Printed conducting polymer strain sensors for textiles

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Abstract

We have used inkjet printing to deposit silver conducting lines and small PEDOT (conducting polymer) sensors onto fabrics. The printed conductors penetrate into the fabric and can be shown to coat the individual fibers within the yarn, through the full thickness of the cloth. The PEDOT sensor has a resistance in the region of a few kilo-ohms and is connected to measuring equipment by printed silver lines with a resistance of a few ohms. In this way, local strains can be measured at different sites on a fabric. The PEDOT responds to a tensile strain by a reduction in resistance with a gauge factor (change in resistance/strain) from –5 to –20. This compares with conventional strain gauges where the gauge factor is normally +2. These sensors cycle to strains of over 10%. We have measured gauge factors as a function of the orientation of the sensing line to the fabric axes, to the strain axes for different fabric structures. We can correlate the gauge factor with the extent to which the twisted multifilament yarns are expected to become laterally compressed. In preliminary tests we have shown that these printed sensors can be used to monitor knee and wrist motions and so could be used to provide information in applications such as rehabilitation from joint damage.

1. Introduction

One application of "smart" textiles would be as an elastic sleeve to detect the extent and range of motions in a knee or elbow joint. This might be done using a single sensor, but it would also be useful to use an array of sensors to detect the full range of motion. As a model we could take the complex array of sensors that surround a joint in a spider or insect leg [1, 2]. With this goal in mind we have been working on printable strain sensors for textiles that could be used in an array for detailed sensing of body motions.

Conducting polymers are an attractive choice for these sensors, they have a high resistance, are flexible and can easily be printed. There have been past studies of polypyrrole and polyaniline gas sensors [3, 4, 5]. More recently, strain sensors have been used in a number of formats, including strips of Lycra elastic fabric impregnated with conducting polymer [6] and impregnated foams as compression sensors for shoes [7].

Our work uses multi-pass inkjet printing [8] to deposit sensing lines of conducting polymer on fabric and to print silver lines to connect the sensors to the monitoring equipment. We use an electroless plating method but a two-step printing method for silver has also been described [9]. The performance of these strain sensors depends on distribution of the conducting polymer through the fabric and on the weave of the fabric.

2. Sensor printing

2.1 The inkjet printing system

Printing was carried out using conventional HP cartridges, emptied and refilled with our test solutions. The drop rate was controlled by a custom-built pulse generator which pulsed a single nozzle on the cartridge. The cartridge was mounted on an arm above an xy motion system that moves the samples, figure 1. In this way, many print cycles could be carried out with controlled time and distance between drops and with the ability to control the temperature and humidity of the sample.

2.2 Formation of Connectors

Formation of conducting leads was attained in two steps. The first was to inkjet print seed layers which were then converted into metallic lines by electroless plating. Silver nitrate (38mM in water) was printed on the woven fabric. Since the ink, upon evaporation, leads to spreading on the substrate the woven fabric was mounted on a heating plate so as to avoid the spreading of the solution. This technique allows the individual droplets to fuse but hinders the formation of large droplets and thus prevents smearing of ink [10]. Lines were printed at 5 cm/sec and 500 drops/sec for 500 cycles. This repeated printing onto fabric at 60^{o}C allows the "ink" to dry on the fabric between cycles. Once the lines, 3 cm long and 0.5 mm wide, are printed, the sample was dipped in an electroless bath of silver [11]. The reducing agent, glucose, reduces the silver ions to metal which is deposited on to the already printed seed layer by an autocatalytic process.

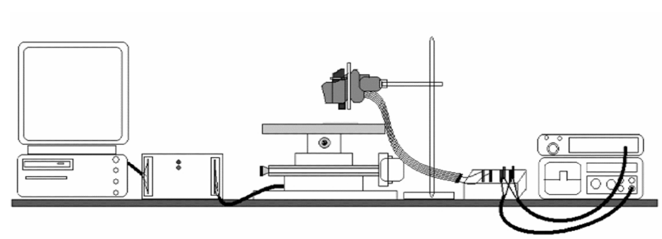

Figure 1 Ink jet printing apparatus.

The bath was maintained at a temperature of 50 degree Celsius and the hold time of 40 minutes. The pH of the bath was kept highly basic at around 12.5. After the sample is subjected to the required set of conditions, it is taken out of the bath and rinsed in hot water followed by a rinse in cold water along with mechanical action such as wringing.

A thick and uniform deposit of silver nitrate was needed on the nylon woven fabric so as to form a continuous network of silver on the printed regions during plating. The resistance of the samples, after they have dried, was measured using Keithley 196 electrometer and also by 4-probe electrical measurements. The probes were kept on the printed region, and the corresponding reading from the front panel is taken down. The value of resistance ranges from 0.7- 1.5 ohms/inch. Based on the linewidth, fabric thickness and volume fraction of silver, we estimate a conductivity of approximately 4 x 10^3 Siemens/cm. This is about 100 times less than that of elemental silver (6.25 x 10^5 Siemens/cm). Unprinted areas of the fabric remain non-conductive.

