Accepted Manuscript

Title: Transparent, flexible, thin sensor surfaces for passive light-point localization based on two functional polymers

Author: Gerda Buchberger Ruxandra Aida Barb Juergen Schoeftner Siegfried Bauer Wolfgang Hilber Bernhard Mayrhofer Bernhard Jakoby

PII: S0924-4247(16)30007-3
DOI: http://dx.doi.org/doi:10.1016/j.sna.2016.01.007
Reference: SNA 9464

To appear in: Sensors and Actuators A

Received date: 7-6-2015
Revised date: 8-12-2015
Accepted date: 7-1-2016

Please cite this article as: Gerda Buchberger, Ruxandra Aida Barb, Juergen Schoeftner, Siegfried Bauer, Wolfgang Hilber, Bernhard Mayrhofer, Bernhard Jakoby, Transparent, flexible, thin sensor surfaces for passive light-point localization based on two functional polymers, Sensors and Actuators: A Physical http://dx.doi.org/10.1016/j.sna.2016.01.007

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Transparent, Flexible, Thin Sensor Surfaces for Passive Light-Point Localization Based on Two Functional Polymers

Gerda Buchberger* gerda.buchberger@jku.at, Ruxandra Aida Barba1# ruxandra-aida.barb@jku.at, Juergen Schoeftnerb2 juergen.schoeftner@jku.at, Siegfried Bauerc3 siegfried.bauer@jku.at, Wolfgang Hilbera4 wolfgang.hilber@jku.at, Bernhard Mayrhoferb5 bernhard.mayrhofer@jku.at, Bernhard Jakoby6 bernhard.jakoby@jku.at

1Institute for Microelectronics and Microsensors, Johannes Kepler University Linz, Altenberger Str. 69, A-4040 Linz, Austria
2Institute of Technical Mechanics, Johannes Kepler University Linz, Altenberger Str. 69, A-4040 Linz, Austria
3Department of Soft Matter Physics, Johannes Kepler University Linz, Altenberger Str. 69, A-4040 Linz, Austria

*Corresponding author at: Now with the Institute of Biomedical Mechatronics, Johannes Kepler University Linz, Altenberger Str. 69, A-4040 Linz, Austria. Tel.: +43 732 2468 4813, fax: +43 732 2468 24801.
#Now with the Institute of Applied Physics, Johannes Kepler University Linz, Altenberger Str. 69, A-4040 Linz, Austria.

tel.: +43 732 2468 9276

tel.: +43 732 2468 6259

tel.: +43 732 2468 6265

tel.: +43 732 2468 6251
Highlights

- We describe the design, fabrication and characterization of large-area sensors for light-point localization.
- The sensor surfaces are transparent, thin (< 30 μm), flexible and matrix free.
- The sensor surfaces are based on only two functional polymers.
- The design allows for simple fabrication technologies such as roll-to-roll-processing, spin-coating and screen printing.
- Applications arise as human machine interfaces mounted on automotive windshields, windows and flexible displays.
Abstract
We present light-point localization by transparent, flexible, thin sensor surfaces based on only two functional polymers: a thin film of pyroelectric poly(vinylidene fluoride) (PVDF) combined with large-area polymer electrodes made of poly(3,4-ethylenedioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS). One of the electrodes is resistive to enable position sensitivity, and both materials are highly flexible and transparent across the visible range of light. We fabricated a one-dimensional sensor strip of 3.5 cm x 0.8 cm size and a two-dimensional 3 cm x 3 cm sensor surface. Both devices used a 25 μm thin PVDF film whose surface was activated by low-energy argon plasma. PEDOT:PSS electrodes were deposited by spin coating onto the PVDF film. The fabricated devices were validated by applying the intensity-modulated light of a red laser diode to the sensor surfaces. Our design enables position sensitivity without the need for active or passive matrix technology or external power supply, and with electronic circuitry placed only at the edges. This allows simple fabrication techniques to be employed, such as roll-to-roll-processing, spin coating and screen printing. Since low-cost polymeric materials can be used, the proposed sensors have a wealth of possible applications in consumer goods.

Keywords: Sensor; large-area; position-sensitive; poly(vinylidene fluoride) (PVDF); transparent; poly(3,4-ethylenedioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS)
1. Introduction

In contrast to microelectronics, macroelectronics aims to enlarge the size of electronic components [1-4]. Progress in this field is rapid, and includes the demonstration of large-area position-sensitive devices which are flexible or stretchable and react to pressure, touch, changes in temperature or incident light [5-19]. Potential applications are, for instance, in electronic skin for robots and room-sized electronic interfaces for ambient intelligence. In this paper, we describe the design, fabrication and characterization of transparent large-area sensors for light-point localization based on only two functional polymers.

