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ScienceDirect

Procedia Technology 15 (2014) 208 – 215

Procedia Technology

2nd International Conference on System-Integrated Intelligence: Challenges for Product and Production Engineering

Arbitrarily shaped 2.5D circuits using stretchable interconnections and embedding in thermoplastic polymers

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Abstract

This contribution describes considerations and very preliminary results in the technology development of thermoplastically deformable electronics and sensor circuits, with the intention to eventually achieve the low-cost fabrication of 2.5D free-form rigid smart objects. The technology is based on the one for elastic circuits, developed and characterized before, which is using soft elastic polymers as materials for the circuit carrier. For 1-time deformable circuits the elastic carrier needs to be substituted by a thermoplastic material. An additional step of thermoforming is necessary after the entire circuit is fabricated on a flat surface, which is the normal industrial practice for circuit fabrication and which thus is also pursued here. First tests have been executed and simple circuits fabricated, using meandered Cu tracks as 1-time stretchable interconnects, PET-G as the thermoplastic carrier and SMD LEDs and zero-ohm resistors as circuit components.

Peer-review under responsibility of the Organizing Committee of SysInt 2014.

Keywords: Stretchable circuits; thermoplastic circuits; 2.5D; 3D; thermoforming, smart objects

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Peer-review under responsibility of the Organizing Committee of SysInt 2014.
doi:10.1016/j.protcy.2014.09.073

1. Introduction

In today's era of ambient intelligence more and more electronic and sensor devices with a growing degree of complexity and functionality are carried along by their users. Such circuits can be transportable (e.g. integrated in transportation vehicles, portable (e.g. carried along in garment pockets, backpacks, etc.), can be worn directly on the body (e.g. smart patches or watches), or even inside the body (smart implants). As a general rule one can state that the form factor of these circuits should be such that it minimally hampers the user. In order to make the device as much as possible "unnoticeable" to the user and integrated in the environment, it should closely follow the curvatures and bending of the vehicle or body part onto/into which it is integrated. There are two options for design and fabrication of such devices, in order to make them unnoticeable and thus to guarantee maximal comfort to the user:

1. Either the components or assemblies should be miniaturized as much as possible, so that size and weight are maximally reduced. If the resulting sizes of the device are small, compared to the radius of curvature of the surface onto which the device will be positioned, then the device can remain flat and rigid without loss of comfort.
2. In cases where after miniaturization the dimensions of the circuit are still large, compared to the bending radius of the surface onto which the device must be placed, or if the circuit is large because of its functionality (e.g. a display or a distributed sensor array), then the circuit cannot remain flat, but should take the shape of the object or body part onto which it is used.

In the current contribution we consider planar circuits only, i.e. circuits where the lateral dimensions (typically 50mm or more) are much larger than the thickness of the circuits (typically 2-3mm or less). In mainstream industrial fabrication environments such circuits are produced on flat carrier substrates (e.g. glass fibre reinforced epoxies). In order to comply with the requirement for non-flat circuits, mentioned above, the assembled circuits from the manufacturing plant should subsequently be deformed to their final shape. A widespread technology, allowing this deformation is the one of flexible printed circuits (FPC's), using a thin (typ. 25-50µm) bendable polymeric substrate (e.g. polyimide) as circuit carrier. Deformation of a flat FPC allows to create cylindrical or conical shapes, which for certain applications is sufficient. However, if the application requires deformation to more complex form factors (e.g. spherical or irregular shapes), FPC's cannot meet this requirement.

Deformation from flat to an irregular shape can be done only if at least parts of the circuit can be elongated (stretched) or compressed. This means that both the circuit carrier substrate, as well as the electronic or sensor circuit should be stretchable. Thus, for the circuit carrier, conventional materials like FR4 (glass fibre reinforced epoxy) or polyimide must be replaced by stretchable materials. According to the application the most appropriate material must be selected. If the circuit is worn on the body, then it can be expected that it will undergo dynamic deformations, i.e. repeated stretching and releasing. In this case an elastic carrier material like PDMS (silicone rubber) or a PU (polyurethane) should be selected. In the case the non-flat circuit will finally be integrated in e.g. a car interior, then most probably the dynamic deformability or elasticity is not necessary, and the circuit can be free-form rigid. The circuit should be subjected to a single deformation step from initially flat to its final rigid irregular 2.5D shape, and therefore the circuit carrier should allow for this deformation. An obvious way to make this single deformation possible is the use of thermoplastic materials, which can be heated until they become soft without change of their chemical composition or properties, subsequently followed by a thermoforming step over a dedicated forming tool, and finally cooling down of the formed object. Next to the circuit carrier also the electronics itself must be deformed. As electronic components are almost always rigid or flexible at the most, deformation of the circuit is achieved by stretching or compression of the electrical interconnections between the components, not of the components themselves.

