Stretchable Circuit Board Technology and Application

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Abstract

An innovative technology for the mass production of stretchable printed circuit boards (SCBs) will be presented in this paper. This technology makes it possible for the first time to really integrate fine pitch, high performance electronic circuits easily into textiles and so may be the building block for a totally new generation of wearable electronic systems. An overview of the technology will be given and subsequently a real system using SCB technology is presented.

1. Introduction

Today nearly all modern electronic is based on printed circuit boards (PCBs). This inconspicuous little piece of plastic and glass fibers is one of the reasons for the enormous grow of the electronic industry. Beside the transistor it is one key for low cost, small size and powerful electronic systems. Especially for wearable devices high end PCBs with their ultra compact multilayer structures allow an extremely high level of integration. The next big invention in this sector was the flexible PCB (FPCB). Its main benefit is the outstanding mechanical property of being flexible. This opened a huge range of new application, because of the cost effective realization of bendable fine pitch interconnections (e.g. in mobile phones). Even though many products use this bend ability only once, in order to conform to warped surfaces (e.g. in automotive applications). A piece of electronic that physically fits to its application will reduce size and cost of the system.

FPCB technology gave designers a new degree of freedom, but still it is a plastic foil which can only conform to simple surface topographies and if it comes to stretching, the FPCB will reach its limits. This is the reason why researchers worldwide are seeking for the next degree of freedom, the stretchable circuit board (SCB). What sounds like a curious future vision is a serious research topic worldwide and of high interest for the industry. Wearable systems that really follow the shape and movements of the body are possible. Technology will change from a foreign, hard object to an integral, soft part of clothing or any other suitable 'near to body' objects (e.g. shoes).

There are many ways to approach this goal and there will be many application specific solutions for this problem. A small collection of current research work can be found in [1-8].

This paper will illustrate the technology which is currently developed during the European research project STELLA [5]. It is a cost effective approach mainly using well-proven techniques from the PCB industry and commercial available materials for mass production oriented research on SCBs. The technology will be described and afterwards a demonstration system is presented to give an idea of how such a system may look and feel.

2. Technology

2.1. Idea

The technology described here was designed with the following criteria:

- A mostly stretchable electronic system should be the final outcome
- Process steps have to be suitable for low/medium cost mass production
- The process must be compatible with standard electronic components/packages

As nearly all electronic components available today are rigid, the system will consist of a stretchable matrix with rigid areas. The details of this hard to soft transition will be discussed in 2.4. This is an essential issue for a stretchable system. Only if the technology is compatible with standard components it will have a chance to come to the market. As it is a goal of the researchers and the industry to bring this technology to the market in the following years, the development is focused on standard processes and commercial available materials.

The base of this technology is an elastic substrate material with specially shaped conductor lines. Later on a solder resist and a surface finish can be applied. In the end the SCB looks like a common single sided PCB, just with the exception that it is stretchable. Electronic components may be assembled and soldered on it and later an encapsulation may be applied where needed. At the end the whole system may be laminated onto fabric or any other suitable surface.

It has to be mentioned that the process discussed here is not the only possibility for the realization of stretchable systems. Variants were developed during the STELLA projects which also show promising results. [4-6, 8]

2.2. Process technology

The whole SCB process is designed to use only little special processing and to adapt to standard PCB manufacturing as much as possible.

As mentioned before an elastic base material was chosen. After intensive testing a thermoplastic polyurethane (TPU) foil from Epurex (Walopur, thickness 100µm) showed the best properties. The TPU remelts at about 170°C. This makes it possible to use the substrate material as a glue for the later application on other materials e.g. fabrics. It is also biocompatible, easily available in big quantities and cost effective. Today it widely used especially in the textile industry, rubber bands in underwear are made of it, or raincoats are coated with TPU. So, polyurethane perfectly fits in the application as a base material for wearable products.

A standard, PCB grade copper (Cu) foil (thickness=35µm) is used as conductor material. Substrate material and Cu foil are joined in a lamination process. Peel tests show an excellent adhesion of the Cu on the TPU, a peel strength of about 2 N/mm is typical. Standard polyimide FPCBs show a peel strength of roughly the half for Cu polyimide adhesion.

Now the base material is ready for structuring, which basically can be done like for a PCB or FPCB. Currently photolithography is used and works very well. Pitches down to 100µm line/space have been realized, which is even better than what most PCB manufacturers guarantee.

