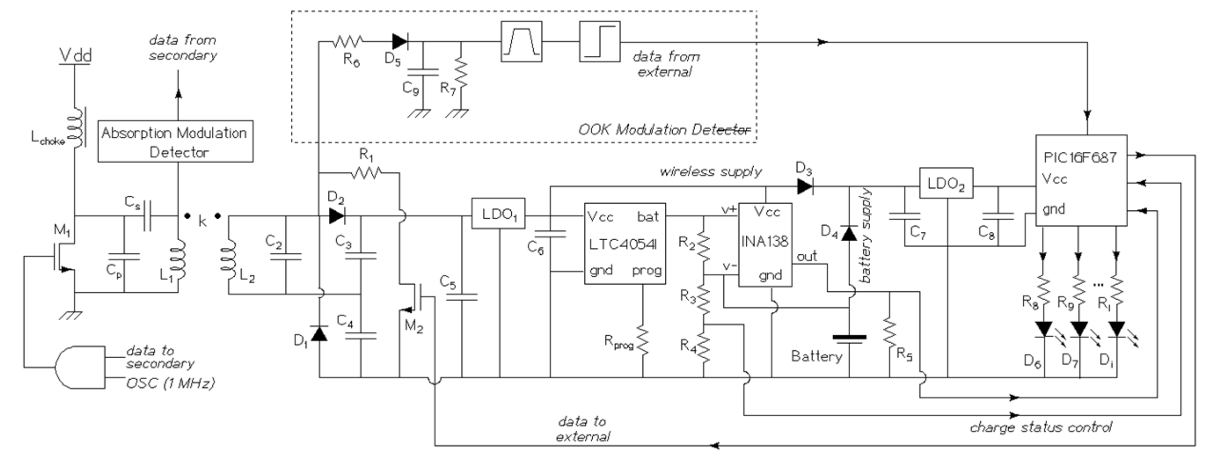


Fig. 79: System schematic of the first demonstrator, version 3

The best available battery suited for the application is the PGEB0053559 from PowerStream. It has a capacity of 65 mAh with a mere 0.5 mm thickness and a nominal voltage of 3.7 V. With the charge current set at 30 mAh, a full recharge is reached in a few hours. This battery is difficult to obtain however so for the final implementation, the PGEB014018 is chosen as a suitable alternative. It has a capacity of 25 mAh, and a thickness of 1 mm. Its nominal voltage is 3.7 V. The integration of the different blocks leads to the schematic depicted in Fig. 79. By comparing Fig. 78 and Fig. 79, it is possible to identify the different building blocks. A note must be added: in this schematic, the resistor R_1 was later replaced with a diode to ensure no leakage currents flow through parasitic drain to source diode.

6.2.2 Second Demonstrator: defined by the user-group and consortium

Through input from both user-group and consortium, the following decisions were made with respect to the first demonstrator:

- The LED array, i.e. the load, is to be replaced with a sensor monitoring a biomedical signal: breathing rhythm, heart rate, temperature, moisture, etc.
- The system is to be simplified by removing the recharge and communication ability from the inductive coupling.
- Wireless communication is to be added to the system.

A combination of a number of these biomedical signals finds its target application in a wearable Sudden Infant Death Syndrome (SIDS) monitoring suit for infants. Although the combination of monitoring both breathing rhythm and ECG was envisaged in an early version of the demonstrator, the actual implementation within this project was simplified to the monitoring of one signal: breathing rhythm. More information on the early version of the demonstrator can be found in [1]. The remainder of the report discusses only the latest version.

The system is to be built up with off the shelf components to create a low cost, reliable, textile integrated monitoring system. Furthermore, it is to be kept modular (based on a master-slave island topology), so that extra sensor islands can be added at any time measuring different parameters influencing SIDS, thereby increasing the reliability of the SIDS prevention suit. The specifications were determined to be:

- Encapsulation and integration through silicone embedding and adhesion.
- Robust monitoring of respiration.
- Distributed island system on flex with stretchable interconnects.
- Battery operated.
- Detection of small tidal volumes with infants.

At first, effort went towards an accurate measurement of breathing rate. This implies the search for an algorithm to detect the breathing cycle. The possibility to also quantify breathing volume was also shortly investigated. In the past, many different principles have been investigated towards this end: measurement of the capacitive, inductive and resistive change of a belt around the chest or abdomen [2]. Breathing rhythm monitoring through accelerometers was chosen because:

- Accelerometer signals are relatively independent of the environment.
- They can be easily encapsulated without affecting the measurements.
- The full encapsulation ensures mechanical robustness to the application environment.
- Possibly, posture information can be extracted from the same signal.

Especially the latter would greatly benefit the system specifications since it is a well-known fact that prone sleep positions lead to increased risk for SIDS [3], [4], [5], [6]. A technique based upon accelerometers to estimate the breathing waveform is refined from [7] for increased insensitivity to motion and posture changes. Dual-axis accelerometers are placed in the transversal body plane. The third axis is normally horizontal during sleep, not registering any acceleration and can therefore be neglected.

During relaxed breathing, respiration is mostly coordinated by the diaphragm [8]. Therefore, measurements are performed on the abdomen, placing the accelerometers ~8 cm laterally from the umbilicus on both sides. (This distance was chosen for testing on an adult. The actual distance for an individual depends on the size of the patient. For newborns, 1-3 cm is more likely.) Using this placement, several measurements were carried out and compared to a Jaeger PulmAssist spirometer, used in the tests as a reference. Two different strategies were tested in order to evaluate their ability to extract the breathing rhythm and amplitude in an accurate and reliable way:

Method 1: The abdomen expands outwards during inhalation, thereby slightly tilting both Y-axes inwards as shown in Fig. 80. This variation in inclination is sensed by the accelerometers and can be derived by projecting the gravitation vector onto the XY-plane of the accelerometers. The specific placement of the accelerometers results in a common-mode signal (sum of the sensed inclination vectors) and a differential signal (difference of the sensed inclination vectors). Common-mode and differential signals are caused by respectively the patient's posture and breathing.

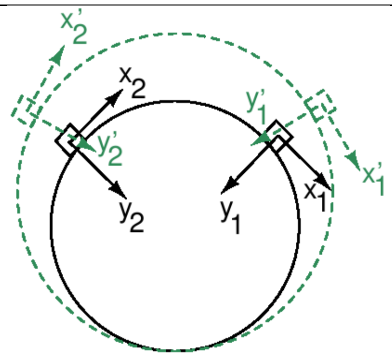


Fig. 80: Inclination change principle. A transverse cross section of the abdomen is shown before inhaling (full line) and after inhaling (dashed line), with the relative positions of the accelerometers.

Method 2: The rhythmic motion of the abdomen wall due to breathing causes the accelerometers to sense a radial displacement. These variations, superimposed on the dominant DC-signal caused by gravitation, can be derived as the modulus of the sensed accelerations in the X- and Y-direction. Both variations were summed to increase the signal sensitivity.

The complete system, of which the block diagram is shown in Fig. 81, is powered by a flexible Lithium-polymer battery of 3.7 V and communicates wirelessly with a computer that displays the results. The system is composed of a master island and sensor islands containing the measurement circuitry for the physiological parameter monitoring. A PCB implementation of the master island is depicted in Fig. 82, also showing the integrated Nordic NRF24L1 module used to wirelessly communicate with a computer.

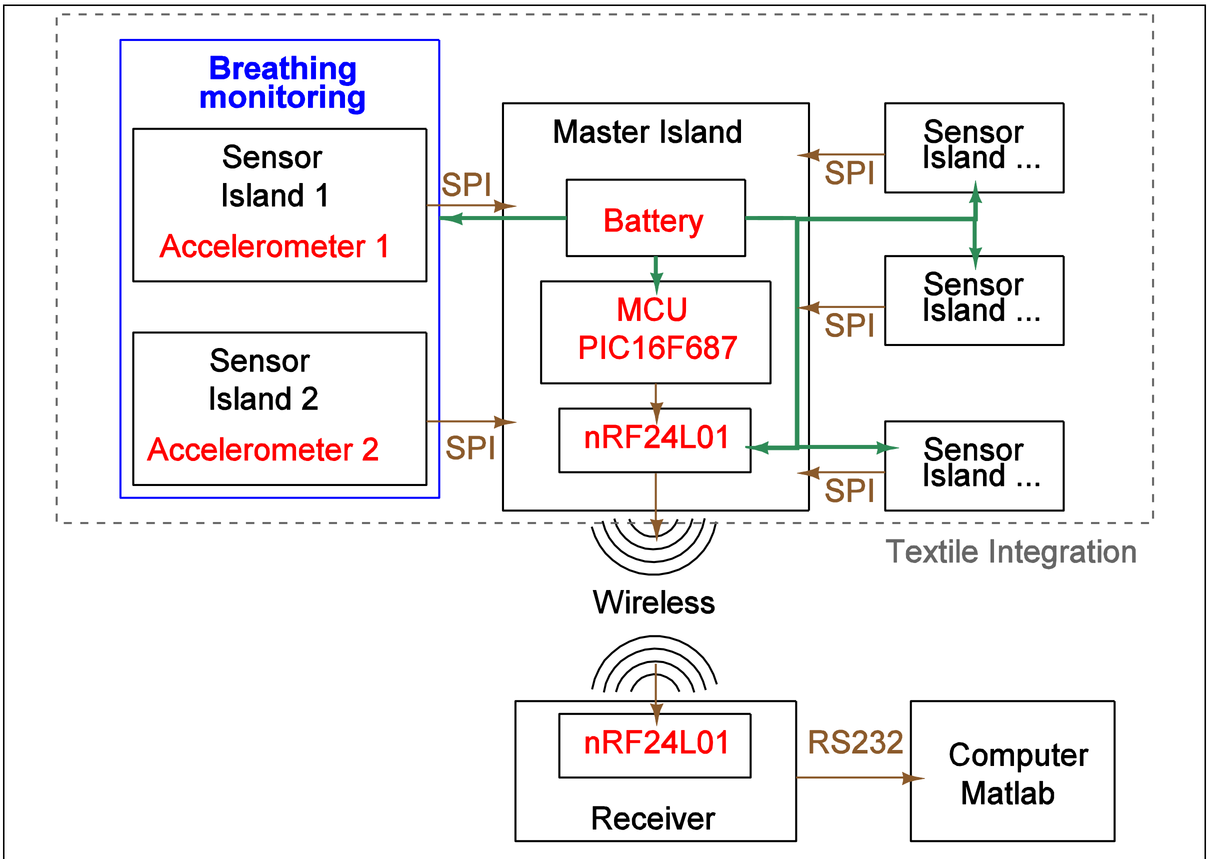


Fig. 81: System block level diagram of the second demonstrator

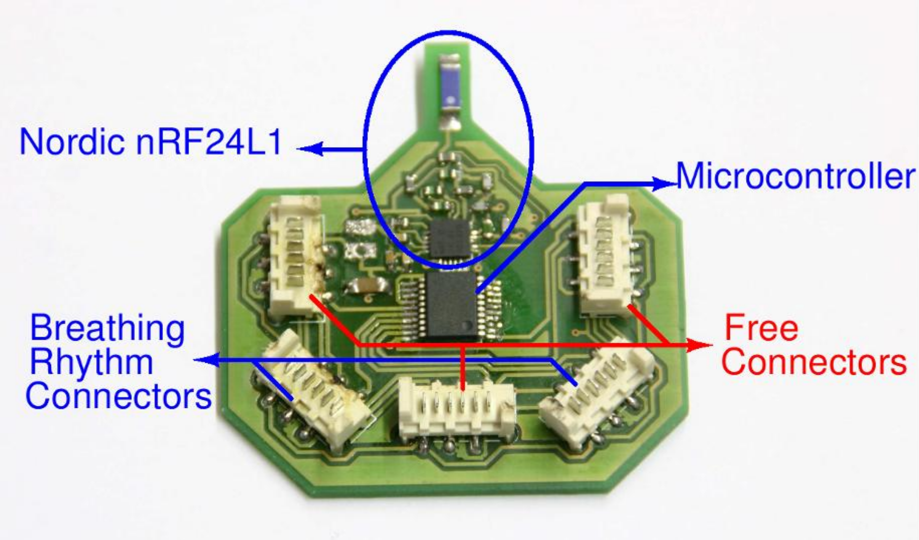


Fig. 82: PCB implementation of the master island, showing the microcontroller and an integrated Nordic nRF24L1 module for wireless communication

In the final implementation, this island (and the sensor islands) will be implemented on flexible carriers, e.g. Kapton foil from Dupont Luxembourg. Interconnections between the islands will be realized by silicone based interconnects that are both flexible and stretchable. The complete circuit can then be embedded into silicone using the MID technology from the UGent CMST Group. In such a way, a network system can be integrated on a large textile area (by silicone adhesion) while still retaining its elasticity. When the current system is integrated with a wireless recharge circuitry through inductive coupling (first demonstrator), a fully encapsulated, textile integrated system monitoring the vital signs of newborns, can be obtained.