Most large-area sensors are based on active or passive matrix technologies for position-sensitivity [1-11], and only few sensor concepts avoid the division of sensor surfaces into a large number of individual sensing elements [12-18]. We used the concept of matrix-free large-area sensors to develop transparent, flexible, thin sensor surfaces for light-point localization. Combining macroelectronics with the field of invisible electronics [17,19-25] will turn hitherto passive surroundings, such as windows and automotive windshields, into human–machine interfaces, thus creating what is called “ambient intelligence”.

The matrix-free concept allows the size of a sensing element to be increased by two orders of magnitude from an area of approximately 1 mm² to approximately 10 cm² [12-18]. The large-area sensors described theoretically in [16] are advantageous for passive stimulus-localization in a wide range of applications; the presented concept has already been used in non- or semi-transparent flexible large-area sensors for touch- and/or light-point localization based on cellular ferroelectrets, in organic photodiodes and in ferroelectric polymers [12-16]. The sensors presented in [12-16] feature simple designs: electronics are placed only at the edges of the devices, and they are based on low-cost flexible – or even stretchable – polymeric materials. This makes them suitable for large-scale production using simple fabrication methods such as roll-to-roll processing, spin coating and screen printing.

Alongside the field of macroelectronics, the field of invisible electronics has been developing [17,19-25]. Flexible devices such as transparent displays and transistors [20,23], transparent, flexible solar cells [21], printable, transparent touch panels [5], semi-transparent sensors for touch- and light-point localization [14,18] and transparent, and even stretchable pressure sensors [17] have been demonstrated. Salvatore et al. [20] succeeded in fabricating transparent, highly flexible thin-film transistors which can even be placed directly on contact lenses for future applications that monitor intraocular pressure.

In this work, we employed poly(vinylidene fluoride) (PVDF) [26-29] and poly(3,4-ethylene dioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS) [30] as active materials for our transparent, flexible light-point localization sensors. Using PVDF as a pyroelectric material [31] enables a sensor design where no external power is consumed for light-point position detection.

For sensor fabrication, we applied the concept we described theoretically in [16], using a highly flexible, transparent, thin film of PVDF together with flexible transparent polymer electrodes made of PEDOT:PSS. In contrast to metal electrodes, PEDOT:PSS electrodes do not restrict the flexibility of the polymer film [32,33], which is a general issue in flexible and stretchable electronics [34]. PVDF or PVDF copolymers with PEDOT:PSS electrodes have been used by researchers in beam-type sensors and actuators [32,33], in flexible but non-transparent optothermal sensors based on active-matrix technology [10], and in transparent, flexible sensor strips for light-point localization [35]. For sensor fabrication, we first activate the surface of the PVDF film by low-energy argon plasma [36] in order to deposit large-area PEDOT:PSS electrodes. One of the large-area electrodes is conductive, while the other is resistive [37-
The fabricated sensors are made of only two low-cost polymer materials and can be produced using simple fabrication techniques such as roll-to-roll-processing, spin coating [40,41], spray-coating [5] and printing [10,33]. Solutions of PVDF-based fluoropolymers are thus applicable [42].

Our concept as described below might also be suitable for other materials. However, it might be necessary to adapt the excitation source to these materials in order to ensure sufficient heating of the pyroelectric film. The human finger might work as an alternative stimulus for future touchless devices [10]. Recently developed transparent electrodes [21,43-47] or alternative pyroelectric materials [48,49] could be employed instead of the materials used in this work. However, one of the electrodes needs to be fabricated with significant sheet resistance [15,16,50]. Recently, pyroelectrics have been discussed and compared mainly with regard to their use in energy harvesting [48,49]. Among other materials for transparent flexible or even stretchable organic electrodes, graphene has been described as a promising alternative to PEDOT:PSS and PEDOT:PSS composites [5,44]. Kulkarni et al. deposited graphene onto PVDF thin films for transparent, flexible infrared (IR) detectors with particularly short response times [44]. Vuorinen et al. used PVDF in combination with graphene-based ink as electrode material to fabricate touch panels that are printable, transparent, and flexible; these devices work in sunlight, under water and in moist environments [5]. Using stretchable electrode materials [45,51,52] and stretchable pyroelectrics [53] renders our whole device concept stretchable, which makes for greater similarity to human skin – the natural role model for large-area sensors [1-4]. Lipomi et al. fabricated transparent conductive films of PEDOT:PSS on stretchable substrates [51] which retain significant conductivity at up to 188% strain. Textile electrodes made of PEDOT:PSS [54] or carbon nanotube composites [55,56] in combination with pyroelectric PVDF fibers [29] might enable fabrics based on our concept in the future. Combining a biocompatible pyroelectric material such as hydroxyapatite thin films [57] with resistive silver or gold films [58] might result in an environmentally friendly and biocompatible sensor technology for light-point localization. Transparent conductive cellulose paper with embedded silver nanowires (AgNWs) might serve as an environmentally friendly alternative electrode material based on natural biomass [46]. Replacing pyroelectric with (organic) photoactive materials [14] might result in low-cost large-area devices with the potential to become ultrathin [60]. However, one of the electrodes needs to possess significant sheet resistance to allow stimulus localization [15,16,50]. Newly developed composites of PVDF [59] and PEDOT:PSS [21,43,45,47,52] might enable higher sensitivity and/or tighter connection between electrodes and electroactive materials for use in highly reliable and robust devices. Low-cost transparent films made of PEDOT:PSS/Ag processed directly from solution improved the efficiency of organic-Si hybrid solar cells, but these devices lacked flexibility [47]. The hybrid-type transparent electrodes in [43] were fabricated by coating carbon nanotubes with PEDOT:PSS films using spin coating or electrophoretic deposition. This type of flexible electrode shows good transmittance and suitable sheet resistances, and can withstand 30 000 bending cycles. The transparent conductive electrode film made from a composite of PEDOT:PSS and exfoliated graphene presented in [45] allows deposition by spray-coating not only onto flexible, stretchable and paper substrates, but also onto photoactive substrates.
2. Design of Transparent, Flexible, Thin Sensor Surfaces and Sensor Strips for Passive Light-Point Localization