Obviously copper is not stretchable, but with a specially developed wire shaping, elongation of more than 100% can be achieved, section 2.3. will describe this in more detail. Other conductor materials were analyzed and tested for this application, but at the end Cu has proven to be the most promising candidate. Conductive inks and pastes would also be an alternative, but their conductivity is much lower more fluctuating if their mechanical properties allow stretching. Also soldering on those conductive pastes is not possible and the resolution of the structuring would not be sufficient. So, astonishingly, a pure metal shows the best properties for a stretchable conductor line. Detailed studies about thin stretched metal films can be found in [1,2].

Figure 1 shows the simplified process flow, beginning from the structured substrate.

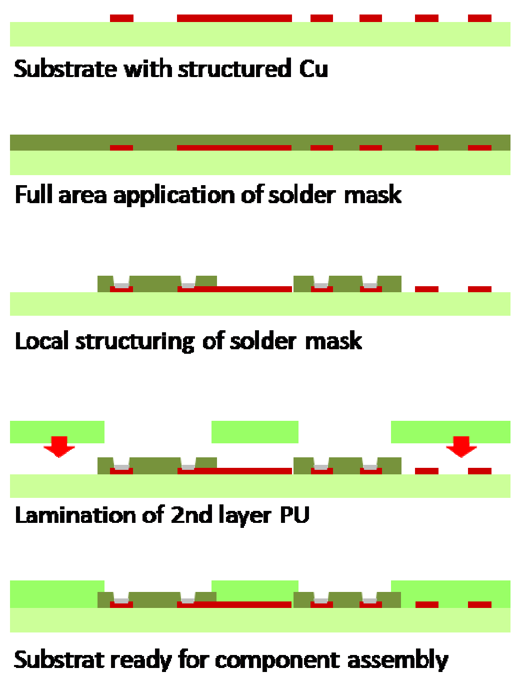

Figure 1. Process flow for SCB manufacturing

The structured substrate could basically be used as it is for simple electronic circuits, but a more sophisticated substrate is created in the following process steps. Solder resist is applied and structured. A standard flex solder mask is used. Today available solder resists are not very stretchable, so it is only deposited where it is needed. In those regions it can also be used to inhibit stretching (more about this in 2.4.). Surface finish for the Cu can be applied before or after this process step. Currently silver is used, as it offers moderate process temperatures. Still the conductor lines outside the solder resist are not isolated; this is done by the next process step. Another TPU foiled is laminated onto the substrate. It was structured before and has openings for the solder resist areas. An overlap between both is wanted to stabilize the whole build-up. The difference between both process steps is that the solder mask may be structured very precisely and offers good solder stop properties. TPU cannot be easily structured so accurately and during melting it deforms a little. Also the solder mask is not stretchable.

All those steps were done using standard PCB manufacturing equipment, with only slightly modified parameters. One big challenge is still the handling of stretchable substrates. Different solutions are currently under investigation. Techniques from the FPCB industry promise good results, e.g. substrates get processed on rigid carriers. Reel to reel production could also be used, making the substrates even cheaper.

2.3. Stretching copper by more than 100%

As mentioned before, the stretchable conductor lines are made of copper. Normally this material is not a good candidate for stretching, as it is only elastic for deformations lower than 0.1%. On the other hand metal springs demonstrate that metal basically can be used for high elastic deformations. It depends on the structure of the used material. The same approach is being used for the conductor lines here. A conductor line is shaped like a two dimensional spring. Figure 2 shows such conductor lines in reality.

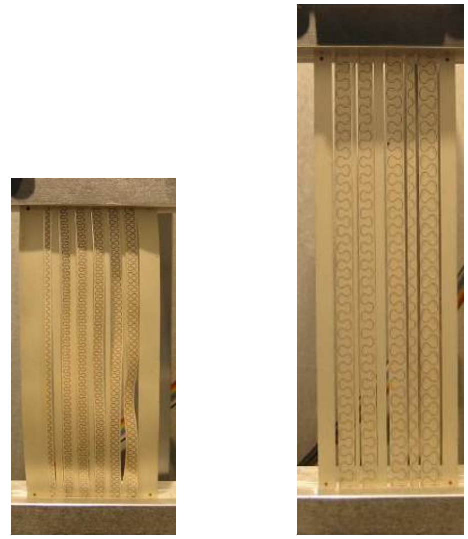

Figure 2. Relaxed (left) and elongated (right) Cu tracks on TPU

Relaxed Cu tracks can be seen in the left picture and the right picture shows the stretched conductors. Each track has been separated for testing purposes, but normally this is not needed.