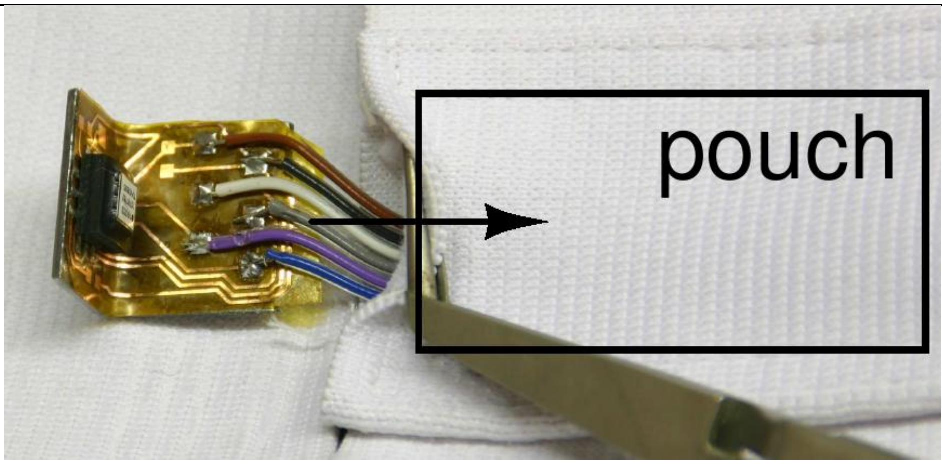


Fig. 83: Components and circuits for this system are integrated with textile by lodging them into pouches. The figure shows an accelerometer with a standard wire connection for the feasibility study.

Where these steps are envisaged for the final implementation, a preliminary demonstrator to prove the full feasibility of the system was not yet integrated with the textile fabrics through silicone adhesion. In this setup, the separate circuits are lodged into pouches on the appropriate locations, as illustrated in Fig. 83. In this case, the sensor islands contain only an accelerometer. The testing of this system is described in paragraph 6.3.3.

6.3 Demonstrators realisation and testing

6.3.1 Preliminary technology demonstrator

To test and to evaluate the development of the technology for stretchable electronics for integration in textile, UGent has designed and fabricated a preliminary demonstrator. This simple, but attractive demonstrator shows a 7x8 stretchable LED matrix which is driven by a flexible driver board (Fig. 84).

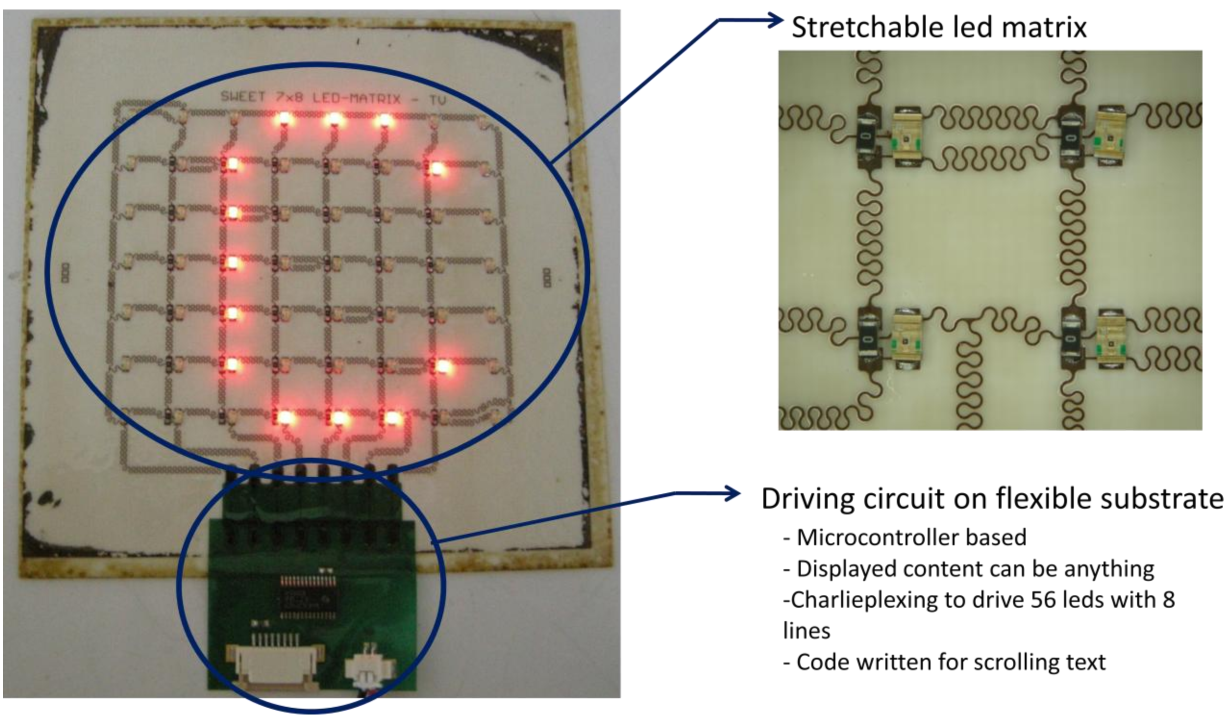


Fig. 84: 7x8 LED-matrix demonstrator

The circuit is embedded in silicone using the SMI technology. Next it is bonded on the textile using plasma bonding as described before. Some pictures of the result are shown in Fig. 85.

The use of the LED's provides a visual way to detect broken tracks in the stretchable matrix. After stretching, bending and crumpling the demonstrator for several times, some (straight) tracks under the components in the stretchable matrix were broken. Ideas for an improved technology exist to prevent this and to increase the reliability of the stretchable circuit.

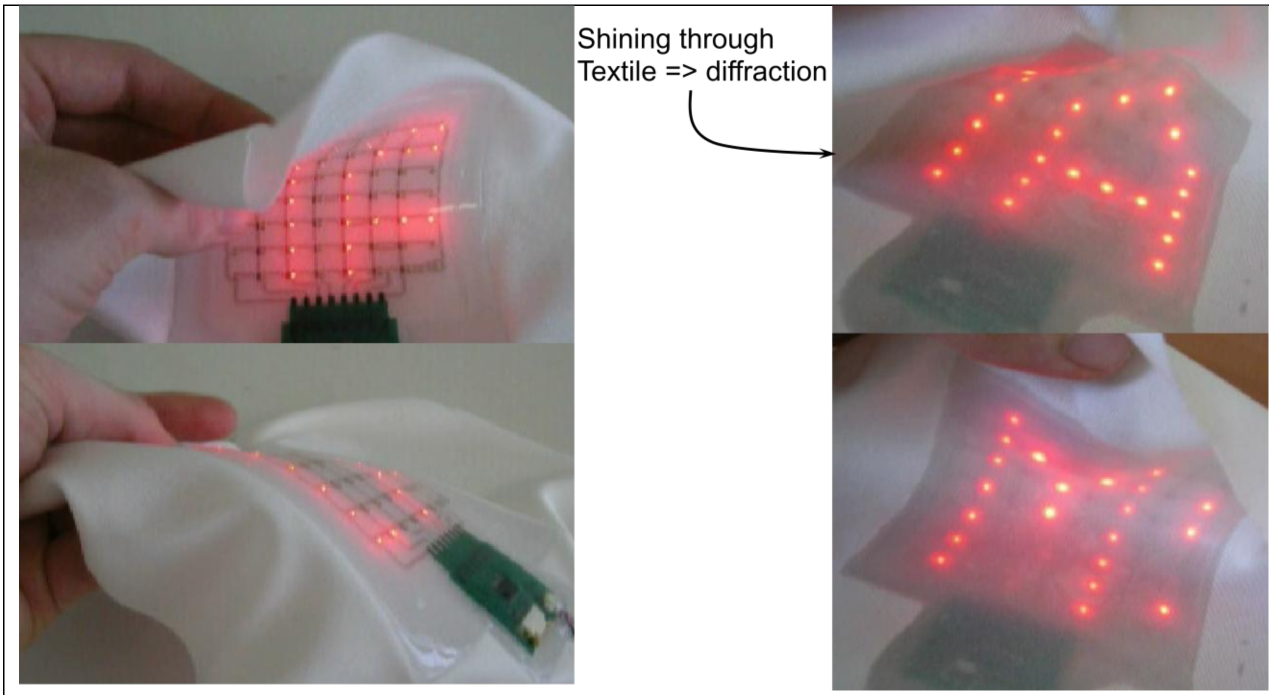


Fig. 85: 7x8 LED-matrix demonstrator, integrated in textile

6.3.2 Testing with the first demonstrator, version 3

First of all, the demonstrator needs a coil to operate. This coil is to be added to the connectors displayed at the right of Fig. 77. To this end a number of coils were tested, such as the ones depicted in Fig. 86.

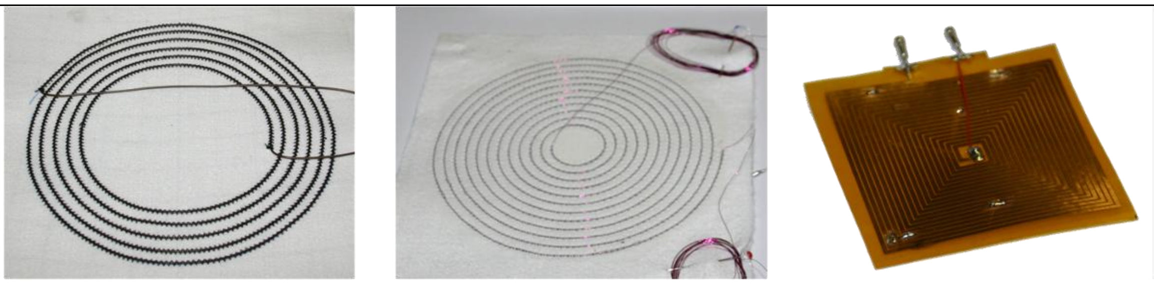


Fig. 86: Different coil implementations that can be used in combination with the first circuitry. Note that these coils have different scales.

The first and second coils were produced by Centexbel Verviers by stitching a wire in a spiral form, the third coil is a flex implementation produced by ESAT-MICAS. Note that the coils are not shown to scale. The first coil is about twice as big as the second and third, which are almost of equal size. The specifications of the receiver antenna were the maximum outer diameter (110 mm), the inductance value ($L = 7\ \mu H$) and a recommended quality factor ($Q = 20$ at 1 MHz). The second textile antenna has been realized as a spiral in a plane with geometrical parameters calculated with an inductance calculator. The drawing of the spiral is first printed on a textile substrate (Fig. 87). This drawing is used as a guide to embroider the final antenna with a copper wire (Fig. 88). The diameter of the conductive wire has been calculated to obtain the same quality factor as the original PCB type antenna (Fig. 89).

