5.2: Low-Cost Planar PTF Sensors for the Identity Verification of Smartcard Holders*

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Abstract

The properties of mechanical flexibility, low-cost and planar geometry make polymer thick film (PTF) sensors attractive for embedded smartcard biometrics. In this paper, PTF piezoelectric and piezoresistive pressure sensors are investigated for their potential to capture spatial human characteristics. However, it was found that the extent to which a smartcard flexes, and the planar sensitivity of both sensor types render this concept infeasible. Nevertheless, PTF sensors have a demonstrable potential to capture other aspects of human-smartcard interaction, and a novel approach to identity verification is discussed.

Keywords

Polymer Thick Film Sensors, Smartcards, Biometrics

INTRODUCTION

Smartcards are of similar dimensions to the familiar plastic banking card, with the important difference of an embedded microprocessor, allowing data to be stored and processed. With the inclusion of modern cryptographic capabilities and advanced security hardware, smartcards may be considered robust, secure and trusted mobile computers. Hence, their applications are diverse and may include: stored value and loyalty applications; micro-payment; and the storage of confidential data. One area of particular interest is the use of smartcards for authentication of individuals at a distance and in the non-repudiation of transactions or document creation [3]. However, such methods are vulnerable unless strong authentication mechanisms bind the holder's identity to the card.

Currently there is interest in the use of biometrics to provide such a mechanism [1]. However, the focus has been predominantly algorithmic - relying upon external sensors to capture biometric characteristics. Not only does such an approach expose the system to the possibility of eavesdrop and playback attacks [8], it may also inconvenience the holder by restricting where the card can be used. For these reasons it is desirable to embed biometric sensors into the smartcard itself, thereby creating an entirely self-contained identity verification system. This is a challenge in terms of the manner of demonstrating identity, and in the method of capturing biometric characteristics. Sensors require to be sufficiently

flexible and robust to withstand normal smartcard usage, and do so in an economically compliant manner.

Polymer thick film (PTF) technology offers the possibility of fabricating low-cost, planar, flexible and robust sensors. As such they appear attractive as a sensing mechanism for embedded smartcard applications. This paper investigates the use of two different PTF force / pressure sensors, namely piezoelectric and piezoresistive sensors. Their fabrication is described and principles of operation derived.

The manner with which an individual can demonstrate their identity to a smartcard is clearly limited by the small physical dimensions of the card and the practical interactions between human and card. Hence the discriminating characteristics could conceivably be based around the features of the finger, and may include: fingerprints [14]; finger-geometry¹; and finger-crease pattern [15].

It is envisaged that a smartcard owner will hold the card in one hand, and present the characteristics of the other hand to an on-card sensor for verification. However, presentation of any of the above characteristics involves applying a load to the smartcard, which from common experience will cause the card to flex. As a smartcard flexes, strains propagate across its surface. But theoretical analysis of both sensor types indicate sensitivities to planar strain, implying that sensors will respond to forces applied elsewhere on the card. From the perspective of capturing any of the above human traits, where spatial (or spatio-temporal) features form the basis for discrimination, this is clearly undesirable.

The work of this paper makes use of finite element analysis (FEA) to assess the extent of strain propagation across the surface of a smartcard. Results are experimentally verified and are shown to have significant implications for the use of simple PTF sensors, bonded to smartcards, for the capture of discriminatory characteristics.

PTF FORCE / PRESSURE SENSORS

Polymer thick-film technology is an established method of circuit fabrication, used in the production of flexible conductors and interconnects [7]. Early development of the techniques was made in the mid 1970s and the approach is still used today in components for calculators, keyboards, mobile phones and a multitude of other devices where low-cost / flexible circuits are required.