Until now our research group has concentrated on the development of technologies for dynamically deformable (= elastic) circuits. Recently however we have also started to work on 1-time deformable, thermoplastic circuits, adapted from the technology principle of elastic circuits. Therefore in this contribution we will first provide a short overview of existing technologies for 2.5D free form rigid circuits, then review the general technology principle for stretchable circuits, as applied by us in both elastic and thermoplastic circuits, and finally we will describe our first developments on thermoplastic circuits.

2. Existing technologies for 2.5D free form rigid circuits

In research and industry there are already a number of technologies available for achieving 2.5D and 3D type of circuits. The two technologies currently used on an industrial scale are the following:

- Using standard PCB technology large area electronics with other than flat shapes are made by interconnecting flat rigid assembled boards using flexible circuitry. A randomly shaped board can hence be approached only by the composition of flat rigid sub-boards, interconnected by means of flexible cables/circuits and mechanical connectors, or by using (expensive) flex/rigid PCB technology. However such a composition of flat rigid boards does not allow evenly or elegantly curved electronic surfaces. Moreover extensive use of connectors decreases the reliability. The pictures below in Figure 1 show examples of industrially produced flex-rigid boards, clearly demonstrating their limitations in terms of freedom of design and random form factors.

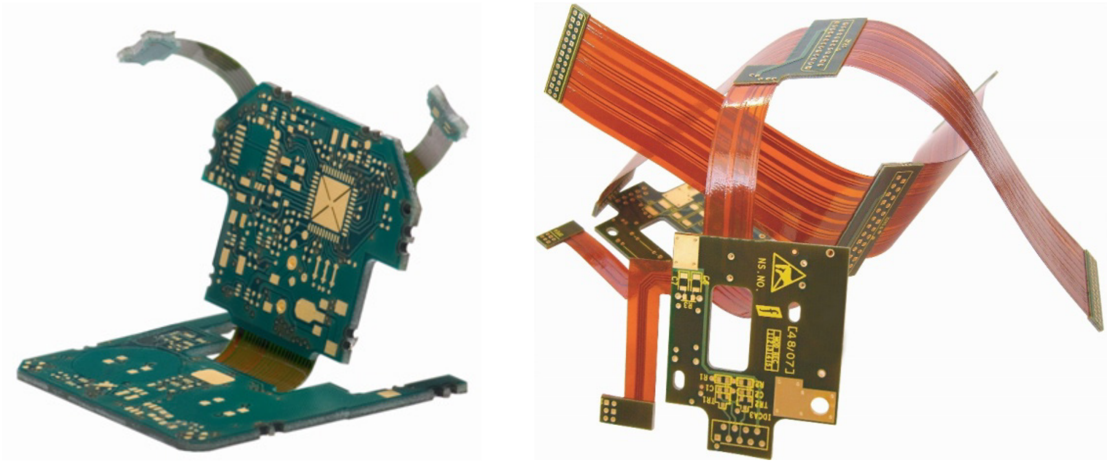

Fig. 1. Examples of industrially produced flex-rigid boards (left : Altium (source : http://techdocs.altium.com/), right : Teknoflex (source : http://www.electronics-sourcing.com), showing their limitations in random circuit deformation.

