

Flex PCB Based Technology for Randomly Shaped Circuits

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Abstract—In this paper we present a technology for the production of randomly shaped 3D electronic circuits. The technology is based on conventional printed circuit board (PCB) technology, thermoplastic polymer encapsulation and thermoforming of the flat polymer carrier with the embedded circuit. Meander shaped Cu lines between components are stretched during the thermoforming while maintaining their interconnection function. The feasibility of this process has been demonstrated by producing functional free-form LED circuits.

Keywords : stretchable circuits; thermoforming; thermoplastics; free-form electronics; 3D.

I. INTRODUCTION

Conventionally electronic circuits are fabricated on flat rigid boards with multiple patterned Cu conductor layers interconnecting the components which are attached to the Cu using lead-free solder. These printed circuit boards (PCBs) provide an efficient and cost effective way for electronics manufacturing. However today there is growing need to integrate electronics in 3D objects, where the electronic circuit should follow the surface shape of the object. Reasons to do so are reduced weight, reduced materials use, increased comfort, more attractive designs, etc. This means that alternatives for the flat rigid boards have to be found. A first way to increase freedom in circuit form factors is to use mechanically flexible circuits instead of rigid ones. In this respect flexible polymer films (PET, PEN, PI (polyimide)) with laminated and patterned Cu conductors or screen printed Ag conductors are possible embodiments of flexible electronic circuits. For economical reasons (throughput) these circuits are still produced in a flat state, and bended only after the complete circuit is finished. This means that a flat flex circuit can be transformed into a cylindrical or conical shape, but no irregular shapes are possible, starting from a flat circuit.

Solutions for producing irregularly shaped circuits however are available or are under development. In a first solution standard rigid sub-boards are mechanically and electrically connected by flexible circuits, as shown in the example of Fig. 1. These connections between flex and rigid parts can be realised either using connectors, or a connectorless flex-rigid technology can be used, which is the case for the circuit shown in Fig.1. However use of connectors reduces the reliability of the complete circuit, while connectorless flex-rigid technology

has a high reliability, but is expensive. Furthermore as Fig.1 clearly demonstrates, such a composition of flat rigid boards does not allow evenly or elegantly curved electronic surfaces, and causes limitations in terms of freedom of design and random form factors.

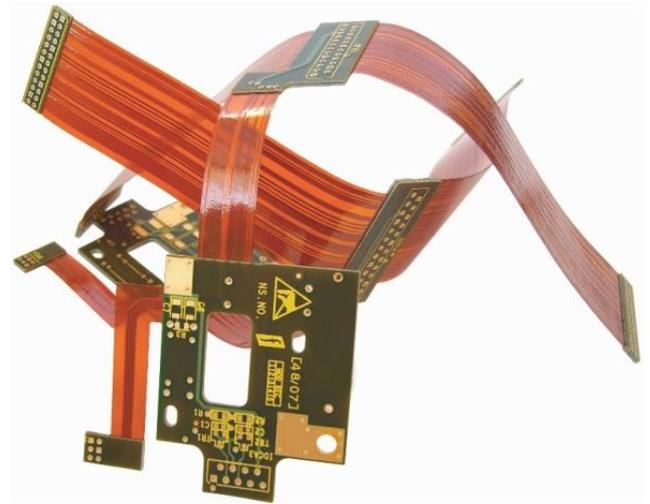


Fig. 1. Example of industrially produced Teknoflex flex-rigid board [1], showing its limitations in random circuit deformation.

A second solution for producing randomly shaped circuits is 3D-MID (molded interconnect device) technology, which allows to produce 3-dimensional electronics and sensor circuits using standard processing steps like laser structuring and copper plating, which makes this technology attractive for industrialisation [2]. An example of a realised circuit is shown in Fig. 2. Some challenges remain however, which, once overcome, would allow a further proliferation and use of this technology. These challenges include : (1) the non-trivial production of circuits with multiple conductor layers (similar to multilayer printed circuit boards), (2) the necessity to assemble the electronic components on a non-flat substrate which is a considerably slower process, compared to standard pick-and-place assembly on flat substrates and (3) the high maximum temperature (around 250°C) during component assembly, if conventional lead-free solder is used, limiting the choice of possible usable circuit carrier polymers.