2.1. Sensor Surfaces for Passive Light-Point Localization in Two Spatial Dimensions

We designed a transparent, thin, flexible sensor surface for passive light-point localization (Figures 1(a) and 1(b)) that consists of a pyroelectric PVDF film in the $\beta$-phase covered by large-area PEDOT:PSS electrodes. The PVDF film is highly flexible, transparent across the visible range of light, and thin, with commercially available thicknesses between 9 $\mu$m and 50 $\mu$m. The highly conductive PEDOT:PSS electrode at the top is formed using a PEDOT:PSS solution with dimethyl sulfoxide (DMSO) as additive. For the resistive bottom PEDOT:PSS electrode, a thin layer of a less conductive PEDOT:PSS solution was used. Electrical ports were fixed to the corners of the device. When the beam of a red laser diode is applied to the sensor surface, the PVDF film heats up locally due to the absorption by the PEDOT:PSS layer, and the pyroelectric effect results in the generation of electrical charges. The charges diffuse to the electrical ports at the corners of the device, where the corresponding electrical signals are measured. The beam of the red laser diode can be localized unambiguously on the sensor surface because the signals have different absolute values and phases depending on the distances between the position of the laser beam and the electrical ports. In order to increase the signal-to-noise ratio, the beam of the red laser diode was intensity-modulated. The resulting pyroelectric signals were detected by a phase-sensitive lock-in amplifier.

2.2. Sensor Strips for Passive Light-Point Localization in One or Two Spatial Dimensions

Further, we fabricated a transparent, flexible, thin sensor strip for passive light-point localization (Figure 1(c)). This in combination with an equivalent circuit based on transmission line theory [16,61] (Figure 1(d)) serves as a one-dimensional model system to illustrate our concept [15,16]. Each element of the sensor strip is modeled by a series resistance and a parallel capacitance, which results in a low-pass filter behavior. The design and the working principle are the same as described in Subsection 2.1. In place of a PVDF film, we used a strip for sensor fabrication, and rather than point-shape contacts, we used lines of conductive silver paste to connect the electrical ports to both ends of the device. The sensor strip on its own is suitable for light-point localization in one spatial dimension. Alignment of several strips side by side enables stimulus localization in two dimensions. The lateral resolution of the resulting device is determined by the width of a single sensor strip.

3. Materials, Fabrication and Measurement Setup

3.1. Materials and Fabrication

A mono-oriented, poled thin film of PVDF in the $\beta$-phase (Piezotech S.A.S, France; [62]) was used for sensor fabrication (Figure 2). According to the specifications of the manufacturer, the film thickness was $t = (25 \pm 5\%) \mu$m, and the material possessed a pyroelectric coefficient of $p_3 = (-25 \pm 25\%) \mu$C/(m$^\circ$K) in
the poling direction. The higher the pyroelectric coefficient $p$ of the functional PVDF film, the greater are the magnitudes of the electrical signals measured. The material was soft with a Young’s modulus $Y = (3200 \pm 20\%)$ MPa and low-weight with a density of $\rho = 1.8 \text{ kg/m}^3$.