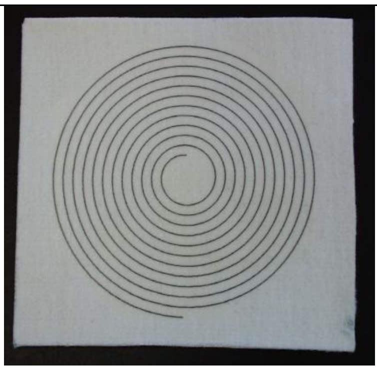


Fig. 87: Print of spiral on textile

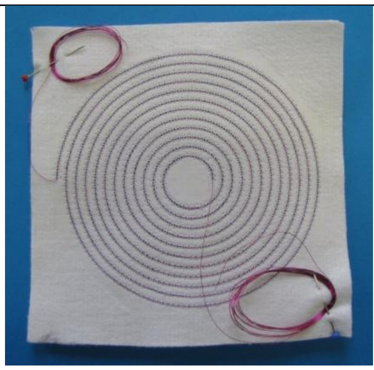


Fig. 88: Embroidered antenna

Fig. 89: Original antenna on PCB

Although all three coils from Fig. 86 show differences in quality factor (Q) and inductance (L) as summarized in Table 4, all three implementations can be used to capture the varying magnetic field and power the system.

Coil	**Quality factor (a.u.)**	**Inductance (µH)**
CentexBel Verviers Coil 1	67.5	7.032
CentexBel Verviers Coil 2	20.5	8.760
KULeuven Flex Coil	23.9	7.144

Table 4: Parameters of the different coil implementations

When a coil is connected, system tests can be achieved. The test setup towards this end is shown in Fig. 90. The first system test is the monitoring of the charge status. This can be tested by measuring the voltage drops across the shunt resistor (directly related to the charge current to the battery) and the battery itself. Both were monitored to determine that charging of the battery indeed occurs.

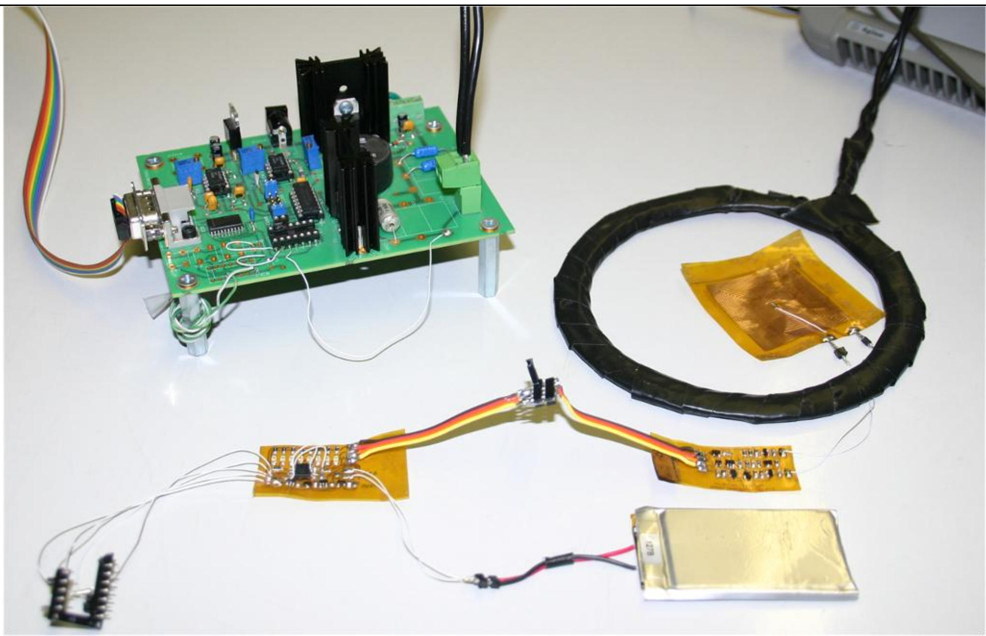


Fig. 90: Test setup debugging the first demonstrator V1.3

A second system test involves the data communication. Through a computer's COM port, a byte is sent from the primary side (Fig. 91, left top graph) to the secondary side and monitored after data modulation (Fig. 91, left bottom graph). Data was also sent from the secondary side to the primary side with a block wave (Fig. 91, right bottom graph) and monitored at the primary side before modulation (Fig. 91, right top graph). Although in this last case, the variation sensed at the primary side seems small, one should note that the entire amplitude drop is about 15 V since one square for that graph represents 50 V instead of 2 V for the top graph.

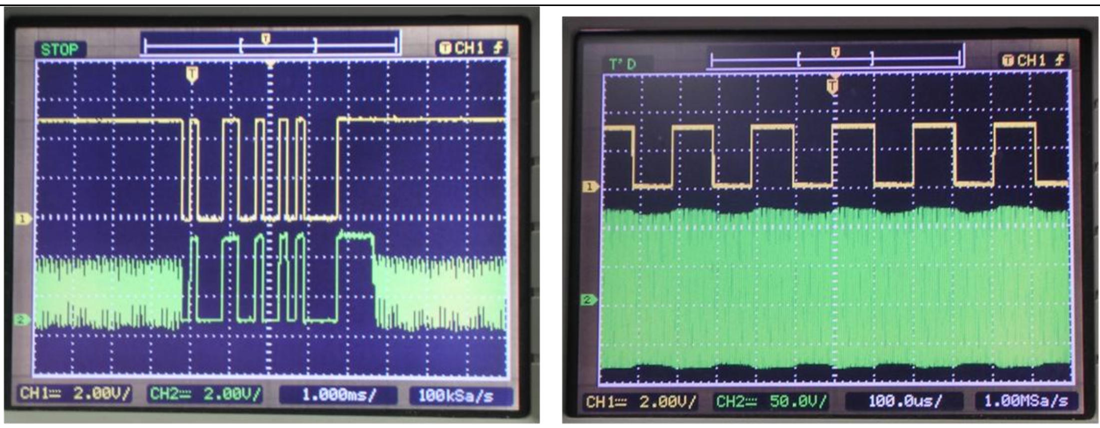


Fig. 91: Oscilloscope graphs for data communication. The left picture shows the signal sent from the primary side (top) and the demodulated signal on the secondary side (bottom). The right picture shows the signal sent from secondary side (top) and the effect on the primary side (bottom).

These tests are also confirmed visually with a programmed microcontroller. Sending the proper codes from a PC to the secondary side will trigger the blinking of a specific

LED in the array for five times. This action will interrupt the normal operation of the LED array showing a gradually increasing coloured scale of the battery charge status (from one LED = battery depleted and charging, to 8 LEDs = battery fully charged). In the absence of the inductive link, only the eighth LED will blink signalling a status "ready to start charging". In this LED array, the first three LEDs are red, the following two are yellow and the last three are green.

Realisation as stretchable circuit

Fig. 92 shows the first demonstrator, realised as a stretchable circuit. The production flow is the one of the laser structuring technology, as described in par. 6.1.1 and as shown in Fig. 3 and Fig. 4. The circuit consists of a coil part (top right of Fig. 92) and a battery part (top left), both with associated passive and active components. The two parts are connected by 4 stretchable interconnections. A detailed view of the interconnection part is shown in the bottom photograph. Note the gradually narrowing meanders from component island to interconnection part in order to insure a gradual flex-to-stretch transition.

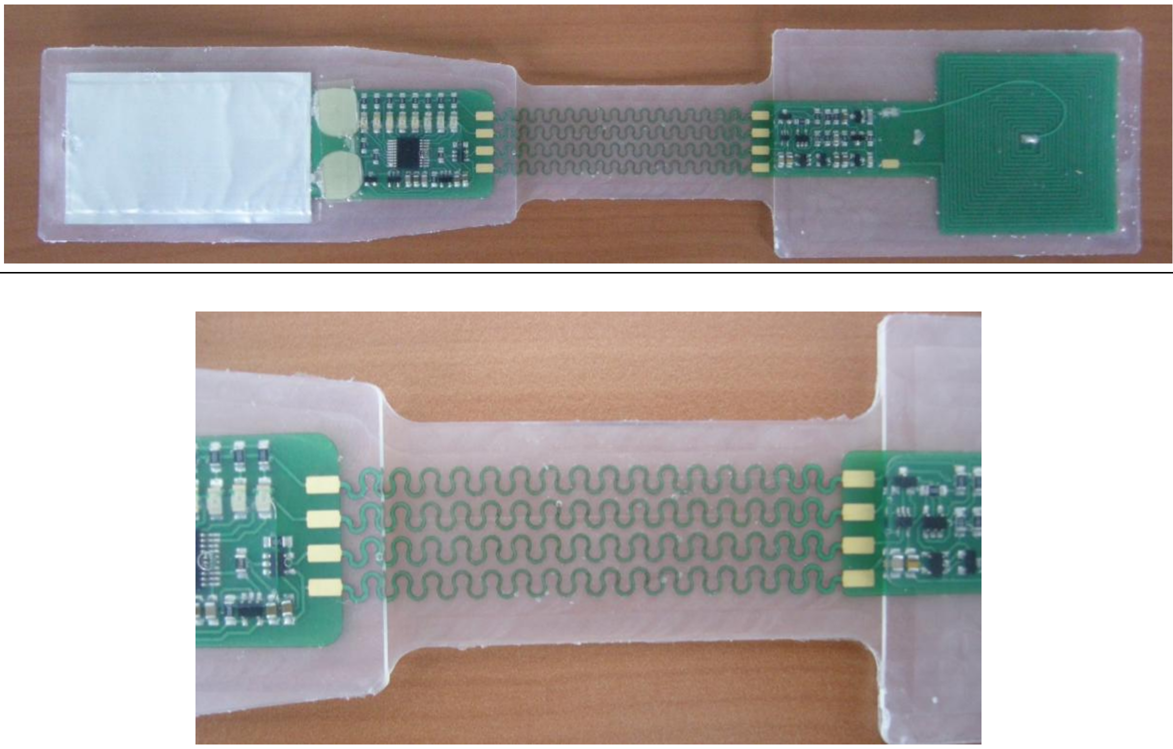


Fig. 92: Demonstrator 1, realised as stretchable circuit; top: complete circuit, showing integrated flexible battery (extreme left) and inductive coil (extreme right); bottom: detailed view of stretchable interconnects

The complete circuit is 260 mm long by 50 mm wide, components are assembled by reflow soldering, and the embedding is done by moulding in PDMS. The complete circuit has the correct functionality as expected and described higher in this paragraph.

6.3.3 Initial testing with the user defined demonstrator

The two methodologies in interpreting the accelerometer signals, discussed in paragraph 6.2.2, were tested on adults, keeping in mind the signal variability when performed on infants. Analog Devices' ADIS16003 accelerometers were used with an accuracy of 1 mg at 60 Hz, built-in SPI communication and consuming less than 2 mA (including SPI interface circuitry). During two-minute tests, of which an example is shown in Fig. 93, the patient was asked to vary his/her breathing amplitude and frequency in a random way. In supine position all breathing cycles were detected. The exact position of the detection however, showed a mean respiration rate error of 3.8% for the inclination method, whereas the magnitude method showed an error of 6.8%.