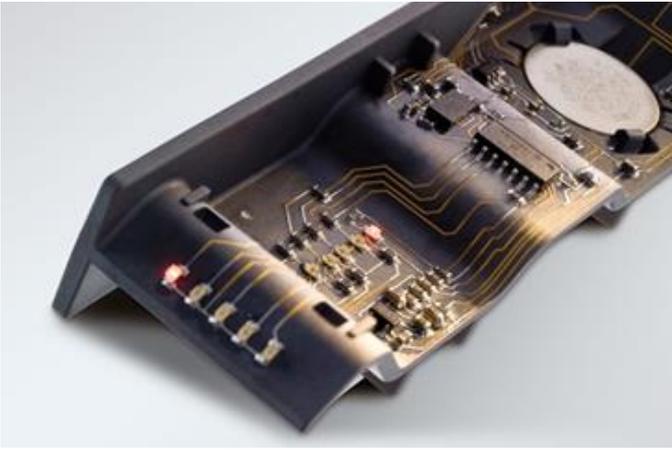


Fig. 2. 3D-MID circuit, with assembled components [3].

In this contribution we present a technology for the production of rigid 3D free-form circuits, based on printed circuit board fabrication technology, and avoiding the above mentioned difficulties of flex-rigid and 3D-MID circuits.

II. PRINTED CIRCUIT BOARD (PCB) INSPIRED STRETCHABLE CIRCUITS.

The technology which is presented here, is based on our technology for PCB inspired dynamically stretchable circuits [4,5]. This technology has following basic properties :

1. The interconnection between the electronic components consists of Cu conductors with thicknesses of typically 17 or 35 μm , just like in standard PCB technology. In fact Cu sheets, intended for standard PCB's, or, preferably, even standard Cu clad PI flexible circuits are used in our stretch circuit fabrication process.
2. 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. For reliability optimization purposes much effort has been spent to optimize the shape of this meander, as well as the design of the transition zone between the stretchable interconnects and the stiff component islands [6].
3. High functionality of the circuits is ensured by the use of conventionally packaged, off-the-shelf available electronics and sensor components, which are assembled on the circuits by mainstream technologies like lead-free SAC (tin-silver-copper) soldering.
4. The "polymer last" approach is adopted : the stretchable circuit, including Cu interconnections and assembled components, is fabricated on a high-temperature resistant, chemically inert temporary carrier, e.g. an epoxy FR4 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 polymer 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. This approach thus requires the transfer of the circuit from a temporary carrier to the final polymer substrate carrier, but has the advantage that conventional PCB processing readily can be copied, because all harsh PCB production steps are performed before applying the final polymer carrier.

III. STRETCHABLE MOULD INTERCONNECT (SMI) PROCESS FLOW

In this paragraph the process flow for our so called Stretchable Mould Interconnect (SMI) technology is explained in detail. Our process for producing rigid 3D electronic circuits consists of 3 main steps :

1. Production of the stretchable circuit on a temporary carrier
2. Transfer of the stretchable circuit from the temporary carrier to the final thermoplastic polymer carrier, the circuit still remaining flat
3. Deforming the thermoplastic carrier and the embedded circuit from flat to its final 3D shape using a thermoforming step.