First, the film was cleaned (Figure 2(a)) in three steps: by an ultrasonic bath (1) in distilled water for 3 to 5 minutes, (2) in acetone for 15 minutes, and (3) in isopropyl alcohol for 15 minutes. We then dried the film using a jet of compressed air. Subsequently, we treated this first surface with argon plasma ($100 \text{ W, } 3 \cdot 10^{-2} \text{ mbar, peak voltage of } 210 \text{ V}$) for around two minutes (Figure 2(b)); this reduced the contact angle of water on the PVDF surface [36] as described in Subsection 3.2 and made the hydrophobic surface more hydrophilic. Further, this improved the adhesion of the PEDOT:PSS electrodes, since we used an aqueous dispersion for electrode fabrication.

We then deposited the conductive, large-area electrode onto the modified PVDF surface (Figure 2(c)). Immediately after the surface modification step, a highly conductive aqueous dispersion of PEDOT:PSS (Clevios™ PH 1000, Heraeus Precious Metals GmbH, [63]) with 3% to 5% dimethyl sulfoxide (DMSO) was spin-coated onto the film at 1000 rpm for twenty seconds. Any visible particles in the solution were removed with the help of a syringe filter. Next, the transparent polymer electrode was cured for two hours at 60°C. According to the datasheet, the “Clevios™ PH 1000” aqueous dispersion of PEDOT:PSS has a specific conductivity of 850 S/cm measured on the dried coating after the addition of 5% DMSO. The solution has a viscosity of 15-50 mPas.

We proceeded to activate the second surface of the PVDF film, again using Ar plasma ($100 \text{ W, } 3 \cdot 10^{-2} \text{ mbar, peak voltage of } 210 \text{ V}$) for around two minutes (Figure 2(d)). Immediately after this step, the resistive PEDOT:PSS electrode was deposited onto the PVDF film (Figure 2(e)). To this end, a moderately conductive aqueous dispersion of PEDOT:PSS (Clevios™ PH 500, Heraeus Precious Metals GmbH, [63]) and distilled water at a mixing ratio of 1 : 1 was spin-coated at 1000 rpm for two seconds onto the polymer film. Then the transparent polymer electrode was cured for two hours at 60°C. According to the datasheet, the “Clevios™ PH 500” aqueous dispersion of PEDOT:PSS has a specific conductivity of 300 S/cm measured on the dried coating after the addition of 5% DMSO. The viscosity of the solution is 8-25 mPas.

Finally contacts were added to the sensor by following this procedure (Figure 2(f)): (1) We soldered a litz wire onto a piece of adhesive copper tape, (2) then glued the adhesive copper tape onto the PEDOT:PSS electrode, and (3) established a conductive connection between the copper tape and the PEDOT:PSS electrode using conductive silver paste. The litz wires had to be highly flexible in order to prevent mechanical distortion of the sensor strips. We mounted the contacts on both ends of the device.

For characterization purposes, we clamped the sensor surface between a plate with a copper film and spring-loaded electrical contact pins with round copper ends; we additionally improved the electrical contact to the copper by means of conductive silver paste.

### 3.2. Material Characterization

We characterized PVDF surfaces by contact angle measurements and by atomic force microscopy (AFM) before and after Ar plasma treatment. Furthermore we studied PVDF with deposited PEDOT:PSS by AFM and measured the transparency, i.e. the transmittance of the fabricated sensors. In addition some
basic tests on flexibility and on reliability of the sensors have been performed. All specimens were prepared as described in Sect. 3.1.

For contact angle measurements we applied droplets of distilled water with a volume of 2 µl using a dosing rate of 1 µl/s (measurement device and software: OCA-series with the SCA20 software for OCA). We measured directly after placing the droplets onto the surface. We chose the contact line manually and used the ellipse fitting method. The contact angle of water on untreated PVDF surface was $90^\circ \pm 3^\circ$ (± 3.6 %; ten droplets). Directly after surface modification by low-energy Ar plasma (100 W), a contact angle of $32^\circ \pm 1^\circ$ (± 4.6 %; ten droplets) was recorded. This proved that the treatment with Ar plasma rendered the PVDF surface hydrophilic, lowering the contact angle by about 60° or 64 %. The achieved reduction of the contact angle was about 20° higher than the one reported in [36], where surface modification of PVDF by low-energy Ar plasma was studied. Therefore the applied procedure makes PVDF surfaces suitable for deposition of aqueous dispersion of PEDOT:PSS. We found no differences between plasma-treated biaxially stretched and mono-oriented PVDF films (both Piezotech S.A.S, France; [62]).