Understanding the dependency between the conductor shape and the strain distribution is essential for the use of the technology, but since a detailed discussion would make up another full paper, only a short overview will be given. More detailed descriptions can be found in [4-6, 8].

Basically a two dimensional spring is formed by a wave or sinus function like structure. The best results were obtained with a horse-shoe like patterning of the copper, which was also used in Figure 2. A stretching of the substrate causes an elongation of this spring. Slight movement of the spring into the third dimension causes an even lower strain in the structure. Results of experimental testing are shown in Figure 3 and 4.

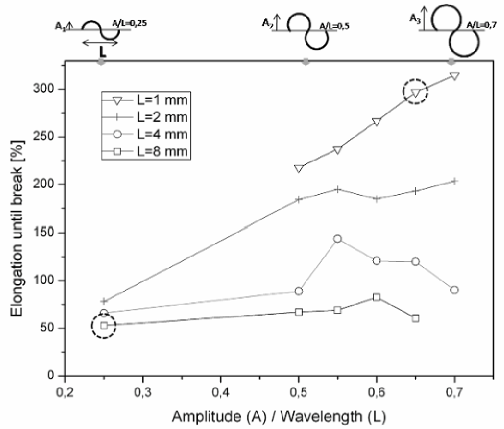

Figure 3. Experimental results for single cycle conductor line elongation testing

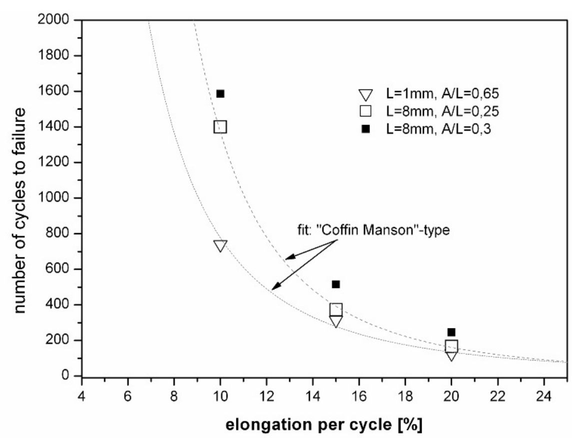

Figure 4. Experimental results for repeated conductor line elongation testing

Figure 3 shows the maximal obtainable stretch of the copper tracks. An amplitude/wavelength coefficient was used for an easier description of the layout. The graphic shows the results for a single stretching and proves that the Cu tracks can be elongated by more than 300%.

Figure 4 gives the results for repeated stretching and shows a high reliability of the spring like structuring. About 1600 stretching cycles at 10% elongation is an impressive proof for the reliability of this technology. Of course less stretching will result in an even higher cycle count.

For the application in wearable technologies on a fabric carrier, the expected stretching would be much lower than 10%, as the fabric material can be made inelastic.

2.4. Mixing hard and soft

Now the base material and the conductor lines are elastic, but still the electronic components are rigid. The transition between both is a critical point in the system design. If both were directly connected the strain in the interconnection would be extremely high and would sooner or later cause a break. A distribution of the strain over a bigger area lowers the local strain and so allows a combination of SCB and rigid components. Figure 5 shows the layout of such a stiffener/strain-distributor.

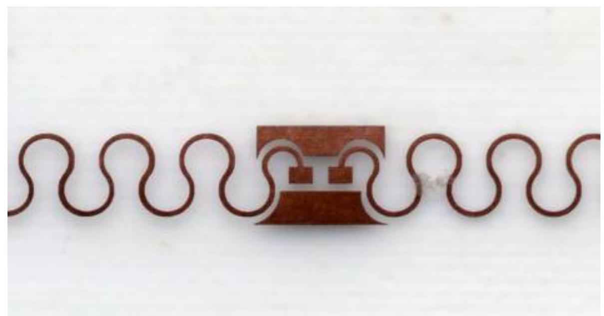

Figure 5. Stiffener structure for SMD LED

Here it was used for a SMD LED. The big copper areas are not stretchable and very stable; the strain has a negative gradient to the outsides. This technique also allows the easy integration of conventional designs into a stretchable system. The area around the wire tracks is filled with a copper area, like a ground plane. Mechanical stress in the circuit can so easily be reduced. As on FPCBs areas with electrical components should be protected from mechanical stress as much as possible and only the wire tracks to the outsides (e.g. connecting a sensor) should be stretched. Another way of protecting the electronic components is to encapsulate them with a stiffer or thicker material. This is also a convenient way to use no more housing for the system, as the substrate now also serves with protection and isolation. This is also a great benefit of this technology as it significantly lowers the weight and possibly also the cost. More information about the encapsulation can be found in [5, 8].