More in detail the process flow consists of following steps, schematically shown in Fig. 3 :

1. A high-temperature resistant, chemically inert temporary carrier (A) (e.g. an epoxy board) is uniformly covered with a pressure sensitive adhesive (e.g. silicone based) (B).
2. In parallel a conventional Cu-clad PI flex (C) is patterned and etched, resulting in a conventional flex circuit (D). Stretchable interconnects are patterned as meanders.
3. The flex circuit is attached to the temporary carrier using roll or vacuum lamination (E).
4. The flex circuit is laser cut, thus separating the functional part(s) from the excess part(s) (F), and the excess parts are removed (e.g. by peeling off) (G).
5. Components are assembled by a conventional SAC solder reflow process (H)
6. On top of the circuit the final polymer carrier layer or layer stack is applied, e.g. by lamination (I)
7. The temporary carrier, including the pressure sensitive adhesive is removed (J)
8. At the bottom of the circuit a second polymer carrier layer or layer stack is applied (K)

The result is a flat stack of polymer materials with an embedded stretchable electronic circuit. This circuit is now subsequently submitted to a thermoforming process (Fig. 4) :

1. The circuit is clamped and heated (A) to temperatures above the glass transition temperature of the polymer, but below the melting temperature, i.e. until the thermoplastic polymer becomes soft (B)