To analyze the surface morphology and roughness we used AFM (Nanosurf MobileS all in one microscope stabilized on a TS-150 table). We characterized PVDF surfaces before and after plasma treatment as well as PVDF with deposited PEDOT:PSS. Surface areas of 20 µm x 20 µm, 40 µm x 40 µm and 80 µm x 80 µm size were studied in the contact mode. We applied the freeware Gwyddion for topography data analysis such as the calculation of the roughness average $R_a$ and the root mean square roughness $R_{rms}$. On the investigated scales we found no significant differences in the surface morphology and in the surface roughness for all tested specimens. All substrates were very smooth with roughness parameters $R_a$ and $R_{rms}$ in the range of tenth of nanometers (mono-oriented PVDF films: $R_a = 36\text{ nm} \pm 7\text{ nm}$, $R_{rms} = 46\text{ nm} \pm 8\text{ nm}$, seven images; mono-oriented PVDF films after plasma treatment: $R_a = 43\text{ nm} \pm 7\text{ nm}$, $R_{rms} = 57\text{ nm} \pm 9\text{ nm}$, eight images; mono-oriented PVDF films + PEDOT:PSS: $R_a = 33\text{ nm} \pm 6\text{ nm}$, $R_{rms} = 45\text{ nm} \pm 9\text{ nm}$, seven images).

The transparency of an exemplary sensor surface on a flexible sample holder is demonstrated in Figure 1b. We measured the transmittances of PVDF films as well as of the characterized sensor strip and sensor surface by a spectrophotometer (UV-VIS Varian Cary 500) in the double beam mode. The transmittances were recorded from 350 nm to 800 nm completely covering the visible range of light (approx. between 380 nm to 750 nm). The transmittances of biaxially stretched and mono-oriented PVDF thin films with thicknesses of 25 µm and 40 µm, respectively, increase from about 85 % at 350 nm to about 92 % at 800 nm. The transmittances of the sensors are between 67 % and 76 % across the measurement range for both devices. They are highest between 650 nm and 750 nm. Later devices are even more transparent, but we did not characterize them as accurate with regard to other properties. These transmittance values are similar to the ones reported for transparent devices in literature, e.g. a bit higher than the transmittance of the printable, transparent, flexible touch panels described in [5].

The flexibility of an exemplary sensor surface on a flexible sample holder is demonstrated in Figure 1b. All fabricated sensors could be easily wrapped around a cylinder with a diameter of 1.27 mm. A change of less than 0.5 % occurred in the measured electrode resistances (Fluke 175 true RMS multimeter) of the characterized sensor strip after performing 50 bending cycles manually over a bending radius of 19 mm. We think that this change is due to aging of the contacts between the conductive silver paste and the PEDOT:PSS layer. The adhesion of the conductive PEDOT:PSS layer to the PVDF film was tested by
performing the tape test (Scotch tape) on an exemplary sensor strip with an area of 2.04 cm². The increase in the resistance before and after the tape test was 4% (Fluke 175 true RMS multimeter).

3.3. Measurement Setup and Procedure
The fabricated transparent devices were characterized using the beam of a red laser diode (Laser Components; AlGalnP Visible Laser Diode, ADL-65055TL, [64]) with a typical peak wavelength of $\lambda = 655$ nm and a light output power of $P_0 = 5$ mW in continuous mode. A similar type of laser diode is used for laser pointers. The beam of the laser diode was intensity-modulated with a frequency $f_0$ using a laser switch (iC Haus, iC-HK, laser switch, [65]).

The sensor strip of 3.5 cm x 0.8 cm size was mounted on a manual translation stage. The beam of the modulated red laser diode was positioned at points that were 0.5 mm apart along the axis of the sensor strip for a total length of 2 cm. At each point, the pyroelectric voltage response of the sensor strip to the modulated beam of the red laser diode was measured at the frequency $f_0 = 20$ Hz by two lock-in amplifiers (DSP Lock-In SR830, $R_m = 10$ MΩ, $C_m = 25$ pF), where the response signals were simultaneously recorded at both ends of the sensor strips. During measurement, one lock-in amplifier provided a TTL signal for the laser switch that also served as the reference signal for both lock-in amplifiers. The reference signal was passed on to the second lock-in amplifier by the TTL sync output at the rear panel of the first lock-in amplifier.

The measurement setup and procedure for the 2D sensor surface resembled those for the sensor strip. The sensor surface of 3 cm x 3 cm size was mounted on a manual x-y translation stage. The beam of the modulated red laser diode was positioned at points 1 cm apart in a matrix in order to characterize the sensor surface with a total area of 3 cm x 3 cm. At each point, a lock-in amplifier (DSP Lock-In SR830, $R_m = 10$ MΩ, $C_m = 25$ pF) was successively connected to the sensor output at each corner of the sensitive sheet in order to measure the pyroelectric sensor response. During measurement, the other three electrical outputs at the corners of the sensor surface were connected to parallel circuits of a resistor and a capacitor which imitated the inputs of lock-in amplifiers. The lock-in amplifier provided a TTL signal for the laser switch that also served as the reference signal for the lock-in amplifier.