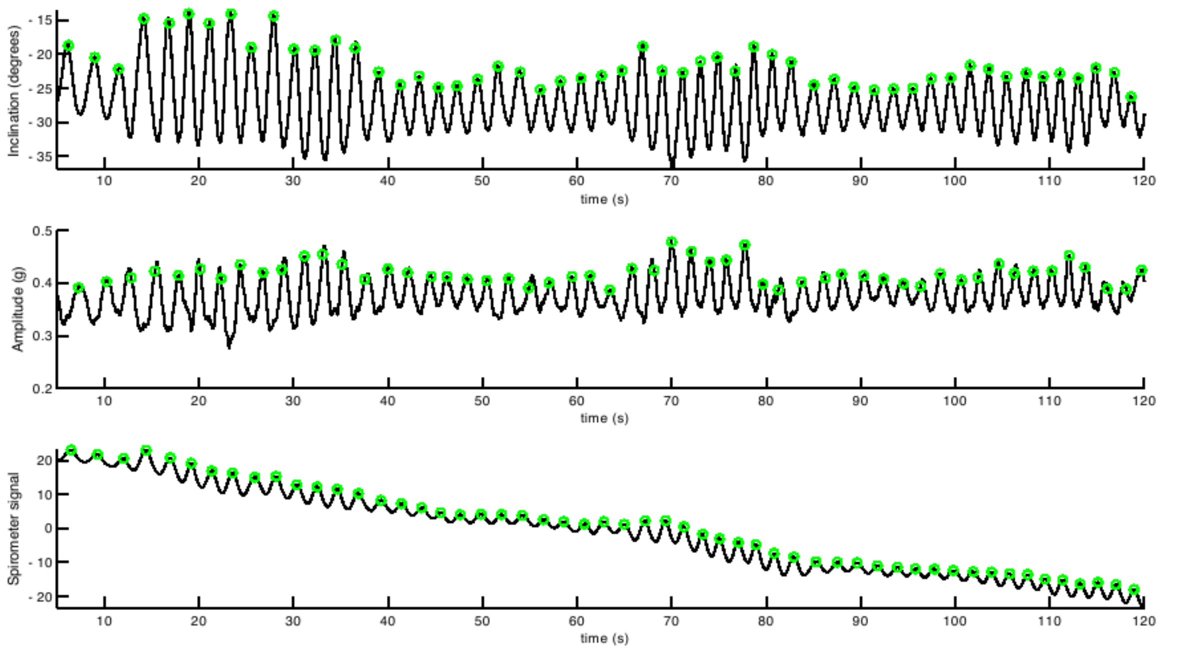


Fig. 93: Two-minute test comparing both methodologies

To assess whether the breathing amplitudes (i.e. flow/volume) could also be extracted from the accelerometer signals, the normalized results were compared to the normalized spirometer amplitudes in the scatter plots shown in Fig. 94. The left graph shows the results of the inclination method whereas the right graph shows the results for the radial displacement method. The R^2-values of the correlation showed again better results for the inclination method: 0.85 compared to 0.46 for the radial displacement method. This proves that the extraction of breathing volume is possible from the accelerometer signals.

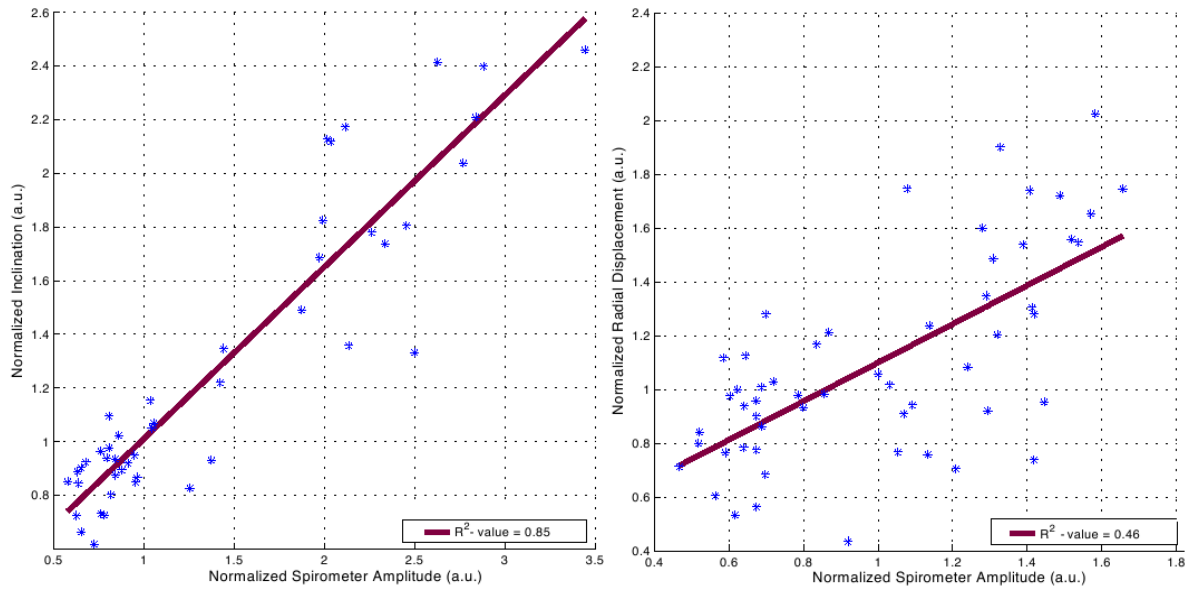


Fig. 94: Correlation between the normalized spirometer results and the inclination method (left) respectively the radial displacement method (right)

During position variation, the peak detection algorithm showed to be insensitive to movements during transitions, even though these variations were not fully cancelled. These results are shown in Fig. 95. All four graphs in this figure use the same X-axis in seconds. The top two graphs show the measurements of inclination method from both accelerometers. These two signals are combined to generate the third graph on which the detection algorithm is applied. In this third graph all peaks caused by the breathing cycle are detected even though two large movement artefact peaks, remain. The last graph shows the patient's posture (delayed due to processing). In this test, the patient started with a supine position (0°). After 20 seconds, the patient rotated 90° (taking a sideways posture) and after another 20 seconds, changed back to supine position.

The test setup used to obtain the results in Fig. 95 is shown in Fig. 96. Herein an adult is shown wearing the suit, and monitored wirelessly. The top picture shows supine laying position and the real-time breathing detection. The middle picture shows a sideways posture where breathing detection continues. Note that the amplitude of variation in this second picture is exactly the same as in the first picture. Only the scale is different because the moving window is recovering from the rotation. The bottom picture shows the combined accelerometer signal (right) compared with a spirometer signal (left).

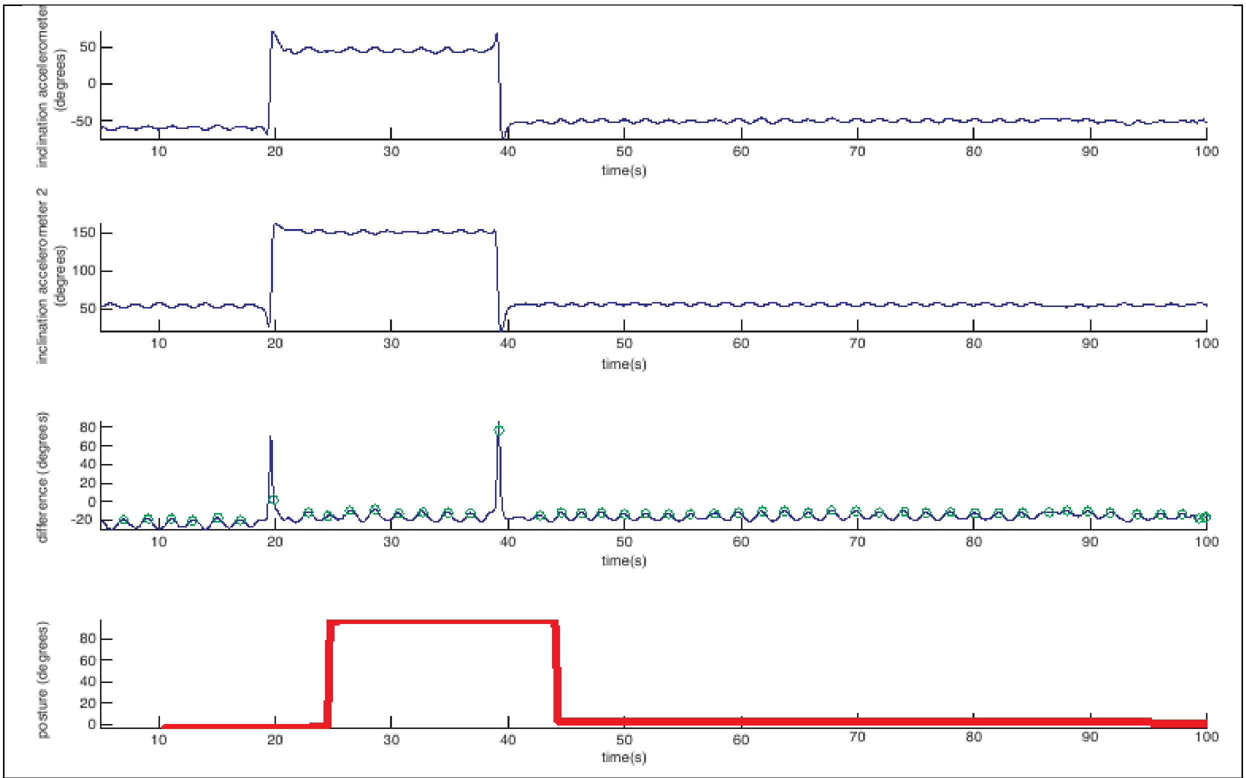


Fig. 95: Robustness test of the algorithm on breathing rhythm detection

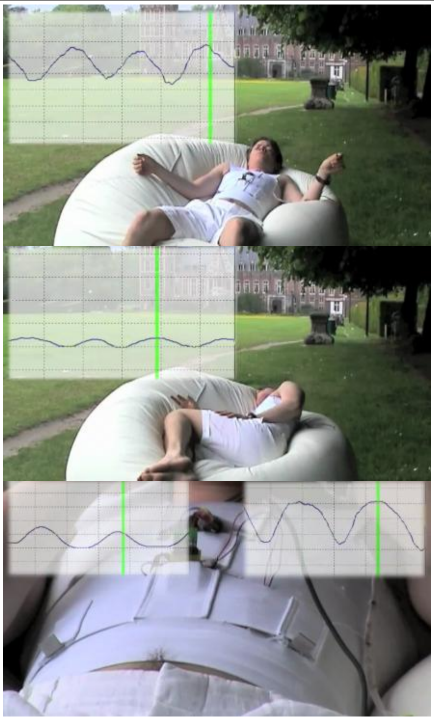


Fig. 96: Pictures of an adult test subject monitoring wirelessly his breathing rhythm. The top two insets show the real-time recorded breathing cycle at different postures, the bottom inset illustrates the comparison between a spirometer signal (left) and the combined accelerometer signal (right).

Because these tests were performed on adults, the difference in tidal volume between these two groups must be addressed. Although this differs significantly between adults and infants, this will only affect the method of radial displacement, focusing on the volumetric change. Because the inclination change method focuses on the geometrical change due to the expansion of the abdomen, effects on the signals from this method are not significant. These tests show the potential and the feasibility of breathing rhythm monitoring using accelerometers. Because both posture and breathing can be detected using the same sensor, a more robust monitoring system is created that can be extended at a later stage with more monitoring systems increasing the robustness even more.

Because of lack of time the circuit was not realised in a stretchable format or integrated in textile. The intention exists to finalise the demonstrator after the official end of the project. To this end separate single layer lay-outs of the sensor and master islands have been made by CMST. Fig. 97 shows a lay-out for the two parts of the UCL sensor circuit with a master island (left) and a sensor island (right), which will contain the proprietary UCL polymer based sensor. This sensor island also contains a humidity sensor (extreme right of the lay-out) for detection of water ingress during use or after washing of the circuit. Master and sensor island will be connected by 6 stretchable interconnections. A similar lay-out for the KULeuven demonstrator has been made, containing 1 master island and 2 sensor islands, onto which the accelerometers are assembled, and with stretchable conductors will be interconnected with the master island.