Not only discrete electronic components can be soldered on the substrate, also whole modules can be assembled. Since the technology now is only single sided, a multilayer module might be needed. Figure 6 shows an encapsulated IC and SMD components, the encapsulation of a module is also possible.

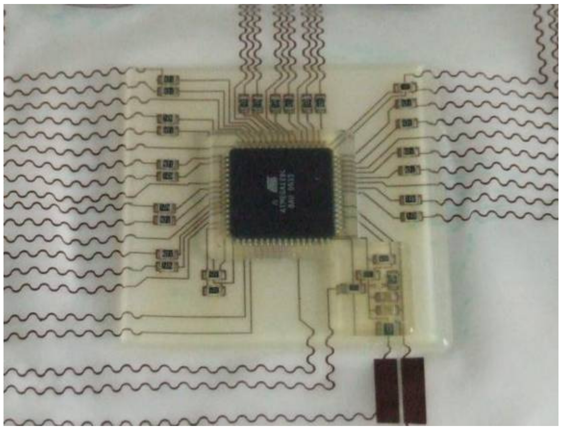

Figure 6. Encapsulated IC and SMD components

Assembly of components and modules can be done by soldering or by conductive adhesives. As the substrate material melts at about 170°C, a low temperature solder must be used. A SnBi solder with a melting temperature of 142°C showed the best results. Fortunately the development of such solders made much progress in the last years. Former problems with wetting have been drastically reduced. Also modern conductive adhesives show very good mechanical properties and would also be suitable for a stretchable system.

Soldering can be done with standard reflow ovens or even with a soldering iron, which is an important feature for extreme low cost production or the connection of external wiring.

3. A real system

3.1. Overview

In this chapter a real complete system based on SCB technology will be described. The system functions as a demonstrator for the technology and it was not intended to be a product.

One design goal was to show the lightweight character of such a system, so a very light dress was chosen as carrying platform. The design of the dress was created together with the system design, in order to achieve a really fashionable.

The very light dress is midnight blue and could be worn on evening receptions, but its design is also modern enough to be fashionable. Figure 7 shows the design concept.

Figure 7. Design concept of the demonstrator

Only on the left side some white lights are randomly distributed over the lower part of the dress. The lights are realized by warm white small SMD LEDs, which are hidden under multiple layers of extremely light fabric material. Each of the 32 lights can be dimmed individually. For a coupling of the user's motion to the lightning pattern, an accelerometer is used. It was the intention to create an electronic feature of the dress that looks more like a discreet accessory than a Christmas tree. Surrounding people might not recognize it at first and think the light is generated by attached gems. So the light feature will be only slightly and positively irritating.

3.2. System Design

The system was designed to show the practical realization of some standard system building blocks:

- System power distribution over medium ranges (up to 50cm) for medium currents (100-500mA)
- Fast communication links (1 Mbit/s)
- Use of standard system buses (I^2C)
- General module interconnection
- Sensor interfacing

System power lines within medium ranges that are lightweight and integrated into textiles with isolation is still a challenge which is successfully demonstrated with the presented system. Due to the very good conductivity of the Cu connections even distances of over 50cm can be bridged without significant power losses. Especially for currents <=100mA this becomes a crucial criteria. Conductive threads which show those properties are normally not isolated and if they are, it is complicated to contact them afterwards. As already described the SCB technology automatically assures the isolation. At the end of the power lines press buttons were punched through the substrate and allow an easy connection. Of course isolation of this interface might also become a topic, but if this connection is placed wisely (e.g. not with direct contact to the body), an isolation might not be needed here.

A block diagram of the whole system is shown in figure 8. The system is split up into different modules. All grey modules are implemented on separate FR4 interposers. Routing on the single sided SCB is now much easier, as the contact pads of the rigid modules can appropriately be distributed. Double sided FR4 substrates are used; a more detailed description of the hardware follows in 3.3. A small, separate battery pack was designed and manufactured by rapid prototyping. It contains a seamless step-up/step-down converter (MAX8625A from Maxim) to generate the 4V system power. This uncommon voltage is needed to power the warm white LEDs, which have a forward voltage of about 3.6V (of course dependent of the forward current).