4. Measurement Results and Discussion
We characterized the response of the transparent pyroelectric sensor strip to the beam of a red laser diode (Figure 3). As we proposed, the amplitudes (Figure 3) correlate significantly with the position of the beam along the axis of the sensor strip $x$ which allows us to localize the stimulus.

The sensor strip was characterized by measuring the absolute voltage values at the electrical ports located at its ends, positioning the beam of a frequency-modulated red laser diode along its axis in 0.5 mm steps (Figure 3(a)). We used a modulation frequency of $f_0 = 20$ Hz. The PEDOT:PSS electrode absorbs the laser light, and thus the laser heats up the pyroelectric PVDF film, which creates a pyroelectric charge at the electrodes $\Delta Q(t) = p_2 \Delta A \Delta T(t) = Q_{pyro,f_0} \exp(i2\pi f_0 t)$ at the position of the laser beam. In the formula, we used the sensor definition of pyroelectricity, as is common for polymers [27,66]. Furthermore, we translated the charge from time space to frequency space, since the lock-in amplifier
measures the response of the system only at the excitation frequency $f_0$. The pyroelectric charge is proportional to (i) the pyroelectric coefficient $p_3 = (-25 \pm 25\%) \mu C/(m^2K)$, (ii) the heated area of the material $\Delta A$ and (iii) the temperature change $\Delta T$. In response to the laser beam, pyroelectric signals with an oscillation frequency $f_0$ are generated at the outputs of the sensor strip. At each position of the laser beam, the absolute values of the output signals were measured at $f_0$ by the lock-in amplifiers. The smaller the distance between the stimulus and the electrical port, the higher is the signal amplitude.

Signal quality can be further increased by normalization (Figures 3(b) and 3(c)), thus making the signals independent of the generated pyroelectric charge $Q_{\text{pyro},f_0}$ and compensating for space-dependent inhomogeneities due to variations in absorption by the PEDOT:PSS electrode or spatial variations in the pyroelectric coefficient. Furthermore, the resulting signals are, to some extent, independent of the magnitude of the applied stimulus (i.e., of the power and size of the laser beam and of its distance to the device). Using normalization procedures, we improved the approximate spatial resolution of the device from about 2 - 2.5 mm to below 1 mm.

The measurement values of the sensor strip were normalized as proposed in [15,16]: First the position-sensitive voltage signals at each end of the sensor strip $|U_{1,f_0}(x)|$ and $|U_{2,f_0}(x)|$ are divided by the sum of the voltage signals of both ends of the device (Figure 3(b)):

$$
\bar{U}_{1,f_0,n}(x) = \frac{|U_{1,f_0}(x)|}{|U_{1,f_0}(x)| + |U_{2,f_0}(x)|}, \quad \bar{U}_{2,f_0,n}(x) = \frac{|U_{2,f_0}(x)|}{|U_{1,f_0}(x)| + |U_{2,f_0}(x)|}. \quad (1)
$$

This normalization procedure leads to values which depend nearly linearly on the position of the laser beam on the sensor surface; this is advantageous for signal processing.

Second, the voltage signal at one end $|U_{1,f_0}(x)|$ is divided by the voltage signal at the other end $|U_{2,f_0}(x)|$ and vice versa (Figure 3(c)):

$$
\bar{U}_{1,f_0,n}(x) = \frac{|U_{1,f_0}(x)|}{|U_{2,f_0}(x)|}, \quad \bar{U}_{2,f_0,n}(x) = \frac{|U_{2,f_0}(x)|}{|U_{1,f_0}(x)|}. \quad (2)
$$

This second normalization procedure increases the range of values compared to the first normalization procedure. However, signal processing becomes more difficult, as the values depend nearly exponentially – and not nearly linearly – on the position of the laser beam on the sensor surface.

We also applied the normalization procedure to the measurement sensor surface data (Figure 4). The absolute voltage amplitudes measured were interpolated in order to obtain 2D signal landscapes. As proposed by our concept, the measurement data is position-sensitive, allowing stimulus localization in both spatial coordinates ($x$ and $y$). Figure 4 shows the normalized measurement data and the interpolated signal landscapes of: (a) the left rear electrical port (Ch 1), (b) the right rear electrical port (Ch 2), (c) the left front electrical port (Ch 4), and (d) the right front electrical port (Ch 3). The smaller the distance between the electrical port and the stimulus, the stronger is the signal.
As described above, signal normalization is necessary to make the signals independent of the magnitude of the applied stimulus (i.e., of the pyroelectric charge $Q_{\text{pyro},f_0}$). As suggested in [12], the signals were normalized analogously to the first procedure applied to the measurement data of the sensor strip (Equation 1): We divide the signal at each electrical port of the device $|U_{i,f_0}(x,y)|$ by the sum of the signals at all ports:

$$\bar{U}_{i,f_0}(x,y) = \frac{|U_{i,f_0}(x,y)|}{|U_{1,f_0}(x,y)|+|U_{2,f_0}(x,y)|+|U_{3,f_0}(x,y)|+|U_{4,f_0}(x,y)|}; \quad i = 1,2,3,4. \quad (3)$$

In [12], a possible algorithm for stimulus localization based on the normalized signal landscapes was described: The position of a stimulus can be determined (1) by recording the signals in response to the stimulus at the electrical ports at the four corners of the device, (2) by normalizing the signals according to Equation 3 and (3) by comparing the normalized signals +/- a threshold to the normalized signal landscapes, yielding the position of the stimulus on the sensor surface.