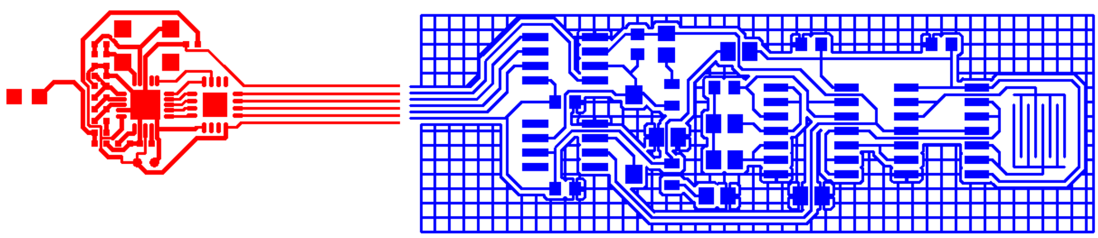
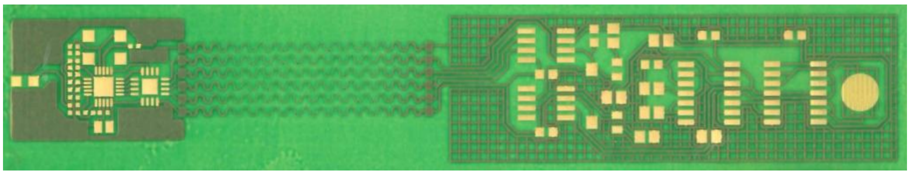


Fig. 97: UCL sensor island (right) and master island (left) lay-outs for realisation as flexible/stretchable circuit

Fig. 98 shows the flex circuits, realised on the base of these lay-outs, and ready for the assembly of the components. The UCL demonstrator (top) has a single stretchable interconnect bus with 6 connections. In the KULeuven demonstrator (bottom) the master island (middle) is connected to each of the two sensor islands with 7 stretchable interconnects. For the final realisation of these demonstrators as stretchable circuits the same technology as for demonstrator 1 will be used, so it is expected that also this implementation will lead to a fully functional circuits.



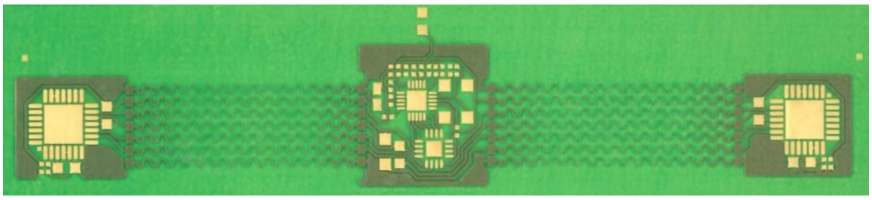


Fig. 98: Flex circuits ready for assembly of the UCL (top photograph) and KULeuven (bottom photograph) user defined demonstrators

7 PUBLICATIONS

7.1 Peer reviewed journals

[1] P. Jourand, H. De Clercq, R. Puers, “Robust Monitoring of Vital Signs Integrated in Textile”, Sensors and Actuators A: Physical, Vol. 161, Issue 1-2, pp. 288-296,2010.

[2] R. Carta, P. Jourand, B. Hermans, J. Thoné, D. Brosteaux, T. Vervust, F. Bossuyt, F. Axisa, J. Vanfleteren, R. Puers, “Design and Implementation of Advanced Systems in a Flexible-Stretchable Technology for Biomedical Applications”, Sensors and Actuators, A: Physical, Vol. 156, Issue 1, pp. 79-87, 2009.

[3] M. Gonzalez, F. Axisa, F. Bossuyt, Y.-Y. Hsu, B. Vandevelde, J. Vanfleteren, “Design and Performance of Metal Conductors for Stretchable Electronic Circuits”, Circuit World, Vol. 35, No. 1, pp. 22-29, 2009.

[4] Y.-Y. Hsu, M. Gonzalez, F. Bossuyt, F. Axisa, J. Vanfleteren, I. De Wolf, “In Situ Observations on Deformation Behavior and Stretching-Induced Failure of Fine Pitch Stretchable Interconnect”, Journal of Materials Research, Vol. 24, No. 12, pp. 3573-3582, Dec. 2009.

[5] N. De Geyter, R. Morent, T. Jacobs, F. Axisa, L. Gengembre, C. Leys, J. Vanfleteren, E. Payen, “Remote Atmospheric Pressure DC Glow Discharge Treatment for Adhesion Improvement of PDMS”, Plasma Processes and Polymers, Vol. 6, Suppl. S, pp. S406-411, 2009.

[6] Y.-Y. Hsu, M. Gonzalez, F. Bossuyt, F. Axisa, J. Vanfleteren, B. Vandevelde, I. De Wolf, “Design and Analysis of a Novel Fine Pitch and Highly Stretchable Interconnect”, Microelectronics International, Vol. 27, No. 1, pp. 33-38(6), 2010.

[7] Y.-Y. Hsu, M. Gonzalez, F. Bossuyt, F. Axisa, J. Vanfleteren, I. De Wolf, “The effect of pitch on deformation behavior and the stretching-induced failure of a polymer-encapsulated stretchable circuit”, J. Micromech. Microeng. 20 (7), Art. No. 075036, 11 pages, 2010.

[8] S. Béfahy, P. Lipnik, T. Pardoen, C. Nascimento, B. Patris, P. Bertrand, S. Yunus, “Thickness and Elastic Modulus of Plasma Treated PDMS Silica-like Surface Layer”, Langmuir 26(5), pp. 3372-3375, 2009.

[9] S. Béfahy, S. Yunus, V. Burguet, J.-S. Heine, M. Troosters, P. Bertrand, “Stretchable gold tracks on flat polydimethylsiloxane (PDMS) rubber substrate”, Journal of Adhesion 84, pp. 231-239, 2008.

7.2 Conference Proceedings

[1] J. Vanfleteren, “Elastic Electronic Circuits and Systems Using Moulded Interconnect Device (MID) Technology”, Proc. (abstracts) MRS Spring Symposium M: Materials and Technology for Flexible, Conformable, and Stretchable Sensors and Transistors, San Francisco, CA, USA, March 25-27, 2008. (invited)

[2] C.N. Santos, S. Yunus, A. Attout, P. Betrand, A. Delcorte, “Oxidative Graft Polymerization of Amino-Silane Modified Substrates”, 7th IEEE International

Conference in Polymers and Adhesives in Microelectronics and Photonics (Polytronic 2008), Garmisch-Partenkirchen, Germany, August 17-20, 2008.

[3] F. Axisa, F. Bossuyt, J. Missine, R. Verplancke, T. Vervust, J. Vanfleteren, “Engineering Technologies for Development of Advanced Stretchable Polymeric Systems”, 7th IEEE International Conference in Polymers and Adhesives in Microelectronics and Photonics (Polytronic 2008), Garmisch-Partenkirchen, Germany, August 17-20, 2008.

[4] F. Axisa, F. Bossuyt, J. Vanfleteren, “Laser based fast prototyping methodology of producing stretchable and conformable electronic systems”, Proc. 2nd IEEE ESTC Electronics Systems-Integration Technology Conference (ESTC-2008), Greenwich, London, UK, September 1-4, 2008.

[5] R. Carta, P. Jourand, B. Hermans, J. Thoné, F. Axisa, J. Vanfleteren, R. Puers, “Design and Implementation of Complex Systems on Flexible-Stretchable Technology Towards Embedding in Textile”, EUROSENSORS XXII Conference, Dresden, Germany, September 7-10, 2008.

[6] R. Carta, P. Jourand, B. Hermans, J. Thoné, F. Axisa, J. Vanfleteren, R. Puers, “Design and Implementation of Complex Systems on Flexible-Stretchable Technology Towards Embedding in Textile”, in Proceedings of Eurosensors XXII, Dresden, Germany, 2008.

[7] P. Jourand, H. De Clercq, R. Corthout, R. Puers, “Textile Integrated Breathing and ECG Monitoring System”, in Proceedings of Eurosensors, XXIII, pp. 722-725, Lausanne, Switzerland, 2009.

[8] J. Vanfleteren, “Technology and applications of flexible and elastic electronics and sensor circuits”, MRS Spring Meeting, Symp. PP, San Francisco, CA (USA), April 13-17, 2009. (invited)

[9] Y.-Y. Hsu, M. Gonzalez, F. Bossuyt, F. Axisa, J. Vanfleteren, I. De Wolf, “A Novel Interconnect Design with High Stretchability and Fine Pitch Capability for Applications in Stretchable Electronics”, Mater. Res. Soc. Symposium, San Francisco, CA (USA), Proc. Vol. 1192, pp. 1192-PP15-03, April 13-17, 2009.

[10] F. Bossuyt, T. Vervust, F. Axisa, J. Vanfleteren, “A New Low Cost, Elastic and Conformable Electronics Technology for Soft and Stretchable Electronic Devices by use of a Stretchable Substrate”, Proc. EMPC2009, European Microelectronics and Packaging Conference, Rimini, Italy, paper 16-S4-9, Vols. 1 and 2, pp. 697-702, June 15-18, 2009.

[11] T. Vervust, F. Bossuyt, F. Axisa, J. Vanfleteren, “Stretchable and washable electronics for integration in textiles”, Proc. China International Forum for Technical Textiles and Nonwovens”, Shanghai, China, 6 pages, October 22, 2009.

[12] H. De Clercq, P. Jourand, R. Puers, “Textile Integrated Monitoring System for Breathing Rhythm of Infants”, MediCon2010 IFMBE Proceedings 29, pp. 525–528, 2010.

[13] M. Gonzalez, B. Vandevelde, W. Christiaens, Y.-Y. Hsu, F. Iker, F. Bossuyt, J. Vanfleteren, O. Van der Sluis, P.H.M. Timmermans, “Thermo-Mechanical Analysis of

Flexible and Stretchable Systems", Proc. IEEE Eurosime 2010, Bordeaux, France, 7 pages, April 26-28, 2010.

[14] T. Vervust, F. Bossuyt, F. Axisa, J. Vanfleteren, "Stretchable and Washable Electronics for Embedding in Textiles", MRS Spring Meeting, Symp. JJ, San Francisco, CA (USA), April 8-9, 2010.

[15] T. Sterken, F. Bossuyt, R. Verplancke, T. Vervust, F. Axisa, J. Vanfleteren, "Lifetime of Stretchable Meander-shaped Copper Conductors in PDMS Subjected to Cyclic Elongation", MRS Spring Meeting, Symp. JJ, San Francisco, CA (USA), April 8-9, 2010.

[16] F. Bossuyt, T. Podprocky, T. Vervust, J. Vanfleteren, "From Single Conductive Layer to Double Conductive Layer Stretchable Electronics", MRS Spring Meeting, Symp. JJ, San Francisco, CA (USA), April 8-9, 2010.

[17] F. Bossuyt, T. Vervust, F. Axisa, J. Vanfleteren, "Improved Stretchable Electronics Technology for Large Area Applications", MRS Spring Meeting, Symp. JJ, San Francisco, CA (USA), April 8-9, 2010.

7.3 Other publications

[1] J. Vanfleteren, "Flexible and Stretchable Circuits for Wearable Electronic Systems", SMT News, No. 2/09, pp. 24-26, April 2009.

[2] J. Provoost, "Elastic Interconnections for Stretchable Electronics", On-Board Technology, pp. 8-9, April 2008.