2.3 Formation of Sensors

A suspension of Poly (3, 4 – ethylenedioxythiophene) - poly (4-styrenesulfonate) (PEDOT-PSS) from Bayer Scientific, 1.3 % by weight, was printed onto mercerized cotton fabric for 500 cycles. The printed lines were about 5 cm long and less than 1 mm wide. The samples were annealed at 90 degree Celsius for about an hour. In this case the polymer partly penetrated the fabric and formed stable conducting lines. The resistance drops as more ink is deposited and is about 5 kilo-ohms at 500 cycles. The conductivity of the PEDOT in the coatings is about 25 S/cm.

For the strain sensing study, the fabric was clamped in jaw placed 2.54 cm apart on an Instron tensile testing machine and the corresponding resistance was recorded on a Keithley Multimeter 196 through a PC using General Purpose Interface Bus (GPIB) as a data acquisition mode.

The microstructure of the printed PEDOT and electroless silver was studied by JEOL JSM 5610 Scanning electron microscope equipped with Oxford Energy Dispersive X-ray System operating at 8 kV.

2.4 Integration of sensors and connectors

Resistance of connectors was 1/ 100 of that of sensor in order to avoid any interference with the data recording. Sensors were integrated with connectors by printing lines of PEDOT, 1 cm in length and about 0.5 mm wide, onto Nylon 66 fabrics in between silver printed lines, as shown in figure 2. The connectors were connected to an external device and the resistance was recorded on Keithley 196 electrometer along, interfaced through GPIB.

3. RESULTS AND DISCUSSION

3.1 SEM and EDX observation

Figure 3, shows a coating of silver around every fiber through the thickness of the fabric. EDX analysis confirms the presence of silver on the fabric, table 1. The second silver immersion step does also result in some silver being deposited on the unprinted regions and some staining but these do not become conducting. EDX also shows that some silver penetrates into the individual Nylon fibers.

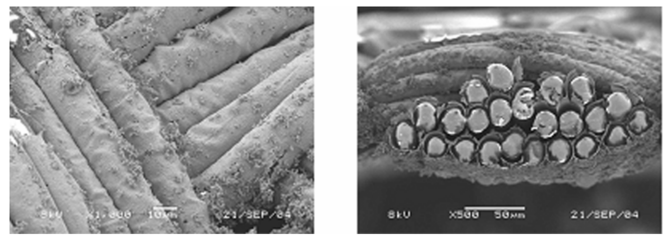

Figure 2 Cross section and top view of silver printed region of a Nylon fabric.

Microscopy of the cotton fabric coated with conducting polymer, in figure 4, shows that part of the polymer forms a thick film on the upper surface of the fabric and cracks on elongation.

Table 1 EDS elemental analysis of silver-coated yarn

	Carbon wt%	Oxygen wt%	Silver wt%
Yarn cross section	52.6	17.9	29.5
Single fiber cross section	63.0	21.7	15.3

3.2 Strain sensitivity

The reversible change in the electrical resistance of PEDOT-PSS printed fabrics with external mechanical strain relaxation reveals that these fabrics show piezoresistivity. For this study 2.54 cm long PEDOT printed cotton fabric was subjected to an elongation of 5% at a rate of 5mm/min on an Instron tensile testing machine, figure 5.

It can be seen that there is an initial increase in the resistance of the PEDOT printed fabric with strain. We believe that this initial increase corresponds to the cracking seen in figure 4 and reported by Li et al. for Lycra fabric with a coating of polypyrrole [12, 13]. Subsequently our samples show a cyclic change in resistance with strain. In this case the resistance decreases as the sample is strained and increases again as the strain is relaxed. It can be seen that a strain of 5% results in a resistance decrease of about 25%, corresponding to a (negative) gauge factor of –5. A similar large decrease in resistance with strain was observed for polypyrrole-impregnated Lycra [6]. This compares with a gauge factor of +2 for most metals, which reflects the normal decrease in cross-section with increase in length. Some semiconductors do show a large positive gauge factor due to the influence of strain on band conductivity [14]. Our samples thus show two zones of conductivity. The surface layer of conducting polymer cracks on stretching while the polymer that penetrates into the yarn becomes more conductive on stretching, probably through better surface-surface contacts within the yarn [15].

However it was not possible to attain original resistance soon after the experiment because PEDOT is printed on cotton woven fabric which shows only 61% of recovery from strain as compared to Nylon fabric (91%) and some knit fabrics (almost 100%),although with time original resistance is recovered.