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¹See for example, the finger scanning device of BioMet Partners Inc. (<http://www.biomet.ch>)

PTF processing generally occurs at temperatures of $<200^{\circ}\text{C}$ allowing films to be printed onto a wide range of thermally compatible substrates. These include flexible materials such as polyester, polycarbonate, polyimide, polyvinyl acetate (PVAc) and acrylic [7]. Hence, the use of polymer thick film technology offers advantages to smartcard sensor systems in that their fabrication techniques are relatively straightforward and have no requirement for clean-room or high temperature processes; can be deposited on a wide range of substrate materials; and are considered to be of relatively low-cost [9]. Indeed, these properties and the inherently simple planar nature of these sensing structures is entirely consistent with smartcard integration.

Polymer thick film pastes generally consist of filler particles bound within a polymer matrix (usually epoxy, silicone, or phenolic resin). For example, gold and silver flakes or copper particles may be used as the filler for conductive pastes, whilst carbon particles may be used for resistive purposes [7].

Whilst the printing of polymer conductors on flexible substrates is well documented, relatively little research has been published on the use of flexible substrates for sensing purposes. By allowing the substrate to deform, higher stresses can be imparted to the sensor than is the case of an undeformed rigid substrate, and thereby exhibiting a higher sensitivity to load. Relevant approaches include the printing of polymer piezoelectric and piezoresistive thick film sensors on flexible polyester substrates [18, 20], and the printing of polymer piezoresistive sensors onto flexible epoxy membranes [5]. In the latter example, an applied pressure causes deformation of the membrane inducing surface strains, which are measured by the resistive elements.

This work considers piezoresistive and piezoelectric PTF force / pressure sensors, printed on flexible substrates, and bonded onto smartcards. Their fabrication is described in the next section.

Sensor Construction

Both sensors are printed onto $125\mu\text{m}$ thick flexible polyester², pre-shrunk by the manufacturer for thermal stability, and offering mechanical flexibility, good electrical characteristics, low moisture absorption, high solvent resistance and very low shrinkage at PTF processing temperatures [7]. Sensors were printed using a DEK flatbed printer³.

The piezoelectric sensor was constructed in the manner of [20]. This is shown schematically in Figure 2 and is a three-layered device comprising of two silver conductive layers (ESL1107 from Electro Science Laboratories⁴) sandwiching an active PZT layer (85% Lead Zirconate Titanate and 15% phenolic resin by weight, 1:1 ratio by volume - providing optimal sensitivity and mechanical stability). The active area of the

device is $16\times 4\text{mm}$, and the thickness of the PZT layer was measured to be $60\mu\text{m}$.

The piezoresistive sensor (see Figure ??) is a single resistive layer of polyimide-based, carbon-filled paste from Electro Science Laboratories (ESL RS15114, $10\text{k}\Omega/\text{square}$), whose thickness was measured to be $20\mu\text{m}$. The dimensions of the active piezoresistive material between electrode connections were measured to be $15\times 9\text{mm}$.

During construction, each layer was printed then dried for 10 minutes using a short wave infra-red dryer⁵ at 110°C . Upon completion of the drying process the sensors were cured for 1 hour at 140°C . The piezoelectric sensor was polarized during the curing process with a poling voltage of 300V (equivalent to an electric field strength of 5MV/m). Wire connections were made using Circuitworks⁶ conductive epoxy (CW2400) and $200\mu\text{m}$ diameter wire.

Both sensors are then bonded onto the surface of smartcard blanks using $50\mu\text{m}$ double-sided adhesive tape⁷.

Figure 1. Piezoresistive Sensor Bonded to Smartcard

Figure 2. Piezoelectric Sensor Bonded to Smartcard

Piezoresistor Principles of Operation

As indicated, resistive components are comprised of conductive particles within a polymer matrix. Hence, electrical resistance is dependant upon the proximity and contact area of the conductive particles. As a force or pressure is applied to the material, strains are induced, causing a deformation of the structure and hence a change in the proximity of the conductive particles and their contact area. Such a change

²Mylar from DuPont Packaging and Industrial Polymers, Wilmington, USA. Web: <http://www.dupont.com>

³DEK 1750RS, from DEK Printing Machines Ltd. Weymouth, UK. Web: <http://www.dek.com>

⁴Electro Science Laboratories Inc. King of Prussia, PA, USA. Web: <http://www.electroscience.com>

⁵DEK1209 IR Dryer

⁶Chemtronics Inc. Atlanta, GA, USA. Web: <http://www.chemtronics.com>

⁷Scotch Double Sided Tape, manufactured by 3M United Kingdom PLC, Bracknell, UK. Web: <http://www.3m.com>

in resistance to the applied force or pressure is known as piezoresistance.