8 OTHER DISSEMINATION ACTIVITIES

Apart from the presentations at International Conferences, mentioned in chapter 7 considerable dissemination activities have been undertaken. It can be stated that the SWEET project has had very extensive exposure to the professional and general public.

Firstly a considerable number of other presentations (additionally to those, mentioned in chapter 7) have been or given, where the SWEET project was mentioned:

[1] J. Vanfleteren, H. De Smet, J. De Baets, A. Van Calster, “Advanced Substrates and Packages for Wearable Electronics and Sensors”, Proc. Opening Symposium Microsystem Technology Lab. High School Zeeland, Vlissingen, The Netherlands, March 2, 2007.

[2] J. De Baets, F. Axisa, D. Brosteaux, M. Gonzalez, T. Löher, D. Manessis, R. Heinrich, B. Schmied, A. Ostmann, J. Vanfleteren, “Stretchable Conductor Technology for Elastic Electronic Systems”, IMAPS UK - MicroTech2007, Hellidon Lakes - Daventry, UK, March 6-7, 2007. (best paper award)

[3] J. Vanfleteren, “Flexible and elastic electronic packaging and interconnection technology”, Holst Centre Hi-T meeting, Eindhoven, April 12, 2007.

[4] J. Vanfleteren, “Flexible and Stretchable Electronic Circuits”, presented at the IMEC Annual Research Review Meeting (ARRM), Brussels, Belgium, October 18-19, 2007.

[5] J. Vanfleteren, “SWEET, Stretchable and Washable Electronics for Embedding in Textiles”, Concertation Workshop on EC-funded projects on Smart Fabrics and Interactive Textiles (SFIT) and Consultation on Future R&D Challenges and opportunities, Brussels, Belgium, February 21, 2008.

[6] J. Vanfleteren, “Comfortabele elektronische schakelingen met gebruik van flexibele en elastische polymeermaterialen”, Minisymposium Pieter Jan Lemstra, Diepenbeek, Belgium, May 29, 2008. (in Dutch)

[7] J. Vanfleteren, F. Bossuyt, M. Demey, P. Coussement, “Sensor devices for motion-tracking”, Evenement “Speelgoed voor de Muzen/Pluck and Play for the Muses”, Gent, Belgium, July 2-5, 2008.

[8] J. Vanfleteren, “Flexible and Stretchable Electronics”, to be presented at the IMEC Annual Research Review Meeting (ARRM), Brussels, Belgium, October 15-17, 2008.

[9] J. Vanfleteren, “Flexible and Stretchable Sensors and Electronics Circuits for Integration in Smart Textiles”, 5th Global Plastic Electronics Conference and Showcase, Dresden, Germany, October 27-29, 2009. (invited)

[10] J. Vanfleteren, “Elastic Circuits based on SMI (Stretchable Mould Interconnect) Technology”, tutorial at 2nd International Workshop on Flexible and Stretchable Electronics, Gent, Belgium, November 16-18, 2009.

[11] J. Vanfleteren, "Electronics and Biosensors for Medical Textiles", Biomedical Textiles Seminar - Innovations & Novel Applications, Brussels, Belgium, June 3, 2010.

[12] J. Vanfleteren, "Flexible and Stretchable Circuits", Euripides Forum, Forum, Paris, France, September 30, 2010. (presentation available from: http://www.euripides2010.eu/download/vortraege/vanfleteren.pdf)

The design, testing and implementation of the SWEET demonstrators were presented, either in a poster session or a presentation, at the following conferences and workshops:

- XII Mediterranean Conference on Medical and Biological Engineering and Computing, Chalkidiki, Greece, May 27-30, 2010.
- EuroSensors 2009, Lausanne, Switzerland, September 6-9, 2009.
- Leuven Medical Technology Center (LMTC) "Technologie voor Slimme Zorg", Leuven, Belgium, June 30, 2009. (workshop)
- Leuven Medical Technology Center (LMTC) Launch Event, Leuven, Belgium February 21, 2008. (workshop)

The SWEET project had an extensive visibility on the internet. Public information on the SWEET project is available from partner's websites:

- http://tfcg.elis.ugent.be/projects/sweet/index.html
- http://www.imec.be/flex-stretch/fs2_abus_sweet.htm
- http://www.centexbel.be/projects/sweet-stretchable-and-wearable-electronics-for-embedding-in-textiles
- http://www.centexbel.be/nl/projects/sweet-stretchable-and-wearable-electronics-for-embedding-in-textiles
- http://www.centexbel.be/fr/projects/sweet-stretchable-and-wearable-electronics-for-embedding-in-textiles

Furthermore right from the start a large number of websites have mentioned the SWEET project. Some of these links, although already more than 3 years old, are still active at the time of writing of this report:

- http://www.gizmowatch.com/entry/project-sweet-to-give-you-stretchable-and-washable-electronics/
- http://www.physorg.com/news103283742.html
- http://thefutureofthings.com/news/33/stretchable-and-washable-electronic-devices.html

- http://www2.electronicproducts.com/Elastic_interconnects_stretch_flexible_circuit_possibilities-article-olrr01_aug2007-html.aspx

Worth mentioning is also that the renowned consultancy agency Frost & Sullivan has published a “white paper” under the title: “Is Stretchable Electronics the Next Big Wave?“. This report is being sold for the price of 2000 EUR (see e.g. (http://www.researchandmarkets.com/reportinfo.asp?report_id=552385&t=t&cat_id).

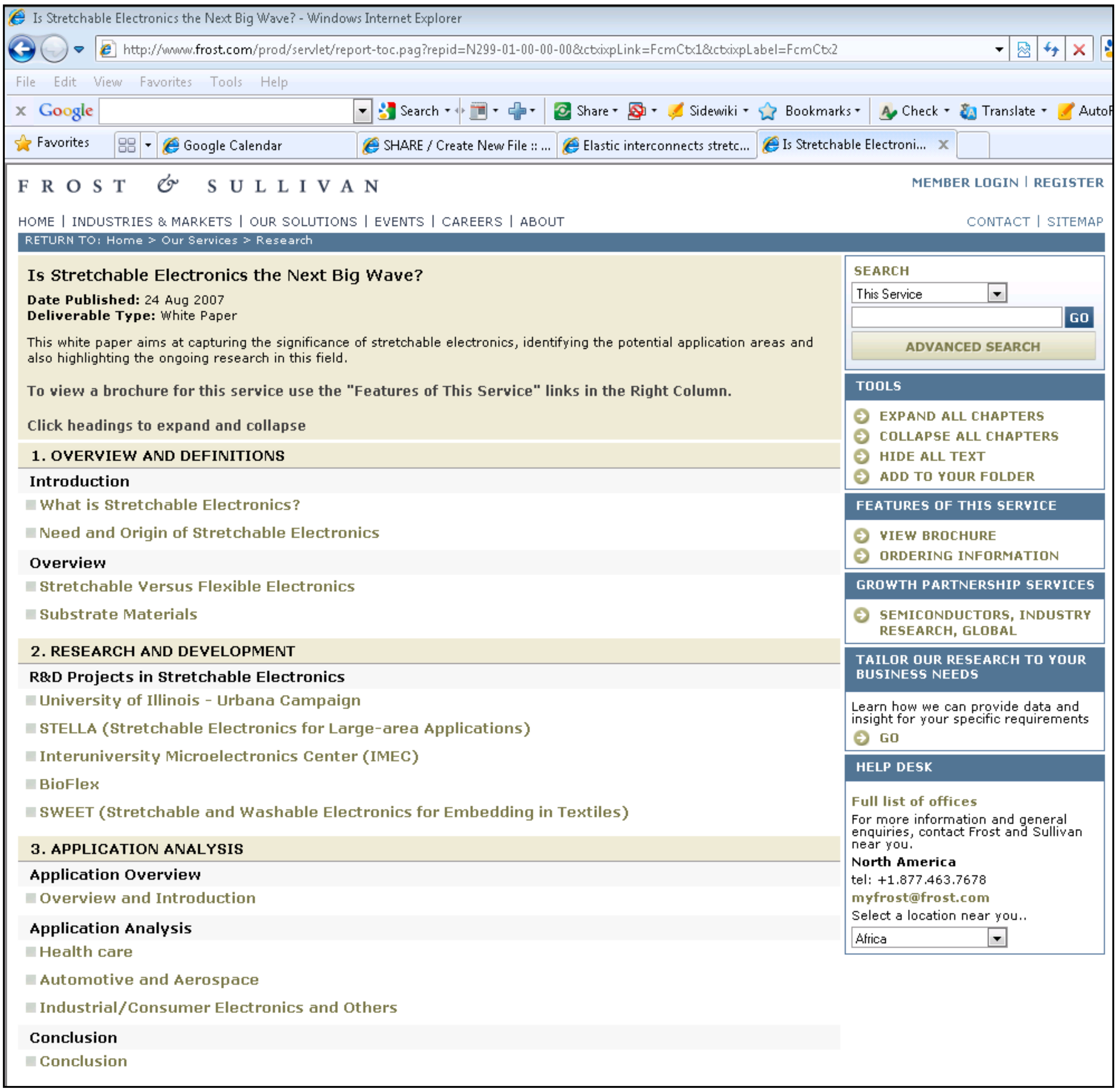


Table of contents (TOC) of this report can be consulted on the website of Frost & Sullivan: http://www.frost.com/prod/servlet/report-toc.pag?repid=N299-01-00-00-00&ctxixpLink=FcmCtx1&ctxixpLabel=FcmCtx2

The figure above shows a screenshot of this page. In the white paper F&S comment on the five most important R&D projects on stretchable electronics. SWEET is part of the selected project group.

In a further, more recent (published June 30, 2008) and more broad report, called "Emerging Trends in Flexible Electronics (Technical Insights)", published by Frost, the SWEET project is mentioned again. The link to this report is:
http://www.frost.com/prod/servlet/report-toc.pag?repid=D124-01-00-00-00

SWEET is commented upon in the section 4 "Innovative Technology Developments" >>> Innovations in Europe and Asia >>> Advancing Electronics Integration in Flexible Substrates.