5. Conclusions and Outlook

We have presented thin (< 26 $\mu$m), highly flexible and transparent sensor surfaces and sensor strips for passive light-point localization. We employed only two polymeric materials – a thin film of pyroelectric PVDF polymer and large-area electrodes made of conductive PEDOT:PSS polymer. In order to demonstrate their position sensitivity, we characterized the fabricated sensors by their electrical signals in response to a red laser diode. Our results prove the feasibility of our approach. The advantages of the presented sensors for light-point localization are: they are simple in design; electronics are placed only at the edges of the device; and there is no need for an external power supply and to divide the large-area sensor surfaces into numerous individual sensing elements. Furthermore, little material is required, and the sensors are low-weight and can be rolled up for transport. Since they can be fabricated using low-cost polymer materials and simple fabrication methods such as roll-to-roll-processing, our sensors are suitable for large-scale mass production. They can be mounted on flexible displays, windows or automotive windshields, acting as large-area human–machine interfaces for what is called “ambient intelligence”. Further, textiles can be woven using the transparent sensor strips. Improvements could possibly be achieved by using an even thinner PVDF film (e.g., with 6 $\mu$m thickness) or by printing the whole device using pyroelectric poly(vinylidene fluoride - trifluoroethylene) (P(VDF-TrFE)) instead of PVDF.

Acknowledgements

This research was funded in part by the Austrian Research Promotion Agency (FFG) under contract number 825348/K-Licht. Dr. Jürgen Schoeftneracknowledges support from the Austrian Science Fund FWF via the project P 26762-N30. Furthermore, financial support of the ERC Advanced Grant Soft-Map and of the COMET K2-Center ACCM is gratefully acknowledged. The authors thank Dr. Reinhard Schwödiauer and Dr. Petr Bartu for stimulating discussions, MTA Agnes Weth for AFM imaging, a.
Univ. Prof. Dr. Johannes Heitz for transmittance measurements, and Dr. Martin Heinisch for photographing the device.
Gerda Buchberger received her Dipl.-Ing. (M.Sc.) in Technical Physics from the Johannes Kepler University Linz (JKU), Austria, in 2010. In her master thesis she developed concepts for flexible touchpads and keyboards based on cellular ferroelectrets. Currently she is the project leader of an industrial project at the Institute of Biomedical Mechatronics and a Ph.D. student at the Institute for Microelectronics and Microsensors at the JKU. Her research interests include soft actuators and flexible sensors based on functional polymers, cooling techniques for high power electronics and biomimetic microfluidics.

Ruxandra Aida Barb received her Dipl.-Ing. (M.Sc.) in Physics Engineering from the Transilvania University of Brasov, Romania, in 2007. In her diploma thesis she designed a four-point probe set-up suitable for precision surface conductivity measurement and performed surface-resistivity measurements on thin films. Ruxandra Aida Barb worked as a project assistant at the Transilvania University of Brasov and then at the Johannes Kepler University Linz (JKU), Austria. At the moment she is a co-worker and a Ph.D. candidate at the Institute of Applied Physics at the JKU. Her research interests include modification of polymer surfaces for applications in bio-technologies.

Juergen Schoeftner received his Dipl.-Ing. (M.Sc.) in Mechanical Engineering – Economics from the Vienna University of Technology, Austria, in 2006 and his Ph.D. in Technical Sciences at the Johannes Kepler University Linz (JKU), Austria, in 2011, respectively. Before his academic career he was employed in the automotive industry (hofer powertrain and hofer powertrain f&e, AVL List GmbH). Since 2011 he works at the Institute of Technical Mechanics at the JKU. Currently he is a research assistant at the Institute of Technical Mechanics at the JKU. He performs simulations in the research areas of coupled system mechanics, driveline phenomena and vibration control.
Siegfried Bauer received the Master and Ph.D. degrees in physics from the Technical University in Karlsruhe in 1986 and 1990, respectively. In 1992 he joined the Heinrich Hertz Institute for Communication Engineering in Berlin, Germany. In 1996 he earned the Habilitation Degree from the University of Potsdam. In 1997 he became a Professor of Experimental Physics at the Johannes Kepler University Linz, Austria. Since 2002 he has been head of the Soft Matter Physics Department. Dr. Bauer's research is devoted to functional soft matter and its application to flexible and stretchable electronics and to energy harvesting.

