Cellular Ferroelectrets for Flexible Touchpads, Keyboards and Tactile Sensors

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***Abstract*— Cellular polypropylene ferroelectrets are flexible and conformable transducer materials with a dominant longitudinal piezoelectric effect. They can be used in a wide range of pressure sensing applications. We present concepts for position sensitive touchpads and keyboards based on piezoelectric materials with a dominant longitudinal piezoelectric effect. As large area electrodes are superimposed onto the ferroelectret and combined with electronics at the edges, complex sensor matrices are avoided. We use a ferroelectretic detector stripe as a model system for the theoretical description of the touchpad and show that this detector can be treated mathematically analogous to a transmission line. We present the solutions of the corresponding differential equations under the appropriate boundary conditions and experimental results that are in agreement to them. For the flexible, ferroelectretic keyboard we use a binary or balanced ternary coding technique profiting from the polarization of the ferroelectret.**

I. INTRODUCTION

Cellular ferroelectrets [1,2] are thin electroactive polymer foams which can be used for large area transducer applications [2], [4-6]. They are soft, flexible and conformable, and they can be mass-produced with simple technologies. Cellular ferroelectrets show a strong longitudinal piezoelectric effect and small transverse piezoelectricity [7-9]. As bending piezoelectricity can be neglected they can be used for flexible and conformable pressure sensing elements. Interesting applications are flexible, ultrathin touchpads [10] and keyboards based on the presented concepts. Such devices are simple in their design and need electronic reading circuitry only at the edges. They allow a costumizable layout [11] since sensor matrices are avoided. In [10] a four-channel ferroelectretic touchpad with an area of 10x10 cm^2 as shown in Fig. 1(a) has been investigated experimentally applying a defined force in a grid with 23x23 elements. It consists of a 70 μm thick film of cellular polypropylene ferroelectret that is placed between two electrodes. One electrode is conductive and grounded, whereas the other is highly resistive. The voltage between the electrodes is measured at the corners of the device. If a

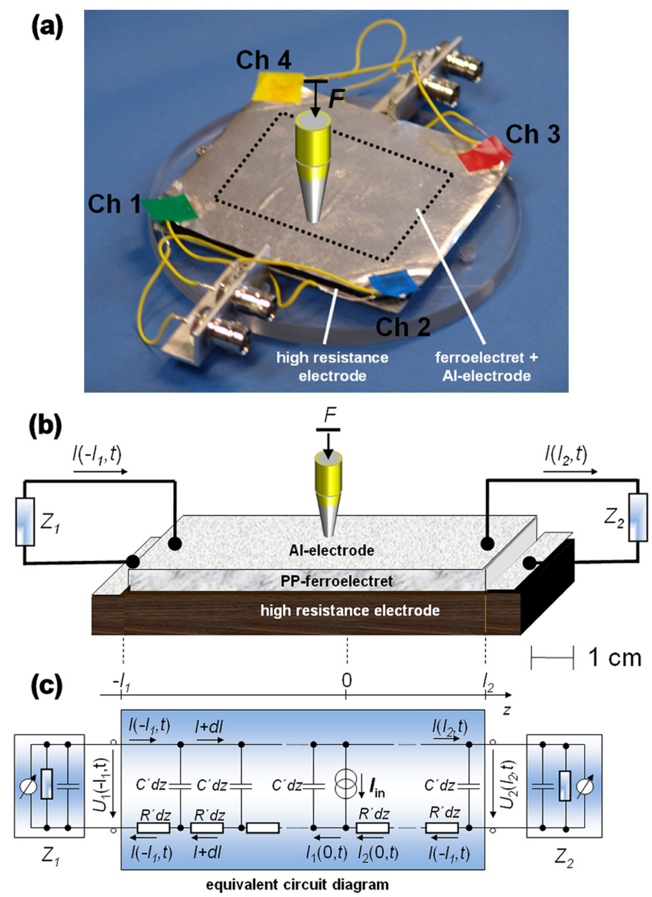

Figure 1. (a) Photo of a ferroelectret touchpad with four output terminals. (b) Scheme of a position sensitive detector stripe and (c) equivalent circuit diagram of the transducer.

force is applied, electric charges are generated by the piezoelectric effect which diffuse to the electrical ports at the corners of the device. The amplitudes of the measured signals are determined by the distance between the location of the applied force and the electrical port. The signals have considerably different amplitudes and therefore the touch

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position can be identified. It can for example be determined by a threshold algorithm without knowing anything about the physical behavior of the touchpad [10]. To find out more about the physics a detector stripe has been designed analogous to the touchpad and has been investigated both theoretically and experimentally. A scheme of the position sensitive detector stripe is shown in Fig. 1(b).