- 3D MID technology provides a means of producing arbitrary free-form shaped devices. Since 10 years this technology has been established for particular applications (see also http://www.3d-mid.de). The technology starts from a moulded polymer onto which a 3D conductor is applied, e.g. by chemical deposition and laser structuring. The components are subsequently assembled onto this 3D conductor circuit, which is for sure not a standard assembly method, not widespread, and only used for certain special applications. The specially modified polymer (filled with additives which can be laser-activated) limits the area of application to specific niches because of economic reasons. The whole device consists of this particular polymer, even areas and volumes without functionality. Additionally, the circuit is generated either by laser-activation or laser-activation plus subsequent additive processes (chemical build-up). The assembly of components onto the 3D surface is difficult but recently has been shown to be possible. Finally, whenever encapsulation of the electronic components is necessary an over-moulding or encapsulation step has to follow. An example of a realised circuit is shown in figure 2.

This short overview shows that there is a need for a technology, which is much closer to conventional PCB technology than is the case for 3D-MID, but which allows generating 2.5D shapes with more flexibility and reliability at a competitive price, as compared to PCB type flex-rigid technologies.

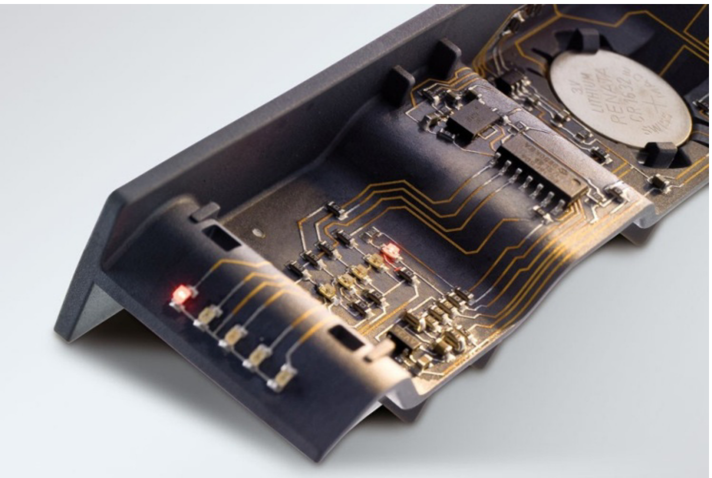

Fig. 2 . 3D-MID circuit, with assembled components (source : http://www.led-professional.com).

3. Printed Circuit Board (PCB) inspired stretchable circuits

As mentioned in the introduction normal circuit carrier materials like rigid FR4 or flexible polyimide materials should be replaced by elastic or thermoplastic materials in order to generate dynamically or 1-time deformable circuits. A general property of these materials which almost exclusively belong to the large class of polymer materials, is that normally they are much less resistant to the harsh chemicals (e.g. Cu etchants) and high processing temperatures (e.g. in lead free solder assembly), used in conventional PCB fabrication and assembly. Therefore currently 2 main approaches for production of PCB inspired stretchable circuits can be discriminated [1, 2]:

- “polymer-first” approach: the base substrate, undergoing further processing, consists of the final elastic or thermoplastic polymer carrier, onto which the conductor for interconnecting the components is applied (e.g. by lamination) as a sheet. The base substrate subsequently goes through the normal PCB production and assembly sequence. This approach is intuitively very similar to conventional PCB processing. Some processing steps however have to be adapted, taking into account the limited chemical and thermal resistance of the polymer substrate. As an example normally no conventional lead-free SAC (tin/silver/copper) solder assembly processes can be used (requiring a maximum temperature of 250-260C), but instead low temperature solders (like SnBi) or conductive adhesives have to be applied.
- “polymer last” approach : in this case the stretchable circuit, including Cu interconnections and assembled components, is fabricated on a high-temperature resistant, chemically inert temporary carrier, e.g. an FR4 or polyimide substrate with a pressure sensitive adhesive (also high temperature resistant) to temporarily hold the circuit. Therefore in this approach all conventional PCB fabrication steps can be applied, including high temperature SAC solder assembly. After finishing, testing and debugging the circuit on this temporary carrier, the final elastic or thermoplastic carrier material is applied in a 2-step process: a first layer of the final carrier is moulded or laminated on top of the temporary carrier and the circuit, then the temporary carrier is removed, and finally the same moulding or lamination step is repeated, now also covering the backside of the circuit. Compared to “polymer-first”, this approach requires the additional step of transfer of the circuit from a temporary

carrier to the final polymer substrate carrier, but has the advantage that conventional PCB production steps readily can be copied.