A Wikipedia item was started on Stretchable Electronics (by UGent/CMST) where also the SWEET project is mentioned and linked to. URL is:
http://en.wikipedia.org/wiki/Stretchable_electronics

A number of popular and professional magazines have published articles where the SWEET project is mentioned:

[1] "Dehnbare Schaltungen: Zukunft oder Vision?", in Markt und Technik, No. 10, , pp. 20-21, March 7, 2008. (in German)

[2] J. Provoost, "Elastic Interconnections for Stretchable Electronics", in On-Board Technology, pp. 8-9, April 2008. (also available on the internet: http://www.onboard-technology.com/pdf_aprile2008/040801.pdf)

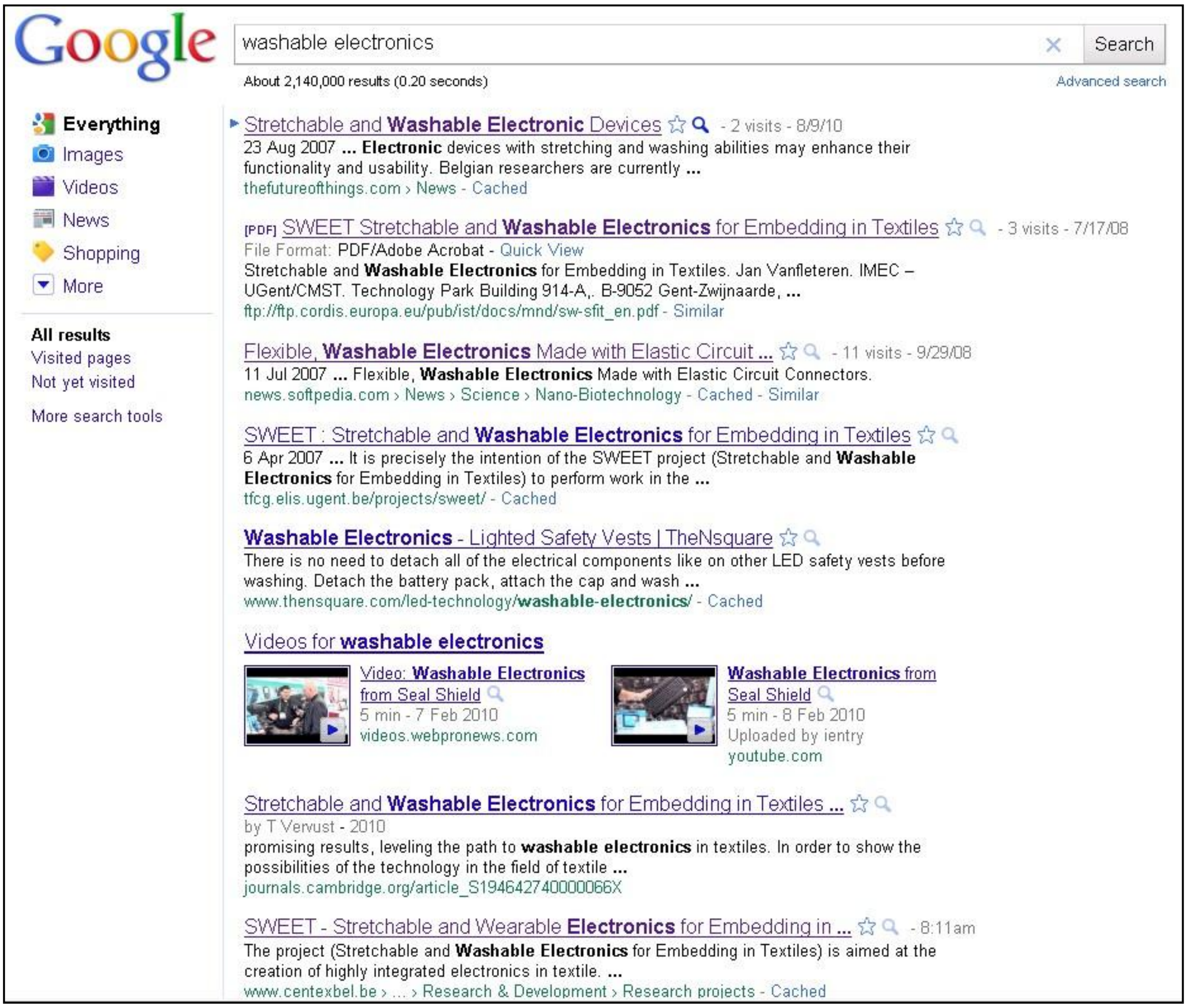
[3] "Interconnessioni Elastiche per l'Elettronica Alungabile", in PCB magazine, February 2008, pp. 32-35. (in Italian)

[4] "Stretching the Limits of Circuitry", in IEEE Computer, Vol. 41, No. 5, pp. 19-21, May 2008.

[5] "Belgian-based SWEET program launches electronic textile project", Veritas et Visus, Vol. 3 No. 2, p. 18, April 2007.

[6] J. Vanfleteren, "Flexible and Stretchable Circuits for Wearable Electronic Systems", SMT News, No. 2/09, pp. 24-26, April 2009.

Finally the SWEET website is ranked very high by search engines as e.g. Google. The screenshot below shows the top search results on Google.com on a relevant search item like "washable electronics" (February 2011). According to this search result, SWEET appears to be one of the reference projects on this subject.


Google
washable electronics
Search
About 2,140,000 results (0.20 seconds)
Advanced search
Everything
Images
Videos
News
Shopping
More
All results
Visited pages
Not yet visited
More search tools
Stretchable and Washable Electronic Devices - 2 visits - 8/9/10
23 Aug 2007 ... Electronic devices with stretching and washing abilities may enhance their functionality and usability. Belgian researchers are currently ...
thefutureofthings.com › News - Cached
[PDF] SWEET Stretchable and Washable Electronics for Embedding in Textiles - 3 visits - 7/17/08
File Format: PDF/Adobe Acrobat - Quick View
Stretchable and Washable Electronics for Embedding in Textiles. Jan Vanfleteren. IMEC – UGent/CMST. Technology Park Building 914-A,. B-9052 Gent-Zwijnaarde, ...
ftp://ftp.cordis.europa.eu/pub/ist/docs/mnd/sw-sfit_en.pdf - Similar
Flexible, Washable Electronics Made with Elastic Circuit ... - 11 visits - 9/29/08
11 Jul 2007 ... Flexible, Washable Electronics Made with Elastic Circuit Connectors.
news.softpedia.com › News › Science › Nano-Biotechnology - Cached - Similar
SWEET : Stretchable and Washable Electronics for Embedding in Textiles
6 Apr 2007 ... It is precisely the intention of the SWEET project (Stretchable and Washable Electronics for Embedding in Textiles) to perform work in the ...
tfcg.elis.ugent.be/projects/sweet/ - Cached
Washable Electronics - Lighted Safety Vests | TheNsquare
There is no need to detach all of the electrical components like on other LED safety vests before washing. Detach the battery pack, attach the cap and wash ...
www.thensquare.com/led-technology/washable-electronics/ - Cached
Videos for washable electronics
Video: Washable Electronics from Seal Shield
5 min - 7 Feb 2010
videos.webpronews.com
Washable Electronics from Seal Shield
5 min - 8 Feb 2010
Uploaded by ientry
youtube.com
Stretchable and Washable Electronics for Embedding in Textiles ...
by T Vervust - 2010
promising results, leveling the path to washable electronics in textiles. In order to show the possibilities of the technology in the field of textile ...
journals.cambridge.org/article_S194642740000066X
SWEET - Stretchable and Wearable Electronics for Embedding in ... - 8:11am
The project (Stretchable and Washable Electronics for Embedding in Textiles) is aimed at the creation of highly integrated electronics in textile. ...
www.centexbel.be › ... › Research & Development › Research projects - Cached

9 VALORISATION, SUPPORT TO INNOVATION AND TRANSFER OF KNOWLEDGE

One of the aims of SWEET is to generate transfer of knowledge and valorisation of the results on a Belgian and an international scale. Different actions contribute to the realization of this aim and will be described below.

9.1 *Patents*

UGent has a policy of protecting its findings through patent applications. As the participating UGent group (CMST) is hybrid IMEC/UGent group, patents, when approved, are owned by both organisations on a 50/50 base. In practise all CMST patent application submissions are managed through IMEC. The examination of the base patent application for the UGent/CMST stretchable circuit technology has been finalised in the USA by USPTO and the patent has been granted. The application is still under examination by the EPO (European) patent office.

For further improved versions of the base technology additional patent applications have been submitted. The current patent portfolio for the technology, forming the base for further exploitation, is listed below:

[1] J. Vanfleteren, D. Brosteaux, F. Axisa, “Methods for embedding of conducting material and devices resulting from the methods”, EP patent application EP 1 746 869 A1, January 24, 2007: EP application, same as [7] ((US 2006 0231288 A1).

[2] F. Axisa, J. Vanfleteren, T. Vervust, “Method for Manufacturing a Stretchable Electronic Device”, US patent application #US 2009/0317639A1, published December 24, 2009: application for alternative version of [7]: meanders made by laser structuring.

[3] P. Limaye, E. Beyne, J. Vanfleteren, “Semiconductor package”, Int. Patent Application number PCT/EP2009/051089, Int. Publication number WO 2009/095486 A2, published August 6, 2009: application for deformable semiconductor package (principle patented, but not demonstrated yet).

[4] F. Axisa, J. Vanfleteren, F. Bossuyt, “Semi-stretchable connection between stretchable and flexible circuitry”, US Provisional Application, IMEC reference number 2008/017, filed February, 2009; “Stretchable electronic device”, PCT application number PCT/EP2009/054353, filed April 10, 2009, Int. Publication number WO 2010/086034 A1, published August 5, 2010: application for improved version of [7] with emphasis on smooth flex to stretch transitions.

[5] J. Vanfleteren, F. Bossuyt, F. Axisa, “Elastic electrical interconnections through conductor support and stretch stop integration”, US Provisional Application, IMEC reference number 2008/100, filed February, 2009; “Stretchable electronic device”, PCT application number PCT/EP2009/054352, filed April 10, 2009, Int. Publication number

WO 2010/086033 A1, published August 5, 2010: application for improved version of [7], including supported meanders and component islands, and stretch stop structures.

[6] J. Vanfleteren, F. Bossuyt, F. Axisa, “Stretchable electronic device with double conductor layer and method for fabricating”, US Provisional Application, IMEC reference number 2009/058, “Stretchable electronic device”, PCT application number PCT/EP2010/051108, filed January 29, 2010, Int. Publication number WO 2010/086416 A1, published August 5, 2010: application [5], complemented with technology for stretch circuits with cross-overs and 2 conductor layers.

[7] J. Vanfleteren, D. Brosteaux, F. Axisa, “Methods of producing a composite substrate”, US patent, application published October 19, 2006, (US 2006 0231288 A1), patent granted #US 7,487,587 B2, February 10, 2009: USPTO application for our base stretch circuit technology; granted US patent where the method claims are granted.

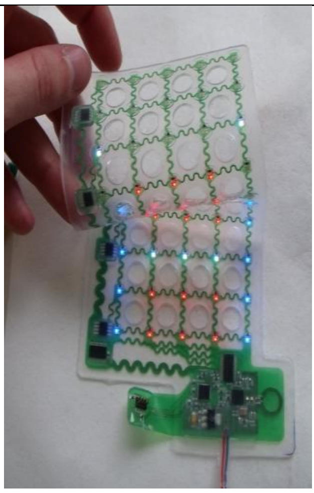
[8] J. Vanfleteren, D. Brosteaux, F. Axisa, “Composite substrate”, US patent application, published April 30, 2009 (US 2009 0107704 A1): application including device claims, derived from [7].

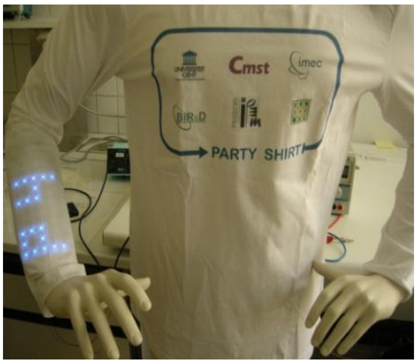
9.2 Follow-up projects

UGent is involved in a number of follow-up projects, which have been approved since the start of SWEET. Indeed, SWEET was the first funded project in the frame of which UGent’s stretchable circuit technology was adapted and applied for smart textile applications. It can be stated that in this way SWEET was the fundamental project for UGent on “smart textiles”. Thus SWEET has created the opportunity for defining itself or being invited to participate in a number of follow-up projects, based on the competence, built in SWEET. In this respect the following projects should be mentioned:

- ***EC-FP7-CA-Systex*:** “Coordination action for enhancing the breakthrough of intelligent textile systems (e-textiles and wearable microsystems)”, Grant agreement No. 224386, 36 months, start May 1, 2008. This Coordination action brings together relevant R&D and industry players in the field of intelligent textiles. It allows the dissemination and potentially the exploitation of the SWEET results on a European scale.
- ***EC-FP7-IP-Place-It:*** “Platform for Large Area Conformable Electronics by InTegration”, 42 months, started February 2010. This integrated project, co-ordinated by Philips aims at the integration of flexible and stretchable circuits with smart textile substrates. The aim is to develop technology for conformable light sources. Applications are situated in health (photonic treatment of skin diseases) and automotive industry (conformable light sources for car interiors). Both SWEET partners UGent-CMST and Centexbel are contractors of this IP. For more information we refer to the Place-It website: http://www.place-it-project.eu/.