II. THE DETECTOR STRIPE AS A MODEL SYSTEM

A. The Detector Stripe as an Analogon to a Two-Wire Transmission Line

The detector stripe can be treated mathematically as a two-wire transmission line, if the electrodes and the polymer are homogeneous enough and the distance of the electrodes i.e. the thickness and the width of the ferroelectretic film are small compared to the length of the detector. In this case the two electrodes correspond to the wires of the transmission line and the ferroelectret to the dielectric medium that separates the conductors. If a small elementary section dz of this line is considered, a quasi-stationary treatment will be sufficient. The transmission line is modeled of an infinite series of elementary sections. Per unit length the line has an inductance L', a capacitance C', a resistance R' as well as a leakage conductance between the wires G'.

B. Differential Equations

According to the transmission line model [12] one gets a pair of coupled differential equations which describe the voltage and current distributions along the transmission line with respect to distance z and time t

$$-\frac{\partial V}{\partial z} = R'I + L'\frac{\partial I}{\partial t} \tag{1}$$

$$-\frac{\partial I}{\partial z} = G'V + C'\frac{\partial V}{\partial t}. \tag{2}$$

If (1) is differentiated with respect to z and (2) inserted in it, the telegraphic equation for the voltage distribution is obtained

$$\frac{\partial^2 V}{\partial z^2} - L'C'\left[\frac{\partial}{\partial t} + \frac{1}{2}\left(\frac{R'}{L'} + \frac{G'}{C'}\right)\right]^2 V + \frac{L'C'}{4}\left(\frac{R'}{L'} + \frac{G'}{C'}\right)^2 V = 0. \tag{3}$$

The same equation is also valid for the current. Equation (3) can be simplified by the Fourier transformation with respect to time and one gets with the propagation constant $\gamma = \sqrt{(R' + i\omega L')\cdot(G' + i\omega C')}$

$$\begin{aligned} \frac{\partial^2 V_\omega(z)}{\partial z^2} - \gamma^2 V_\omega(z) = 0 \\ \frac{\partial^2 I_\omega(z)}{\partial z^2} - \gamma^2 I_\omega(z) = 0. \end{aligned} \tag{4}$$

The solutions of (4) are waves

$$\begin{aligned} V(z,t) &= \int \left(A_\omega \cdot e^{\gamma z} + B_\omega \cdot e^{-\gamma z}\right)\cdot e^{i\omega t} d\omega \\ I(z,t) &= \int \frac{1}{Z_0}\cdot\left(-A_\omega \cdot e^{\gamma z} + B_\omega \cdot e^{-\gamma z}\right)\cdot e^{i\omega t} d\omega \end{aligned} \tag{5}$$

with amplitudes which are connected according to (1) and (2) by the characteristic wave impedance $Z_0 = \sqrt{(R' + i\omega L')/(G' + i\omega C')}$.

C. Equivalent Circuit Diagram and Boundary Conditions

The voltage amplitudes at both ends of the detector stripe are measured by an oscilloscope whose input impedance determines therefore the boundary conditions at the detector ends. The touch point is modeled as a current source with a current strength of I_{in}. It marks the zero-point of the used coordinate system. For a first qualitative approximation we assume a single excitation frequency (ω= 0.55 Hz). The distance of the right end of the detector stripe to the touch point is denoted by l_2 and that of the left end by l_1. The length of the detector stripe is therefore $l = l_1 + l_2$. The complete equivalent circuit diagram is depicted in Fig. 1(c). The boundary conditions which current and voltage have to fulfill are

$$\begin{aligned} V_1(0) &= V_2(0) \\ I_{\text{in}} &= I_1(0) - I_2(0) \\ Z_1 &= -V_1(-l_1)/I_1(-l_1) \\ Z_2 &= V_2(l_2)/I_2(l_2). \end{aligned} \tag{6}$$