We begin by considering a thin isotropic slab of resistive material, whose current flow is parallel to its length, and its resistance R , is given by

$$R = \rho \frac{l}{wt} \quad (1)$$

where ρ is the resistivity of the resistor material and l , w and t are the length, width and thickness of the resistor in the x , y and z directions, respectively (Figure 3).

If the film sensor is subject to orthogonal stresses, σ_x , σ_y and σ_z , then strains, ε_x , ε_y and ε_z will be induced and the structure will deform, as shown in Figure 3.

Figure 3. Stress-Strain Schematic

The relationship between applied stress and resulting strains is given by the general stress-strain equations [?], which are stated as

$$\begin{aligned} \varepsilon_x &= \frac{\sigma_x}{E} - \frac{\nu}{E} (\sigma_y + \sigma_z) \\ \varepsilon_y &= \frac{\sigma_y}{E} - \frac{\nu}{E} (\sigma_x + \sigma_z) \\ \varepsilon_z &= \frac{\sigma_z}{E} - \frac{\nu}{E} (\sigma_x + \sigma_y) \end{aligned} \quad (2)$$

where ν and E are Poisson's ratio and Young's Modulus of the sensor material, respectively.

It can be shown that the proportional change in resistance, $\frac{dR}{R}$, is a function of applied strains, such that

$$\frac{dR}{R} = G (d\varepsilon_x + d\varepsilon_y + d\varepsilon_z) + \varepsilon_x - \varepsilon_y - \varepsilon_z \quad (3)$$

where G is known as the piezoresistivity coefficient and is defined as

$$G = \frac{1}{\rho} \frac{\partial \rho}{\partial \varepsilon} \quad (4)$$

For a sensor bonded to a smartcard, and is thin in comparison to the card, then the planar strains of the sensor conform to the planar strains of the card. That is

$$\begin{aligned} \varepsilon_x(f) &= \varepsilon_y(c) \\ \varepsilon_y(f) &= \varepsilon_x(c) \end{aligned} \quad (5)$$

where the labels (f) and (c) are used to denote the sensor film and card, respectively.

The out-of-plane, normal strain, $\varepsilon_z(sensor)$, is found by solving (2), to give

$$\varepsilon_z(f) = -\frac{\nu_f}{(1-\nu_f)} [\varepsilon_x(c) + \varepsilon_y(c)] + \left[1 + \frac{2\nu_f^2}{(1-\nu_c)} \right] \frac{\sigma_z}{E_f} \quad (6)$$

Hence, given the planar strains of the smartcard surface, corresponding to the position of the sensor, the piezoresistive response can be calculated using the normal strain, ε_z , given by (6), and equation (3), for the proportional resistance change. (3) shows clearly that a piezoresistive film exhibits sensitivity to planar strain, and hence, the flex of a card has a significant influence on the response of a sensor bonded to it.

Piezoelectric Principles of Operation

As indicated, the piezoelectric film is composed of piezoelectric particles, suspended within a polymer matrix. An applied stress causes compression or tension of the film which is transferred onto the piezoelectric material, and charge is thus generated. Its response can be described as [20]:

$$Q = A [d_{31} (\sigma_x(c) + \sigma_y(c)) + d_{33} \sigma_z] \quad (7)$$

where, Q is the charge generated (Coulombs), d_{33} and d_{31} are the piezoelectric coefficients (C/N), describing the charge generated across the thickness of the film in response to normal and planar stresses, respectively, and A is the sensor area onto which the stress is applied. $\sigma_x(c)$ and $\sigma_y(c)$ are the planar stresses acting upon the sensor film due to the smartcard. σ_z is any external stress, normal to the plane of the sensor, and acting upon the sensor directly.