The two approaches have a number of common features:

- The interconnection between the electronic components consists of Cu conductors with thicknesses of typically 17 or 35µm, just like in standard PCB technology. In fact Cu sheets, intended for standard PCB's are used in our stretch circuit fabrication process.
- The stretchability of the interconnections is guaranteed by shaping the conductors not as straight lines, but as meanders, more precisely as connected circle segments. In this way dynamically or 1-time extensible interconnections are created. In the case of elastic carriers materials the Cu meanders act as 2-dimensional springs. Much effort has been spent to optimize the shape of this meander, as well as the design of the transition zone between the elastic stretchable interconnects and the stiff component islands [3].
- High functionality of the circuits is ensured by the use of conventionally packaged, off-the-shelf available electronics and sensor components, which can be assembled on the circuits by mainstream technologies like soldering or adhesive assembly.

Using these 2 approaches, technology development of elastic circuits has been intensively studied and quite a few functional demonstrators have been produced and evaluated, mainly for wearable, on the body applications. As an example in figure 3 a blue light therapy device is shown for the treatment of RSI (repetitive strain injury). This device is a result of the co-operation in the frame of the EC FP7-PLACE-it project [4]. It has been designed by Philips and fabricated by imec, using the "polymer last" approach. The inset clearly shows the meander shaped Cu interconnections, as well as the operating solder assembled blue LEDs.

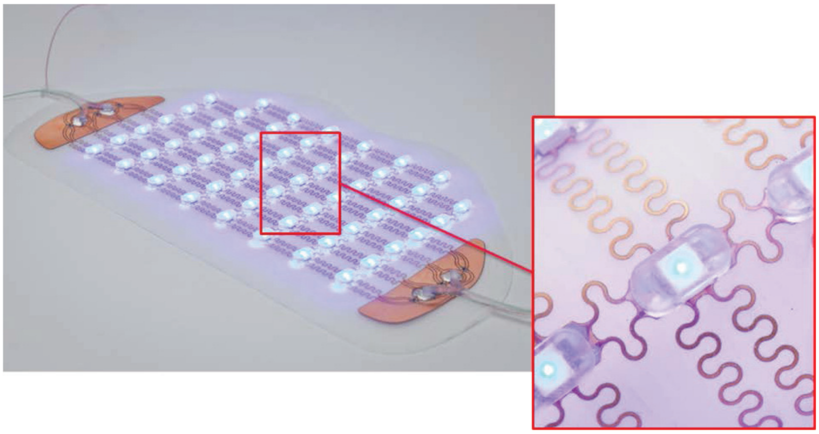

Fig. 3. Elastically stretchable circuit, used as blue light therapy device (in co-operation with Philips) [4]. Total length of the device is about 250mm.

4. Thermoplastically deformable circuits

The same principles, as used to fabricate elastic circuits, can now be applied for the production of rigid free form circuits. Again circuits can be built, either directly on the final carrier material, using the "polymer-first' approach, or on a temporary carrier with eventual embedding in the final carrier, using the "polymer-last" approach. However the use of thermoplastic circuit carrier materials instead of elastic materials, now generates new challenges for the technology development:

- In case of elastic circuits, the substrate is deformed with minimal forces, without any thermal load, in order to bring it from the flat-state (as-produced) to the desired 2.5D shape. For thermoplastic circuits a significant additional step is necessary to achieve the transition from flat to 2.5D. The thermoplastic polymer must be heated up to or above the softening temperature where it is possible to plastically deform the polymer with reasonably low forces. During this thermoforming process also the components and interconnections inside the carrier material are subjected to an additional thermal and mechanical loading step. A trade-off exists between these 2 loading modes: heating at higher temperatures will reduce the necessary deformation force and vice versa. Heating and forming steps of a thermoforming process are illustrated in figure 4.
- Elastic circuits are designed to withstand many cycles of extension and compression. For thermoplastic circuits normally only one single deformation (during the forming step) is necessary. Developments in thermoplastic circuits will therefore focus on larger 1-time deformations, compared to elastic circuits where the focus is on smaller multi-cycle deformations.