To solve (5) under the above boundary conditions and in the case of a single excitation frequency the following ansatz is made for negative z-values $(-l_1 \le z < 0)$

$$\begin{aligned} V_1(z) &= V_{11}e^{\gamma z} + V_{12}e^{-\gamma z} \\ I_1(z) &= 1/Z_0\left(-V_{11}e^{\gamma z} + V_{12}e^{-\gamma z}\right) \end{aligned} \tag{7}$$

and a similar one for positive z-values $(0 \le z \le l_2)$

$$\begin{aligned} V_2(z) &= V_{21}e^{\gamma z} + V_{22}e^{-\gamma z} \\ I_2(z) &= 1/Z_0\left(-V_{21}e^{\gamma z} + V_{22}e^{-\gamma z}\right). \end{aligned} \tag{8}$$

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D. Matrix Equation and Solutions

Ansatz (7) and (8) leads to the matrix equation

$$\begin{pmatrix} 1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 \\ \left(1-\frac{Z_1}{Z_0}\right)e^{-\gamma l_1} & \left(1+\frac{Z_1}{Z_0}\right)e^{+\gamma l_1} & 0 & 0 \\ 0 & 0 & \left(1+\frac{Z_2}{Z_0}\right)e^{\gamma l_2} & \left(1-\frac{Z_2}{Z_0}\right)e^{-\gamma l_2} \end{pmatrix}\begin{pmatrix} V_{11} \\ V_{12} \\ V_{21} \\ V_{22} \end{pmatrix} = \begin{pmatrix} 0 \\ I_{in}Z_0 \\ 0 \\ 0 \end{pmatrix}. \quad (9)$$

Substituting the solutions of (9) in (7) and (8) gives for negative z-values $(-l_1 \le z < 0)$

$$V_1(z) = -\frac{I_{\text{in}}Z_0}{2}\cdot\frac{e^{-\gamma z}\left(e^{2\gamma(l_1+z)} - z_{W1}\right)\left(e^{2\gamma l_2} - z_{W2}\right)}{\left(e^{2\gamma l} - z_{W1}z_{W2}\right)}$$
$$I_1(z) = \frac{I_{\text{in}}}{2}\cdot\frac{e^{-\gamma z}\left(e^{2\gamma(l_1+z)} + z_{W1}\right)\left(e^{2\gamma l_2} - z_{W2}\right)}{\left(e^{2\gamma l} - z_{W1}z_{W2}\right)}. \quad (10)$$

for the voltage and current distributions along the detector stripe. For positive z-values $(0 \le z \le l_2)$. one has to exchange in (10) z for $-z$, z_{W1} for z_{W2} and l_1 for l_2. The reflection factors z_{W1} and z_{W2} are defined by $z_{Wi} = (Z_0 - Z_i)/(Z_0 + Z_i)$ with $i = 1,2$.

E. Experimental Results

Electrical ports are connected to the highly resistive electrode at both ends of the detector stripe. The conductive Al-electrode at the top of the ferroelectret is grounded. The detector stripe is mechanically fixed to a computer-controlled x, y-translation stage (Linos x.act), where a force of approximately 0.55 N is applied by an electromagnetic plunger with a diameter of 5 mm. A detector stripe with a length of 12 cm is actuated every 2 mm along its axis. The amplitudes of the transient voltage signals at both ends of the detector stripe are measured by an oscilloscope (Le Croy, Waverunner 6100A; 1 MΩ input resistance). The port voltages are given by

$$V_1(-l_1) = \frac{I_{\text{in}}Z_0}{2}\cdot\frac{e^{\gamma l_1}(-1+z_W)\left(e^{2\gamma l_2} - z_W\right)}{\left(e^{2\gamma l} - z_W^2\right)} \quad (11)$$

$$V_2(l_2) = \frac{I_{\text{in}}Z_0}{2}\cdot\frac{e^{\gamma l_2}(-1+z_W)\left(e^{2\gamma l_1} - z_W\right)}{\left(e^{2\gamma l} - z_W^2\right)}. \quad (12)$$

Comparing (11) and (12) with the measured voltage amplitudes the absolute values, $|V_1(-l_1)|$ and $|V_2(l_2)|$, have to be taken.