For a piezoelectric sensor bonded to a smartcard, and adhering to the conditions of (5), the planar stresses $\sigma_x(c)$ and $\sigma_y(c)$ acting on the sensor, due to the strains of the smartcard, can be found by solving (2) to give

$$\sigma_x(c) = \frac{E_f}{1-\nu_f^2} (\varepsilon_x(c) + \nu_f \varepsilon_y(c)) + \frac{\nu_f}{1-\nu_f} \sigma_z \quad (8)$$

and

$$\sigma_y(c) = \frac{E_f}{1-\nu_f^2} (\varepsilon_y(c) + \nu_f \varepsilon_x(c)) + \frac{\nu_f}{1-\nu_f} \sigma_z \quad (9)$$

Given the strains of the substrate ($\varepsilon_x(c)$ and $\varepsilon_y(c)$), and the normal stress upon the sensor (σ_z), the charge generated by a piezoelectric sensor, bonded to a substrate, can be found using (7) with the planar stresses, $\sigma_x(c)$ and $\sigma_y(c)$ given by equations (8) and (9).

SMARTCARD FINITE ELEMENT MODEL

It is the intention of this work to capture the general mechanical characteristics, rather than absolute detail, of a smartcard responding to an applied load. As a result some aspects of the real smartcard will be omitted, including the processor contact pads, the underlying laminate construction and the curved corners of a real card. This model treats the smartcard as a simple rectangular plate of uniform thickness and homogenous material.

Material Properties

Before commencing any finite element modelling, the material properties of both smartcard and sensors must be specified. The smartcard finite element model requires that Poisson's ratio, Young's modulus, and the mass density of the smartcard are known. Poisson's ratio and Young's modulus are required for both sensor materials, and additionally, the piezoresistive and piezoelectric coefficients must be estimated. The values used are summarised, and referenced in Table 1.

Table 1. Summary of Material Properties

Property	Assumed Value	Source	Additional Information
E_c	$3.1 \pm 0.5 \text{ GPa}$	[4]	Cantilever Deflection
ν_c	0.38	[16]	-
ρ_c	$1.38 \times 10^3 \text{ kg/m}^3$	[16]	-
E_{pR}	4.1 GPa	[4]	Rule of mixtures
ν_{pR}	0.4	[16]	-
G	10.6	[19, 2]	Inferred
E_{pE}	26.4 GPa	[4]	Rule of mixtures
ν_{pE}	0.4	[4]	-
d_{33}	9 pC/N	[18]	-
d_{31}	-4 pC/N	[18]	-

Additional Information

Young's modulus of the smartcard was measured using the method of cantilever deflection [4]. Taking measurements from six smartcards, Young's modulus was found to be $3.1 \pm 0.5 \text{ GPa}$, with a standard deviation of 0.2 GPa. This compares with 2.7 GPa for bulk PVC [16].

Unfortunately, since the sensors are printed onto substrates, cantilever deflection is not an appropriate measurement approach for the sensor films. For this reason, the simple rule of mixtures was used to estimate Young's modulus for both sensors. This is stated as

$$E_{\text{composite}} = P_1 E_1 + P_2 E_2 \quad (10)$$

where $E_{\text{composite}}$ is Young's Modulus of the composite mixture, P_1 is the volume proportion of material 1 with modulus E_1 , and P_2 is the volume proportion of material 2 with modulus E_2 .

Equation (10) was used to calculate Young's modulus of the piezoelectric film, with a 1:1 mixing ratio of phenolic resin ($E = 4.8 \text{ GPa}$, [16]) and PZT-5H ceramic piezoelectric ($E = 48 \text{ GPa}$, [17]). Although the piezoresistive film is comprised of graphite within a polyimide binder, its true composition is proprietary, and hence unknown. The assumption of a 1:1 mixing ratio of graphite ($E = 4.8 \text{ GPa}$, [16]) to polyimide ($E = 3.3 \text{ GPa}$, [16]), is therefore made.