Wolfgang Hilber obtained his Dipl.-Ing. (M.Sc.) in Technical Physics and his Ph.D. in Technical Sciences at the Johannes Kepler University Linz, Austria, in 1993 and 1997, respectively. His professional experiences include research projects at the Carinthian Tech Research (CTR GmbH) in Villach, Austria, at the Johannes Kepler University Linz, Austria, and in the R&D division of E+E Electronics GmbH, Austria. He conducted development projects in the field of thin-film sensor technology. Since 2006 he is an assistant professor at the Institute for Microelectronics and Microsystems at the Johannes Kepler University Linz in the field of microsensors and microfluidics.

Bernhard Mayrhofer graduated from a secondary technical school for electronics and communication engineering in 2000. Since 2002 he is employed at the Institute for Microelectronics and Microsystems, and works there as a technician for electronics supporting Ph.D. and diploma students. In 2006 he started to study alongside his job and received his Dipl.-Ing. (M.Sc.) in Mechatronics and Economics from the University of Applied Science Wels, Austria, in 2010. His main working fields are the development of readout electronics for liquid sensors and 3D-rapid prototyping.
Bernhard Jakoby obtained his Dipl.-Ing. (M.Sc.) in Communication Engineering and his Ph.D. in Electrical Engineering from the Vienna University of Technology (VUT), Austria, in 1991 and 1994, respectively. From 1996 to 2001 he worked at the Delft University of Technology and at the Robert Bosch GmbH in Germany. In 2001 he joined the Industrial Sensor Systems group of the VUT as an associate professor. In 2005 he was appointed full professor for Microelectronics and Microsensors at the Johannes Kepler University Linz, Austria. He is currently working in the field of liquid sensors and monitoring systems.
References


Figure 1: (a) Schematic diagram of a transparent, flexible, thin sensor surface with resistive electrodes for passive stimulus-localization. The sensor is based on only two functional polymers: pyroelectric poly(vinylidene fluoride) (PVDF) polymer and conductive poly(3,4-ethylene dioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS) polymer. (b) Photograph of a transparent, flexible device that is based on our concept; the device is fixed to a sample holder. (c) Design of a transparent, flexible, thin sensor strip with resistive electrodes for passive light-point localization. (d) Equivalent circuit diagram of the transducer [15,16]. Resistances and capacitances per unit length dominate in the fabricated devices and lead to low-pass filter behavior.
Figure 2: Fabrication process of thin, flexible, transparent sensor surfaces for light-point localization. (a) Cleaning of the PVDF thin film. (b) Activation of the top surface by low-energy Ar plasma. (c) Spin coating of highly conductive PEDOT:PSS with 3% to 5% DMSO for the conductive electrode (Clevios PH 1000). (d) Surface modification of the bottom surface using low-energy Ar plasma. (e) Spin coating of a thin layer of PEDOT:PSS (Clevios PH 500) with distilled water at a 1:1 ratio for the resistive electrode. (f) Contacts by means of silver paste, adhesive copper tape and flexible wires soldered to the copper adhesive tapes or by clamping.
Figure 3: Position-sensitive measurement data from the transparent pyroelectric sensor strip. (a) Absolute voltage values measured at the left end $U_{1,x}(x)$ (red circles) and at the right end $U_{2,x}(x)$ (blue squares) of the pyroelectric sensor strip versus position of the light point. (b, c) Normalization procedures lead to signals which are independent of the pyroelectric charge; thus, space-dependent inhomogeneities due to variations in the absorption by the PEDOT:PSS electrode or spatial variations in the pyroelectric coefficient are compensated for. The resulting voltage signals for the left end (red circles) and the right end (blue squares) are plotted (b) on a linear scale for the first normalization procedure ($\bar{U}_{1,n}(x)$ and $\bar{U}_{2,n}(x)$) and (c) on a logarithmic scale for the second normalization procedure ($\bar{U}_{1,n}(x)$ and $\bar{U}_{2,n}(x)$).
Figure 4: Position-sensitive measurement data from the transparent, pyroelectric sensor surface. The normalized absolute voltage amplitudes $\tilde{V}_{i}(x,y)$ for the electrical ports $Ch_i = 1,2,3,4$ are shown as blue spheres and were interpolated to obtain the 2D signal landscapes. Normalized measurement data and interpolated signal landscapes of (a) the left rear electrical port (Ch 1), (b) the right rear electrical port (Ch 2), (c) the left front electrical port (Ch 4), and (d) the right front electrical port (Ch 3).