TABLE I. PARAMETERS

Parameter	***Value***	***Parameter***	***Value***
R' (measured)	≈ 2,8 GΩ/m	L', G'	Can be neglected.
C' (calculated)	≈ 16 nF/m	I_{in} (free)	≈ 90 nA

The piezo-current is a free parameter, while R', C', G' and L' have been either measured or calculated approximately to get Z_0 and γ. The respective parameters are shown in Table I. The reflection coefficient z_W has been calculated using the input impedance Z according to the specifications of the instrument. The experimental results together with the calculated values are shown in Fig. 2 (a). A unique position detection requires the elimination of the force-dependent piezo-current by normalization according to

$$V_{1,n}(-l_1) = \frac{|V_1(-l_1)|}{|V_1(-l_1)| + |V_2(l_2)|}$$
$$U_{2,n}(l_2) = \frac{|U_2(l_2)|}{|V_1(-l_1)| + |V_2(l_2)|}. \quad (13)$$

The normalized measurement data together with the calculated values are given in Fig. 2(b).

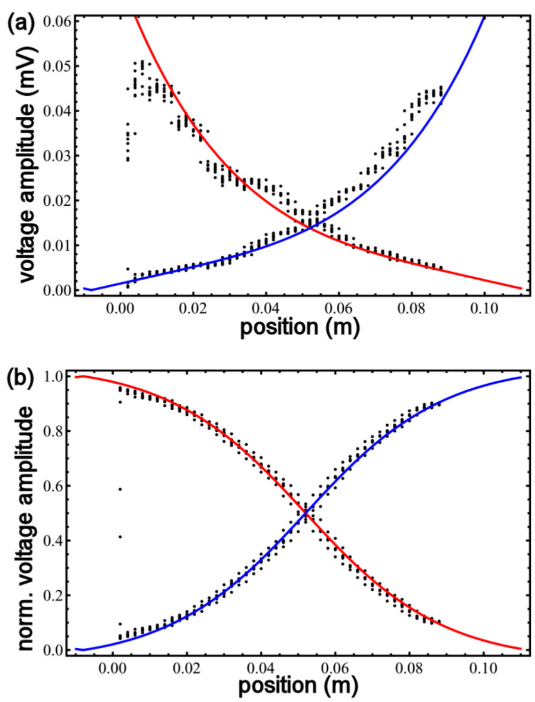

Figure 2. (a) Measured and calculated voltage amplitude at the left (red curve) and the right port (blue curve) versus distance, respectively. (b) Normalized voltage amplitudes versus distance for the left (red curve) and right port (blue curve). Ten measurement cycles have been performed.

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III. KEYBOARD OR KEYPAD USING A BINARY OR BALANCED TERNARY CODING CONCEPT

Monomorphs, bimorphs and multimorphs from polar polymer electrets have been studied for their usage in transducer and optical waveguide applications [13-15] and cellular polymer films have been stacked in order to improve the sensitivity of piezoelectretic microphones [16]. The combination of these two techniques, a stack of piezoelectric layers with alternating polarizations, enables a new coding concept for keyboards. The scheme of a binarily coded keyboard based on a piezoelectric material with a high d_{33}-coefficient is shown in Fig. 3. The pushed key can be determined measuring the transient voltage signals. They have positive or negative amplitudes depending on the polarization of the touched layers. The number of keys, k, that can be coded in such a way, scales with the number of functional layers, l, according to the power law

$$k = 2^l = \{2, 4, 8, 16, 32, 64, ...\}. \qquad (14)$$

Using the two polarization states of the ferroelectret and an inactive material, the keys can be coded ternarily, too. The respective number of keys, k, with l functional layers is

$$k = 3^l - 1 = \{2, 8, 26, 80, 242, ...\}. \qquad (15)$$

For many applications three or four layers are sufficient.

IV. CONCLUSION

We presented concepts for flexible and conformable touchpads, keyboards and tactile sensors. They can be further extended to flexible transparent devices using poly(vinylidenefluourid) with transparent conductive polymer electrodes e.g. PDOT. In combination with flexible organic displays flexible touchscreens can be fabricated. Additionally a theoretical model for a one-dimensional ferroelectretic touchpad has been developed that is in good accordance with the experimental data. With the help of that model the behavior of the ferroelectret touchpad can be better understood.