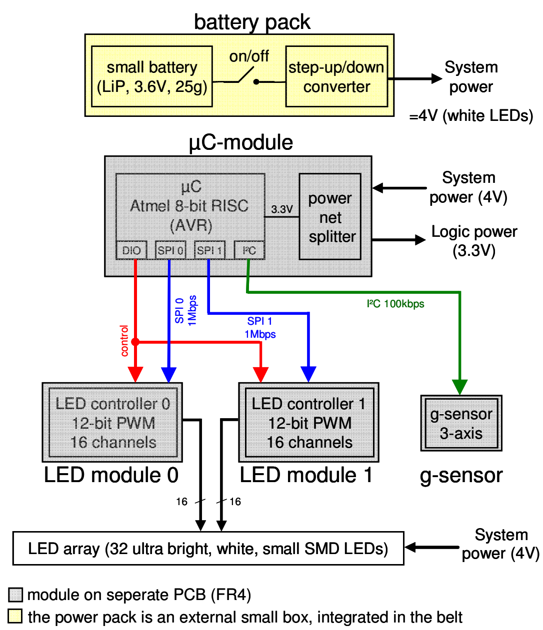

Figure 8. Block diagram of the system

On the µC-module the system power is split into the logic power of 3.3V and the LED power of 4V. Especially the accelerometer (MMA7455L from Freescale) works only up to 3.6V. The battery box is hidden in the belt of the dress and with the very light rechargeable lithium-polymer battery the system runs about 8 hours.

The heart of the whole system is the microcontroller. An AVR (8bit RISC) microcontroller (ATmega644P) is used. It can easily be in-system programmed and with 8 MIPS it is powerful enough to generate nice lightning effects or even perform some simple digital signal processing (FIR filtering, etc.).

Two LED drivers (TLC5940 from Texas Instruments) control the brightness of the 32 LEDs. Every controller has 16 individual channels which are operated by a pulse width modulated constant current sink. Input data is passed to the controller via a simple synchronous serial interface (SPI). A data rate of 1Mbit was chosen and no problems on the SCB were observed with this. Some control signals are needed for those drivers and connected to the GPIOs of the controller.

An accelerometer with an I²C interface was chosen to prove the compatibility of this standard bus with the curled conductor lines in practice. A distance of about 30cm lies between microcontroller and accelerometer, the special conductor shaping causes an even longer effective wire length, but no failures or problems were observed for this bus in standard operation mode at 100kbit/s. All communication links were working fine when the dress is worn in practice and special designed software drivers assure robustness when outside RF signals would cause bit failures. This means the dress is compatible with mobile phones or other wireless devices.

3.3. Hardware

Figure 9 shows the FR4 modules in comparison with a 2 Euro cent coin.

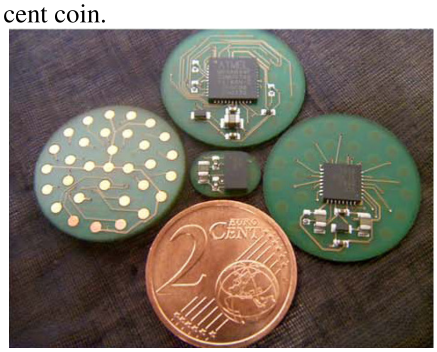

Figure 9. The FR4 modules (top: µC, right: LED driver, middle: accelerometer)

A round design with evenly distributed backside pads, similar to LGAs or QFNs, was chosen. Mechanical stress is minimized by the round shape. Low temperature solder (SnBi) was used for the assembly. Thickness of the substrates is 500µm and a line/space

ratio of 150µm with 100µm vias allows easy routing. All ICs are QFN (µC and LED driver) or LGA (accelerometer) packages which makes small modules possible. Currently modules with 500µm pitch backside contacts and a transfer molding encapsulation are under development.
After soldering the modules were underfilled with flip chip underfiller, in order to obtain maximal system reliability. No encapsulation was used yet for the modules, so the electronic can still be seen. Also a special optical encapsulation for the LEDs is still under development.
Figure 10 shows the assembled modules and LEDs on the SCB. Light fabric was used as carrier material.