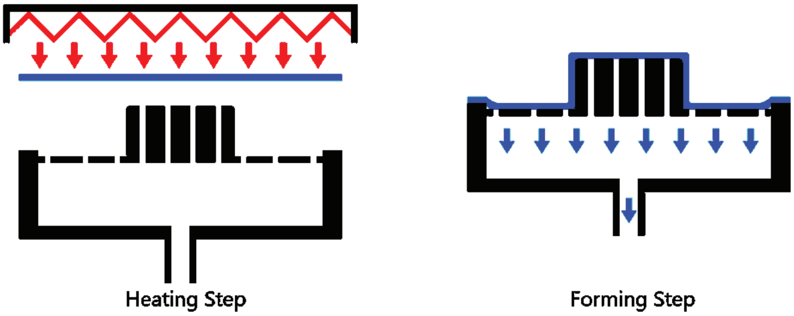

Fig.4. Thermoforming principle: a flat thermoplastic polymer substrate (represented as a blue line), possibly including an embedded circuit, is heated to or above the softening point (left); the circuit is deformed over a dedicated tool using vacuum (right). Subsequently the circuit is cooled down until it becomes rigid again and removed from the forming tool (not shown).

The developments on thermoformed circuits, using the technology, described above, have started only very recently in our research group and elsewhere. Both approaches, mentioned in section 3, are being investigated. The topic of thermoplastic circuits is the focus of study in the newly started EC FP7-project TERASEL (Thermoplastically deformable circuits for embedded randomly shaped electronics) [5], bringing together 15 partners from 6 different countries, and targeting applications in automotive, lighting and consumer electronics industries. In order to predict elongations of the interconnections as a consequence of the thermoforming, modeling of the thermoforming process at each position of the 2.5D object, is going on at the moment. Using readily available circuit designs, in fact meant for elastic circuits, first thermoforming experiments were carried out. For the first trials mostly polyethylene terephtalate glycol-modified (PET-G) materials were used. These have glass transition temperatures around 80°C and are said to be very suitable for thermoforming. Figure 5 shows the result of a first thermoforming experiment, using a non-optimized design for elastic circuits. A flat A4 size circuit was deformed to a 2.5D circuit with a hemispherical shape in the centre of the substrate. The maximum forming temperature was around 120°C. The role of the meanders, ensuring the maintenance of electrical conduction, even under severe deformations, is clear from the pictures. As could be expected, deformation under thermoforming is maximal at the base of the hemisphere and very small at the top. Width of the Cu tracks is 200µm in this case. Conductivity of the tracks remained the same after thermoforming, even for severe deformations.

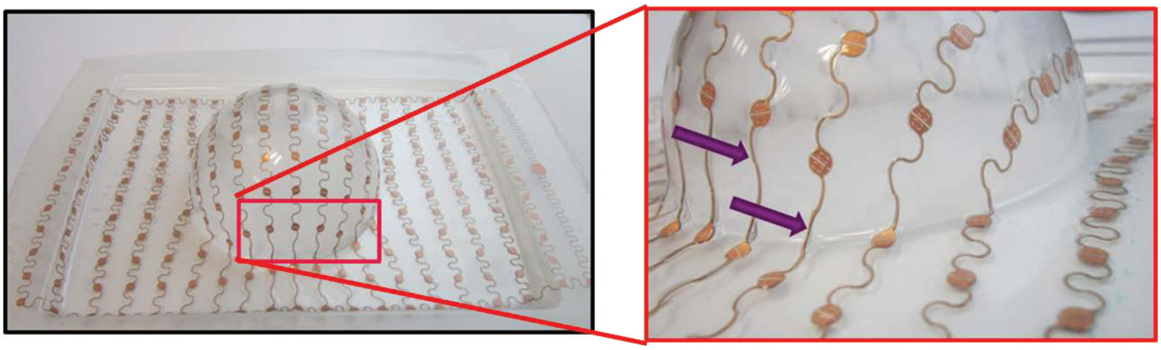

Fig.5. First thermoforming experiment, using a non-optimized design, inset (right) shows full extension of meanders.