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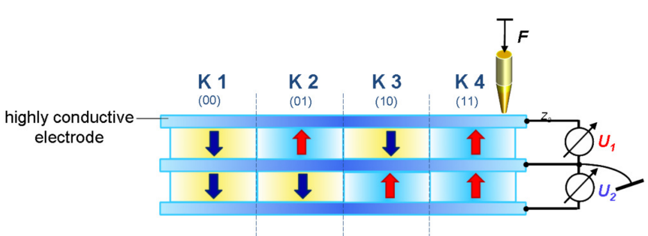

Figure 3. Scheme of a keyboard with four keys which are encoded binarily. As two layers are used four keys can be encoded at maximum.

REFERENCES

[1] M. Wegener and S. Bauer, "Microstorms in cellular polymers: A route to soft piezoelectric transducer materials with engineered macroscopic dipoles," ChemPhysChem, vol. 6, pp. 1014-1025, 2005.

[2] S. Bauer, R. Gerhard-Multhaupt, and G. M. Sessler, "Ferroelectrets: Soft electroactive foams for transducers," Physics Today, vol. 57, pp. 37-43, February 2004.

[3] M. Lindner, S. Bauer-Gogonea, S.Bauer, M. Paajanen, and J. Raukola, "Dielectric barrier micro-discharges: Mechanism for the charging of cellular piezoelectric polymers," J. Appl. Phys., vol. 91, no. 8, pp. 5283-5287, 2002.

[4] Diverse sensor applications based on ferroelectrets, e.g. a bed sensor, developed by the company EMFITech Ltd., Finland, www.emfit.com.

[5] Vandal-proof ferroelectretic keypads called EMFi keypads developed by the company SCREENTEC, Finland, www.screentec.com.

[6] I. Graz, M. Kaltenbrunner, C. Keplinger, R. Schwödiauer, S. Bauer, S. P. Lacour, and S. Wagner, "Flexible ferroelectret field-effect transistor for large-area sensor skins and microphones," Appl. Phys. Lett., vol. 89, no. 7, 073501, 2006.

[7] G. M. Sessler and J. Hillenbrand, "Electromechanical response of cellular electret films," Appl. Phys. Lett., vol. 75, pp. 3405-3407, 1999.

[8] G. S. Neugschandtner, R. Schwödiauer, M. Vieytes, S. Bauer-Gogonea, S. Bauer, J. Hillenbrand, R. Kressmann, G. M. Sessler, M. Paajanen, and J. Lekkala, "Large and broadband piezoelectricity in smart polymer-foam space-charge electrets," Appl. Phys. Lett., vol. 77, pp. 3827-3829, 2000.

[9] G. S. Neugschwandtner, R. Schwödiauer, S. Bauer-Gogonea, S. Bauer, M. Paajanen, and J. Lekkala, "Piezo- and pyroelectricity of a smart polymer-foam space-charge electret," J. Appl. Phys, vol. 91, no. 8, pp. 5283-5287, 2002.

[10] G. Buchberger, R. Schwödiauer, and S. Bauer, "Flexible large area ferroelectret sensors for location sensitive touchpads," Appl. Phys. Lett., vol. 92, no. 12, 123511, 2008.

[11] Keyboards with a costumizable layout are defined and introduced for example on the webpage http://www.artlebedev.com/everything/optimus/

[12] E. Hallen, Electromagnetic theory, London: Chapman&Hall, 1962, ch. 32, pp. 401-420.

[13] S. Bauer-Gogonea, S. Bauer, and R. Gerhard-Multhaupt, "Monomorphs, bimorphs, and multimorphs from polar polymer electrets," Braz. J. Phys., vol. 29, no. 2, pp. 306-317, June 1999.

[14] M. Jäger et al., "Poling and characterization of polymer waveguides for modal dispersion phase-matched second-harmonic generation," J. Opt. Soc. Am. B, vol. 15, no. 2, pp. 781-788, February 1998.

[15] S. Bauer-Gogonea, S. Bauer, W. Wirges, and R. Gerhard-Multhaupt, "Pyroelectrical investigation of the dipole orientation in nonlinear optical polymers during and after photoinduced poling," J. Appl. Phys., vol. 76, no. 5, pp. 2627-2635, September 1994.

[16] J. Hillenbrand and G. M. Sessler, "High-sensitivity piezoelectric microphones based on stacked cellular polymer films," J. Acoust. Soc. Am., vol. 116, no. 8, pp. 3267-3270, December 2004.

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