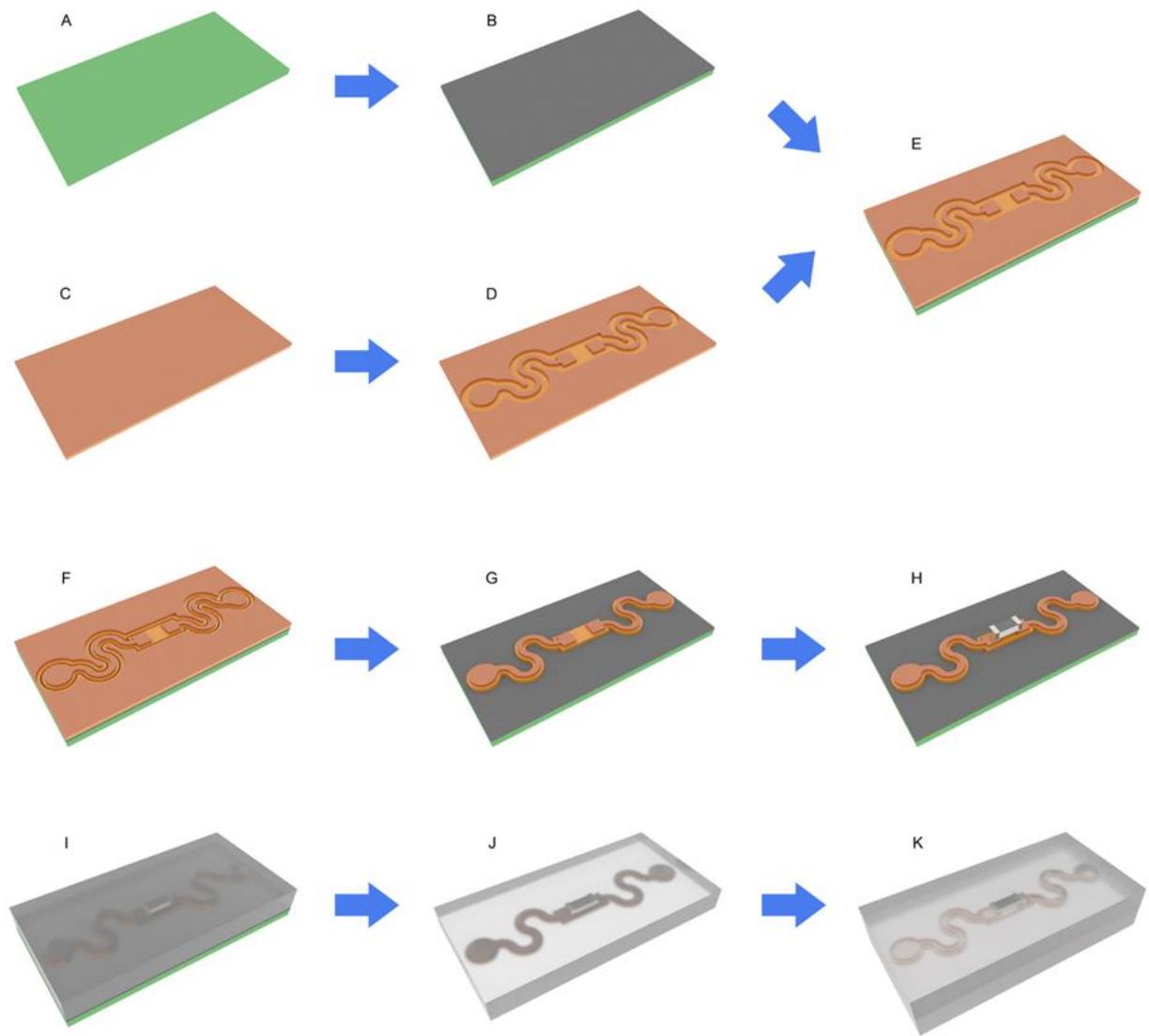


Fig. 3. Stretchable Mould Interconnect (SMI) process flow

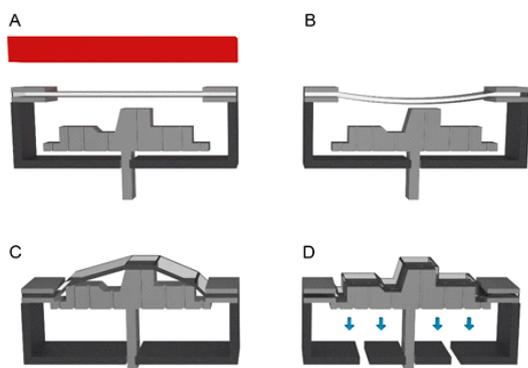


Fig. 4. Thermoforming process.

2. A thermoforming tool, determining the final shape of the 3D circuit is pressed against the soft polymer stack and embedded circuit (C)

3. A vacuum is applied below the tool (vacuum forming), or a high pressure above the circuit (high pressure forming), or both, so that the soft polymer (together with the embedded circuit) deforms and closely follows the shape of the forming tool (D)

4. The polymer cools down until it becomes rigid again, and the tool is removed from the formed circuit (not shown).

Fig. 5 shows the role of the meandering interconnects. Before thermoforming all interconnections in the flat substrate have meander shapes as in the horizontal flat, right hand part of Fig. 5. After thermoforming the initially flat circuit over a positive hemispherical tool, resulting in the object, shown in Fig. 5, the meanders in the stretching zone undergo an elongation, which in this case is the largest at the base of the hemisphere. The meanders in this zone become almost straight lines, as indicated by the arrows in Fig.5, however without losing their interconnection function.

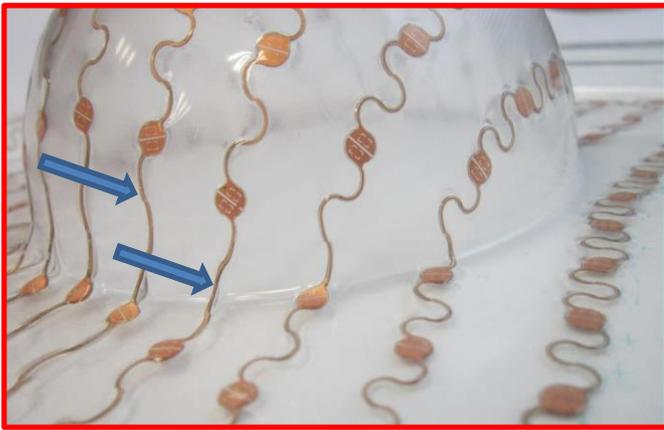


Fig. 5. Meander stretching after thermoforming

The feasibility of the process including embedded functional circuits, was shown with a number of demonstrators. Fig.6 shows a simple LED circuit before and after thermoforming. It is clear that the components and the interconnections withstand heat and forces during the thermoforming step.