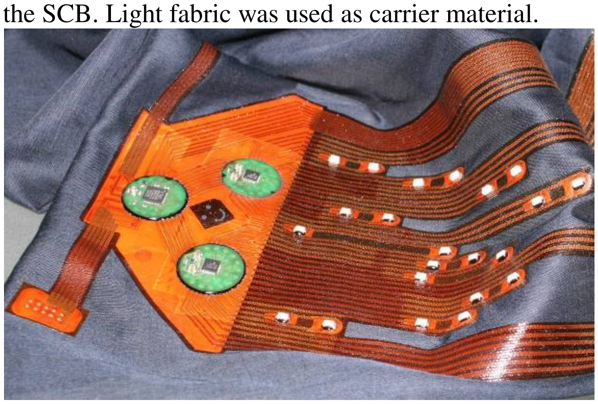

Figure 10. Assembled system on SCB/fabric

3.4. Software

As this paper is focused on the hardware realization this section will be very short, just some corner stones will be given.
As already mentioned a diamond like twinkle effect is achieved by covering the LEDs with fabric. Additionally some software light effects were added.
In idle mode the light intensity of each individual LED is billowing, similar to the stars in the sky in a cloudless night. When the person who wears the dress starts moving, a wave of light runs through the LEDs similar to the wave caused by a drop of water in a silent lake.
Special care was taken to make the communication drivers robust, as the system is not located on a mainboard, but integrated in a dress. Surprisingly even near to powerful RF-sources nearly no disruption of the communication was noticed.

3.5. How it looks and feels

Figure 11 shows the final product.
On the left side the lights are shining through the fabric. The battery pack is embedded in the belt on the back and a SCB based flat cable was laminated onto the inside of the belt. Belt and dress are electrically connected by press buttons hidden under the fabric and also separated from the body by fabric.

Figure 11. The complete light dress (Klight)

The Movement of the light translucent fabric is not changed by the integrated electronic, since the SCB is extremely thin (<200µm) and lightweight. So the light nature of the whole dress is not changed by the electronic what is ideal for such a large wearable system.

4. Conclusion

A technology for the creation of a new kind of wearable systems was described. Its unique appearance was demonstrated by a complete wearable system for fashion applications.
More complex systems can be created based on this technology that may include wireless links and/or advanced sensor systems. Applications could reach from simple cables or sensor connections to complete systems in the medical sector.
The technology is still under development, but high interest from the industry was recognized and will

hopefully lead to production in the next years. Even now this technology could already be used for prototype or low volume systems for special high value applications, with only moderate modifications.
Of course the SCB technology will not replace the common PCB for wearable systems in general, but it may become a building block of highly innovative products in the near future.

5. Acknowledgements

The demonstrator would not look as fashionable as it does, if it was designed by us engineers. That is why we would like to thank our young ambitious designer Mareike Michel for her creative work.
All this work would not have been possible in this quality without the other project partners of the STELLA project, nor without the founding of the European Union.

6. References

[1] T. Li, Z. Huang, Z. Suo, S. P. Lacour, S. Wagner, "Stretchability of thin metal films on elastomer substrates", *Appl. Phys. Lett.*, vol. 85, no. 16 (2004) pp. 3435-3437

[2] S. P. Lacour, J. Jones, S. Wagner, T. Li, Z. Suo, "Stretchable interconnects for elastic electronic surfaces", *Proceedings of the IEEE on Flexible Electronics Technology*, vol. 93, no. 8 (2005), pp. 1459-1467

[3] D.-H. Kim, J.-H. Ahn, W. M. Choi, H.-S. Kim, T.-H. Kim, J. Song, Y. Y. Huang, Z. Liu, J. A. Rogers, "Stretchable and Foldable Silicon Integrated Circuits", *Science*, 320 (2008) 507-511

[4] M. Gonzalez, F. Axisa, M. Vanden Bulcke, D. Brosteaux, B. Vandevelde and J. Vanfleteren, "Design of metal interconnects for stretchable electronic circuits", *Microelectronics Reliability,* 48 (2008) 825–832

[5] Website of the European research project STELLA, http://www.stella-project.de/

[6] M. Gonzalez, F. Axisa, F. Bossuyt, Y.-Y. Hsu, B. Vandevelde and J. Vanfleteren, "Design and Performance of Metal Conductors for Stretchable Electronic Circuits", *Proc. of the ESTC 2008*, September 2008, London, UK. 1-4

[7] T. Someya and T. Sakurai, "Integration of Organic Field-Effect Transistors and Rubbery Pressure Sensors for Artificial Skin Applications", *2003 IEEE International Electron Devices Meeting,* pp. 203-206 (2003)

[8] T. Löher, R. Vieroth, M. Seckel, A. Ostmann, H. Reichl, „Stretchable electronic Systems for wearable and textile Applications", *VLSI Packaging Workshop of Japan, 2008, VPWJ 2008. IEEE 9th*, pp. 9-12