The piezoresistivity coefficient, G , of the resistive ink requires to be known, but unfortunately this quantity is not ordinarily quoted on data sheets. However, G is related to the gauge factor, $GF = \frac{dR}{R\epsilon}$, as derived in [19], such that

$$G = \frac{GF - 2}{1 - \nu_{\text{substrate}} - \nu_f \frac{1 - \nu_{\text{substrate}}}{1 - \nu_f}} + 1. \quad (11)$$

The gauge factor is commonly measured, indeed Arshak [2] reports its measurement for the piezoresistive material used in this work. Taking Arshak's median measurement of $GF_L = 4.5$, and using $\nu_{\text{substrate}} = 0.22$ for alumina and $\nu_f = 0.4$, it is found that $G \approx 10.6$.

Mesh Characteristics

The smartcard is modelled with rectangular shell elements, which are generally considered to be appropriate for thin planar geometries, as exhibited by smartcards [6]. The physical dimensions of smartcards are specified by an ISO standard⁸, and are provided in Table 2.

Table 2. ISO Standard Dimensions

Measurement	ISO Specification (mm)
Length	85.6
Width	54.0
Thickness	0.76 ± 0.08

To remove the uncertainty in the ISO standard thickness, the thickness of six cards from the same batch was measured using a screw-gauge micrometer, and the mean thickness found to be 0.815 mm with a standard deviation of 0.005 mm. This value is used as the element thickness, and the planar area of the card was discretised into a mesh of 17×11 elements.

Constraints

With a smartcard held in hand, a user restricts the vertical displacement of the two longitudinal edges. The hand in contact with the smartcard may impart, or inhibit rotation of the edges, and compression may be applied across the width of the card. Furthermore, these constraints are non-uniform, asymmetrical, and are likely to vary between individuals. Complicating the situation further, real constraints are likely to be dynamic - changing as an individual presents the characteristics of her other hand for verification. In reality, the way in which a user interacts with a smartcard is complex.

Without extensive analysis of real constraints imposed by a number of users holding cards in their hands, a quantitative assessment of constraints is beyond reach. For this reason it was decided to apply only simple constraints with which one may have some confidence. Hence, this FE model applies only vertical displacement constraints to the edge nodes of the card's longitudinal edges.

Loading Conditions

As already stated, the manner of interaction between an individual and a smartcard sensor system is limited, but may be

⁸ISO7816-1:1998 Identification cards - Part 1: Physical characteristics. Web: <http://www.iso.ch>

considered to include a finger touching, pressing and tapping upon the card. Whilst the absolute characteristics of this interaction are dependant upon the properties of the sensing mechanism, and hence cannot be determined at this stage, it was deemed important to apply loads similar in magnitude to those which might be expected during the presentation of real discriminatory characteristics. At the disposal of this work was a calibrated (ceramic) piezoelectric force sensor, but piezoelectric sensors tend to exhibit poor static or quasi-static responses, thereby eliminating the capture of a finger touching or pressing. Hence the force magnitude of fingers tapping on the sensor were recorded.

To estimate the force magnitude with which a user taps, five volunteers were instructed to tap the sensor with as little or as much force as desired, randomly varying the strength of their taps as the session progressed. Each participant provided between 250 and 400 taps, and from the data collected, the modal tapping magnitude was found to be $\sim 2.5\text{N}$. It is assumed that a reasonable estimate of fingertip area is $\sim 1\text{cm}^2$, and hence a static 2.5N load is distributed over 1cm^2 and used as the input to our model.

RESULTS AND ANALYSIS

Four load cases were considered, each being applied along the central longitudinal axis of the card at intervals of 1cm , and starting at a point 5mm from the short edge, furthest from the processor contacts. Hence, 4cm of longitudinal distance was investigated, and believed to represent most of the space available to an on-card sensor system. The displacement map resulting from a load whose center is 2cm along the longitudinal axis is shown in Figure 4. The maximum out-of-plane displacement is around 0.85mm , and the smartcard is seen to flex along its central longitudinal axis.