Furthermore a preliminary test circuit was designed, intended to be used with the hemispherical forming tool. The circuit was produced on an A4 size PET-G substrate, using the "polymer-first" approach. Width of the Cu tracks is 100µm, and SMD components (LEDs and zero-ohm resistors) are assembled using isotropic conductive adhesives. After circuit fabrication and component assembly the circuit is thermoformed, in a rough initial try without embedding the components in an additional polymer layer. The results analysis of these first experiments is still going on and will be disseminated in a forthcoming publication, where the influence of meander shape, component orientation, bond pad designs, on the assembly yield will be discussed. First qualitative results however show that thermoplastic deformation of a circuit with assembled components is feasible.

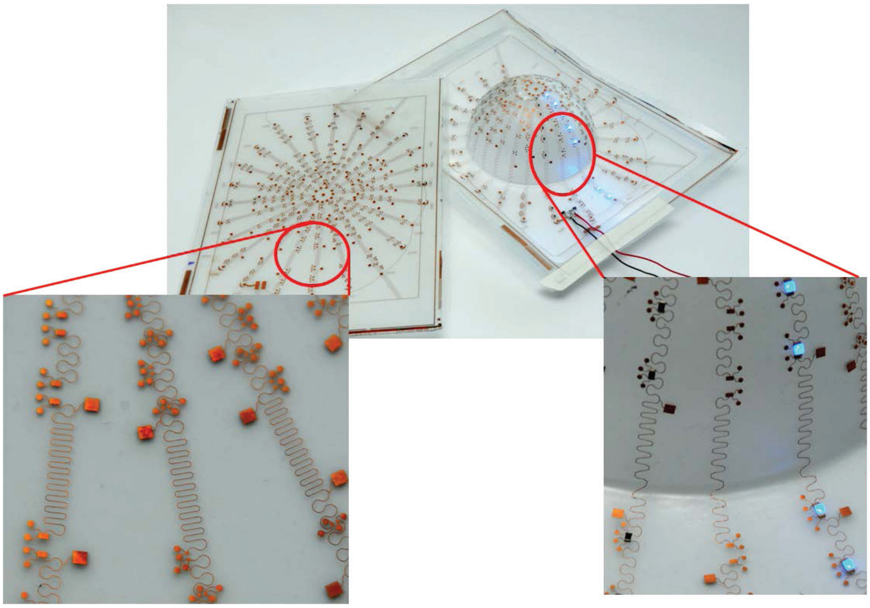

Fig. 6. Results of a further thermoforming experiment, using a preliminary dedicated design, detail pictures show Cu meanders before (left) and after (right) the deformation step. A series circuit of 8 LEDs and 8 zero-ohm resistors is realized and demonstrated.

Figure 6 for example shows the operation of a very simple thermoformed circuit, consisting of the connection in series of 6 LEDs and 6 SMD LEDs. On the left hand side of the top picture the flat A4 sized, "polymer-first" type circuit is depicted, while the right hand side shows the same circuit, after assembly of the components and subsequent thermoforming. The detail photographs show the meanders before (left) and after (right) deformation. Again the largest deformations appear at the base of the hemisphere.

5. Conclusions and outlook

In this contribution preliminary work has been reported on the development of technology for free form 2.5D electronic circuits. The technology development is being done with cost efficiency and later industrialisation in mind. To this end in a first series of production steps the electronics circuits are produced on flat substrates in a way compatible with standard printed circuit board (PCB) manufacturing and assembly practices. The final 2.5D shape is obtained by a subsequent thermoforming step of the initial flat 2D circuit and its embedding thermoplastic circuit carrier. First experiments with functional test circuits, including LEDs, have shown that at least these test components and their electrical interconnections can withstand the thermal and mechanical stresses imposed by the polymer embedding and thermoforming steps. Hence technologies for PCB based 2.5D circuits, using the described strategy seem to be feasible. Substantial work needs to be performed before the technology is ready for industrial implementation. In the near future we will work towards optimisation of meander designs as a function of degree of elongation, nature and thickness of the embedding thermoplastic polymers, etc. An important challenge is also to be able to deform a given flat circuit to a 2.5D shape with predictable final spatial positions of components and interconnections. Multiphysics modelling methods will be developed to optimise the circuit design and lay-out methodology.

Acknowledgements

The work reported here was carried out in the frame of the European Commission (EC) funded projects FP7-PLACE-It and FP7-TERASEL, and of a PhD grant, funded by the Center of Excellence of Nano-manufacuturing Applications (CENA). We wish to thank these organizations for their support.

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