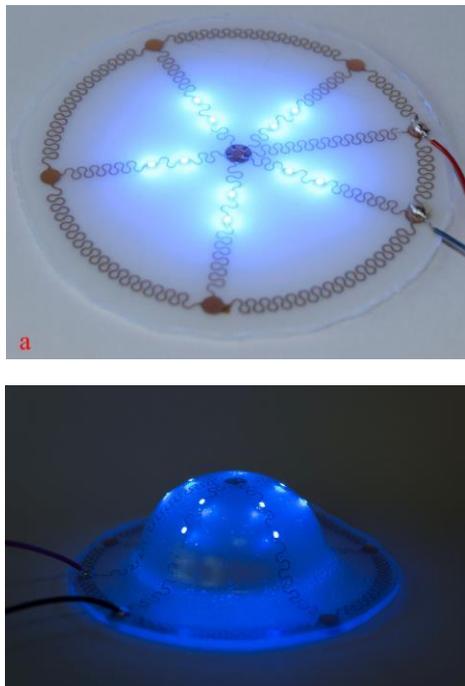


Fig. 6. Thermoplastic circuit, including 10 LEDs and 5 resistors : flat circuit after embedding in a thermoplastic polymer (top); the same circuit, 3D shaped after thermoforming (bottom)

Fig.7 shows the possibility to generate circuits with more irregular shapes. In this case a LED mask is designed and realised. For a perfect fit the forming tool is derived from a 3D scan of the wearer's face. 20 mid-power Worldsemi WS2812 RGB LED packages with integrated driver are assembled in 3 LED strings. The embedding polymers are commercially available materials : (1) SABIC Lexan 9030 PC (polycarbonate), thickness 250 μm and (2) Bayer Material Sciences Platilon U4201 AU TPU (thermoplastic polyurethane), thickness 100 μm . This stack of 2 polymers is applied by vacuum lamination on both top and bottom of the

circuit, with the TPU in contact with the circuit, thus ensuring a good adhesion of the polymer stack to the circuit.

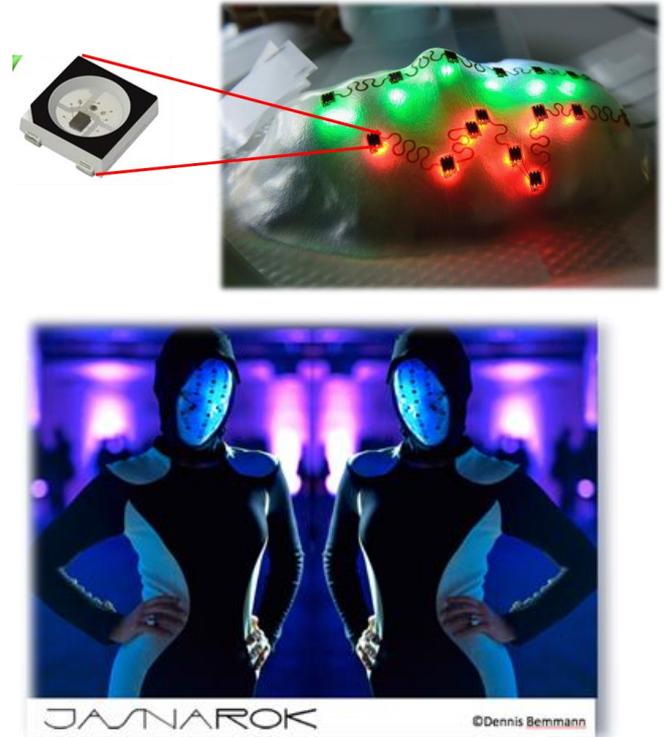


Fig. 7. Thermoformed LED mask, designed by artist Jasnarok [7].

IV. CONCLUSIONS AND OUTLOOK

A technology has successfully been developed for the production of 3D free-form electronic circuits. The technology is especially useful in cases where circuits with low component density over the surface are needed. As the technology consists mainly of standard PCB technology steps on one hand and polymer processing steps on the other, it is believed that industrialisation of the technology should be possible in reasonably short term.

A remaining challenge is the replacement of the laser structuring of the meanders by a higher throughput technology for high volume production (e.g. punching). Moreover a circuit lay-out tool must be developed, allowing to design a flat circuit, which after forming will result in the 3D circuit with components at their desired positions.

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