Figure 4. Vertical Displacement Resulting from a Static 2.5N Load

The FEA results⁹ were used to calculate the mean planar strains of the smartcard's surface corresponding to the sensor positions of Figures 1 and 2. These mean strains were then used with equations (5), (6) and (3) to compute the theoretical piezoresistive sensor responses, and with equations

⁹Using AutoFEA v7.0, from AutoFEA Engineering Software Inc. CA, USA. Web:<http://www.autofea.com>

(8), (9) and (7) to compute the theoretical piezoelectric sensor responses. The results are shown in the second column of Tables 3 and 4, respectively. It should be noted that load case 2 refers to the sensor positions as shown in Figures 1 and 2.

Table 3. Piezoresistive Sensor Results

Load Case	Theoretical $dR/R\%$	Experimental $dR/R\%$ (Std.Dev.)	Expt/Theoretical
1	-0.52	-0.46 (0.02)	88.6%
2	-0.73	-0.58 (0.02)	80.1%
3	-0.44	-0.39 (0.04)	88.0%
4	-0.34	-0.29 (0.03)	86.2%

Table 4. Piezoelectric Sensor Results

Load Case	Theoretical Q(nC)	Experimental Q(nC) (Std.Dev.)	Expt/Theoretical
1	-7.2	-1.5 (0.2)	21.2%
2	-11.1	-2.1 (0.1)	18.9%
3	-5.1	-1.1 (0.2)	20.8%
4	-3.8	-0.81 (0.1)	21.4%

Although the largest sensor responses occur during load case 2 (as one would expect), this analysis indicates that both sensor types respond to loads applied elsewhere on the card. Taking for example the sensor responses due to load case 4, in which the center of the load is applied 1.5cm from the sensor, the theoretical sensor responses are 47% and 34% of the response due to direct loading of the sensors.

Experimental Verification

In an attempt to experimentally replicate the FEA conditions, a supporting apparatus was devised, such that the longitudinal edges of a smartcard could be constrained in the vertical out-of-plane direction only. A mechanism for applying loads to the card, at positions corresponding to each load case, was constructed.

As loads were applied to the piezoresistive card, the response signal was recorded and its static equilibrium value, noted. In the case of the piezoelectric sensor, loads were removed, rather than applied, to ensure that dynamic loading of the sensor did not occur. The measurement process was performed at least thirty times for each load case, and the data used to compute mean and standard deviations of the responses. The results are presented in column 3 of Tables 3 and 4, for the piezoresistive and piezoelectric sensors, respectively.

Both sets of experimental results show clearly the effects of card flexing. Again using load case 4 for illustration, it is observed that the sensor responses are 50% and 39% of the direct sensor loading case, for piezoresistive and piezoelectric responses respectively.

The experimental results compare well with the theoretical analysis for the piezoresistive sensor responses. However,

this is not the case for the piezoelectric sensor. The problem is believed to stem from the estimation of Young's modulus of the piezoelectric composite. We used the rule of mixtures method (10), which assumes that the two materials in the composite are exclusively and homogeneously mixed. This is most likely not the case, as the presence of air gaps within PZT-phenolic films have been observed [18]. Air gaps within the composite will significantly reduce Young's modulus, and although further determination is beyond the scope of this work, reducing this value has been shown to bring theoretical results closer to experimental.

CONCLUSIONS

The properties of flexibility, robustness, low-cost and the planar geometry of simple piezoresistive and piezoelectric PTF films, are entirely compliant with smartcard integration. As such they appear attractive for smartcard biometric sensors. However, as this work has shown, such sensors exhibit sensitivity to planar strains, and as a result of smartcard flex will respond to loads applied elsewhere on the card. This makes the capture of spatial or spatio-temporal human characteristics infeasible.

Nevertheless, the utility of simple PTF sensors in capturing other discriminating characteristics has been demonstrated [10, 12]. In [10] we bond singular piezoelectric sensors onto smartcards, and use them to capture the pressure response of finger-taps. Employing the verification algorithms of keystroke dynamics [13], we demonstrate discriminatory performance comparable to many contemporary biometrics, whilst complying with the constrained computational resources of a typical modern smartcard platform [11].

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