- ***EC-FP7-IP-PASTA***: "Integrating Platform for Advanced Smart Textile Applications", started October 2010. This integrated project is co-ordinated by CMST (ir. Johan De Baets). PASTA will focus on making electronic packages conformable to the properties of textiles. The ambition of the project is also to enable high-volume manufacturing of smart textiles using these new types of electrical component integration.
- ***BiR&D-"LED T-shirt"***: The BiR&D (Belgian Industrial Research and Development association (http://www.birdbelgium.com/) started in 2009 a programme for "Interdisciplinary Master of Science thesis", addressed to Belgian Universities and associated High-Schools. SWEET partner UGent, together with the UGent IPEM (Institute for Psycho-acoustics and Electronic Music) were selected for support by BiR&D of the Master Thesis cluster "Music game with LED T-shirt". The key technological component, developed in the master thesis, was a 10x5 LED matrix, integrated in the sleeve of a T-shirt. The pictures below show the realised circuit before integration (left), and the results after integration in a separate piece of textile (middle) and in a T-shirt (right). Circuit design and production as a stretchable circuit was done at CMST, integration in textile was performed at Centexbel. Moreover out of the 6 supported projects, the UGent project is one of the 2 projects, selected for receiving the student award (http://www.birdbelgium.com/call2009/awards-call). The award ceremony has taken place on March 18, 2011 at the Solvay Library, Brussels.





- ***UGent-IOF-SEAT***: "Sensors en Elektronica voor Ambulante Toepassingen" - "Sensors and Electronics for Ambulant Applications". This is a project, funded by the Industrial Research Fund (IOF) of Ghent University. In charge of this project a permanent post-doc co-worker (dr. Wim Christiaens) has been hired (since February 2009) as business developer. His task is the exploitation of R&D results, obtained by the members of the consortium. "Exploitation" ranges from publications over generation of follow-up projects up to the creation of spin-off companies. Partners with a wide variety of expertise (engineering, medicine, material science, musicology) are members of the SEAT consortium. UGent/CMST serves as the coordinator. It is clear that also the exploitation of the SWEET results is part of the assignment of the SEAT business developer.

Finally during execution of SWEET there was a link to the FP6 EC funded project ***STELLA*** (Stretchable Electronics for Large Area Applications). In this project where UGent/CMST was participating (as IMEC group), technology for stretchable electronics was developed and was used by a number of end users, among which Verhaert (also member of the SWEET follow-up Committee). A number of the end user demonstrators, among which the Verhaert demonstrator, but also the Philips and Urgo demonstrators finally were to be integrated in textile. However in STELLA there was no specific textile partner present. Therefore the SWEET technology proved to be very useful for STELLA and the Verhaert demonstrator was realised, making use of the SWEET knowledge.

9.3 Interaction with follow-up Committee

A follow-up Committee was active from the start of the project on. This group of mainly industrial potential users of the technology and applications, developed in SWEET steered the developments by e.g. suggesting demonstrators, specifying them, etc. six-monthly meetings between the SWEET consortium and the follow-up Committee were organised to this end. Following companies have concluded a CDA (Confidential Disclosure Agreement) with the consortium and thus effectively were allowed to the meetings and the private pages of the SWEET website in order to get access to the relevant documents like presentations and meeting minutes: Alsico, Domo, Luxilon, Verhaert, Dow Corning Corporation, NXP Semiconductors, Recticel, Agfa, Gent University Hospital, Fibertex, DesleeClama and Zenso. Besides exchange of information, also effective co-operation with some of these members has taken place, is still going, or is planned. Following interactions between the SWEET consortium and certain members of the follow-up Committee should be mentioned in this respect:

[1] Dow Corning has been the preferred PDMS (silicones) material supplier of the consortium. The company has assisted the consortium with free material samples and very useful advice on how to use the materials. The motivation for this co-operation is that successful developments in SWEET can eventually mean use of the Dow Corning materials in this new type of applications. In June 2008 a European wide meeting of Dow Corning divisions was organized at the Dow Corning Seneffe (Belgium) site. New applications of Dow Corning

materials were presented and entered a contest. SWEET delivered a poster and demonstrator samples for the water resistant stretchable circuits and intelligent textile application. Out of more than 30 contributions, Dow Corning marketing managers selected our application as the most promising one. After the end of the SWEET project, the co-operation between UGent/CMST and Dow Corning is continued. We heard that Dow Corning is planning to extend its activities on developing new PDMS materials for electronics applications.

[2] During the project Fibertex has formulated a request for use of demonstrator samples to the SWEET consortium. Fibertex wants to awake interest from their customers in intelligent textile, more in particular in upholstery with embedded illumination. It was decided that SWEET will fabricate 2 types of demonstrators for Fibertex' purposes: (1) a high brightness, low information content LED-row and (2) a 7x8 LED matrix with scrolling message (but lower brightness than demonstrator (1). The process of generation and signing of the "Limited Use and Non-Disclosure Agreement", regulating the use of the samples by Fibertex has been concluded. Preliminary samples for demonstrator (1) have been produced by UGent/CMST, and positively evaluated (4-fold larger light coupling of LEDs to fibres, compared to previous Fibertex results. Demonstrator (2) has not been produced due to lack of resources. Installation of a stretch circuit platform at CMST, planned for 2011, will open new possibilities. Once the platform is running it is highly probable that we will re-contact Fibertex and check if they are still interested in the subject.

[3] Alsico: at the final SWEET review meeting and in recent contacts (February 2011) Alsico has expressed very strong interest in applying the SWEET technology for its applications in Smart Professional Workwear. In a brainstorm on the subject, which Alsico organised with more than 100 potential customers present, it became clear that for practical applications like suits with integrated sensors or light sources, washability and wearing comfort are of utmost importance for successful introduction on the market. These are the subjects on which SWEET strongly has focused and has made significant process. Alsico mentions that in the Far East, production and use of such kinds of products has started (e.g. suits for road workers with integrated safety light sources). The technology used is however much less sophisticated (concerning comfort and washability) than what the SWEET consortium can offer at the end of the project. One of the main roadblocks for immediate industrialisation of the SWEET technology, which Alsico has identified, is the existing gap between the textile and the electronics manufacturing industry: Alsico is ready to try to integrate SWEET-like modules in its garments, but until now was not able to identify electronics manufacturing companies which can deliver these type of modules on an industrial scale (with sufficient volumes, reproducibility, yield and

moderate cost). Therefore one of the ambitions should be to bridge this gap and to set up a value chain, involving companies from electronics and textiles in order to achieve this goal.

[4] Recticel: in SWEET silicones were used as elastic embedding materials for UGent's stretchable circuit technology. The process of Liquid Injection Moulding, used to apply the PDMS, is one of the challenging steps for industrialisation of the whole stretchable circuit production process. In discussions with Recticel (Mr Mario Genetello) we identified an alternative for the use of silicones, namely application of PUR (poly-urethane) as the embedding material. Recticel is highly specialised in the processing of PUR for a wide variety of products. CMST and Recticel have identified PUR casting and spraying as potential candidates for embedding stretchable circuits. An effective bilateral co-operation between Recticel and CMST has started, in the frame of which CMST delivers test samples to Recticel, who embeds them using their PUR processing technologies. First results are quite encouraging, and this co-operation will continue in the coming months.

9.4 Other valorisation actions

At KULeuven, four candidates have worked partially on the SWEET project towards obtaining a PhD: Bart Hermans, Riccardo Carta, Philippe Jourand and Hans De Clercq. Their research on experiments and prototypes developed within the SWEET project has and will have contributed substantially to their PhDs. Both Bart Hermans and Riccardo Carta are writing their PhDs and the defences are scheduled for December 2010. At UGent, the PhD of ir. Thomas Vervust will mainly contain material, obtained during his work in the frame of SWEET. The completion of the PhD is scheduled end of 2011.

The experience gained in the SWEET project has also partially helped in the formation of a KULeuven/MICAS spin-off company, called Zenso. The company started as a BVBA in April 2007, and converted in an NV in March 2008. Founders are Bart Hermans and Johan Coosemans, and the focus of Zenso is on innovative electronic key solutions, dedicated to the client. They offer expertise in sensors, data-acquisition, wireless power and data transmission, embedded systems, firmware, GUI, PCB layout etc. The main business is the development of small series of PCB modules into fully operational systems, from concept to final product. Services can range between feasibility studies, over prototype development, up to support into serial production. Zenso is thus not an immediate spin-off of the SWEET project, in the sense that the scientific results of the project are not valorised in this company. However, the basic experience gained in the development of the demonstrators has helped these entrepreneurs to build a stronger backbone for their company.

KULeuven/MICAS is now part of the “Leuven Medical Technology Center (LMTC)”, which was launched on February 21st, 2008 (Universiteitshallen).

After the end of the SWEET project, co-operation between partners UGent and Centexbel has continued, not only in the frame of the Place-It project, but also on an informal base, and especially on the further improvement of washability. More in particular CMST has realised washing tests samples, according to the ideas of Fig. 74 and Fig. 75, and Centexbel is currently executing washing tests on these samples. First results show indeed a significantly improved reliability and washability. Hopefully these positive results will be confirmed by continued testing, and if so, will surely contribute to the potential of transfer of the technology to real applications.

Thanks to a.o. SWEET UGent’s technology on stretchable circuits has come to a level of reproducibility and reliability where transfer seems to be feasible to an environment in which more and larger area circuits can be built. As an intermediate step towards full industrialisation CMST has the plan to install at its premises a kind of pilot platform on which to a large extent the complete production of larger area (up to about 400 mm x 300 mm) can be executed. To this end CMST has foreseen an investment of 300 keuro to enlarge its fabrication facilities and to acquire the necessary equipment. This will allow CMST to better fulfil the increasing demands for evaluation samples, and to convince potential industrial production and application partners of the value of the technology. The installation and ramp up of this platform is scheduled for the second half of 2011.

Next to setting up its own platform CMST is in parallel contacting various industrial partners in order to investigate a possible industrialisation of certain steps of its stretchable circuit technologies. These partners are currently local (located in Flanders) and include a PCB circuit manufacturing company, an electronic assembly plant, and 2 companies, specialised in polymer processing (of which Recticel, already mentioned, is one). With these companies CMST is setting up informal co-operations, involving exchange of test samples, in order to evaluate the execution of particular steps of the stretch circuit technology in an industrial environment. For textile integration CMST continues for the moment to co-operate with Centexbel, but also has access to interested textile manufacturing companies like Alsico. These connections will surely be exploited in future. In this way these activities help to create a Belgian value chain, necessary for the future production on an industrial scale of washable and comfortable smart textiles.

10 ACKNOWLEDGEMENTS

The consortium wishes to sincerely thank the Belgian Science Policy for its financial support. It is believed that this support has created strong links between the different involved R&D groups. Before SWEET no links between UCL-PCPM and the other participating groups were existing and it can be stated that the project has revealed significant new potential scientific co-operations between the different research groups. In this respect it is regretful that the BELSPO TAP programme has not been continued.

The consortium wishes to explicitly thank Mrs Anna Calderone of BELSPO for her stimulating and correct guidance of the project. The consortium appreciated the fact that partners could almost fully concentrate on the scientific and technical work without facing too much administrative overhead.

The consortium finally wishes to cordially thank all members of the SWEET follow-up Committee for their enthusiastic and highly valued discussions, advices and contributions to the project. Many links between these industrial advisors and the SWEET research partners have been created thanks to SWEET and it is encouraging to notice that after the end of SWEET these contacts are maintained and in some cases result in effective co-operation.

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