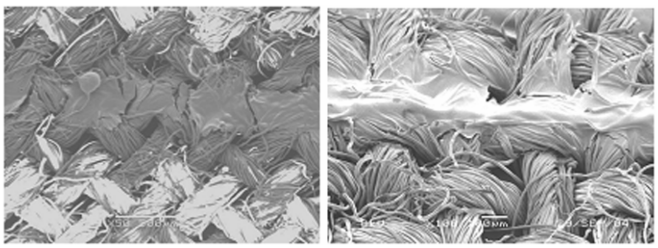

Figure 3 PEDOT-printed cotton before and after 10% elongation

3.3 Sensing mechanism

As mentioned above, the printed PEDOT shows a two-stage response to strain. Over the first few cycles, the resistance increases as the surface layer, shown in figure 4, cracks. Subsequently the material shows a stable response over many cycles. This response is a decrease of resistance with increasing strain, with a flattened top to each cycle as the fabric becomes relaxed.

The mechanics of a woven fabric are complex, but much of the response to tensile strain is in untwisting of the individual short (staple) filaments within the yarn in the manner of a twisted telephone cord [16]. This untwisting is accompanied by lateral compression between the filaments. Thus, if we view each short filament as being coated with conductor, the decrease in resistance is due to compressive stresses increasing fiber-fiber contact. One expected consequence of this model would be that low-twist, loose yarns would show more response for a given strain as the fibers more into much closer contact. The response of a fabric may, of course, be more complicated as yarns also move within the fabric.

Table 3 shows measured gauge factors for different fabrics specified in Table 2, test directions relative to the main fabric axis and relative to the line direction, and test speed. Multiple tests on single samples and multiple samples of similar sensors show good reproducibility for gauge factor within 10%. It can be seen that the twill fabric and the plain fabric tested on the fabric diagonal give especially high negative values.

The thicker, coarser twill fabric shows a greater response as contacts are initially poor. This fabric also shows a higher gauge factor for lines printed across the fabric axes where contact at yarn-to-yarn crossing points is also important. For the diagonal tests, the line is parallel to the fabric axes but the tension direction is at 45 degrees to the line. This response then reflects a combination of tension and shear on the line. These differences are potentially important as an ideal sensor would be able to distinguish strains on different axes.

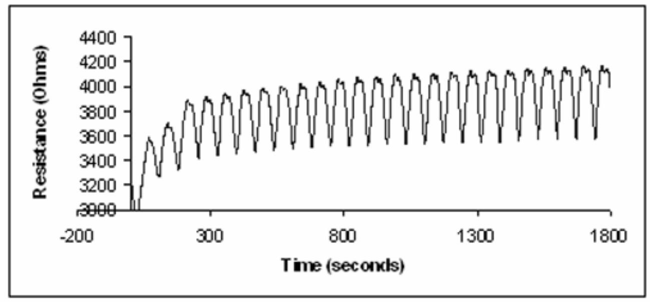

Figure 4 Resistance of PEDOT-PSS sensor with 25 repeated cycles of strain to 5% and relaxation.

Table 2: Fabric specifications

	Yarn Count	Construction	Weight g/m^2	Twist /inch
Cotton Twill	14.75/1 Warp & Fill	106 X 56	2 58	17warp and fill
Cotton Poplin	20/1 Warp, 17/1 Fill	80 X 50	1 80	15 warp, 13 fill
Combed Cotton Warp Sateen	40/1 Warp, 30/1 Fill	130 X 70	1 55	27 warp, 22 weft

Table 3: Sensor Gauge Factor at different print angles, test angles and speed

	Gauge Factor				
	Sensor line angle to fabric axes			Diagonal Tension	High speed
	0º	45º	90º		
Plain	6.0	9.5	5.5	14.0	7.50
Twill	12.0	9.0	11.5	9.5	12.0
Sateen	6.0	6.8	6.0	7.0	9.9

3.4 Identification of Human Motions

In order to explore the applicability of this system to analyzing joint motion, an assembly of sensors and connectors was placed on human knee, as shown in figure 6, and wrist with the help of tape.

Four trials for each motion, bending of knee and twisting of wrist, was carried out at both slow and fast speed and corresponding change in resistance was recorded with the help of Keithley 196 Electrometer and GPIB. Both time and frequency domain analysis was carried out of the readings as a part of digital signal processing.

To reduce the noise in the original data a mean filter was employed. This is a simple sliding-window spatial filter that replaces the first value in the window with the average (mean) of all the data values in the window. The plots, shown in figure 7, are the two trials after removing running average and taking twice mean filtering in the time domain. A pseudo-sinusoidal wave is shown in the data after doing signal processing. Approximate 7 pseudo-sinusoidal cycles are contained in 50 sec. In the frequency domain, existing data was used to estimate the power spectral density.

The plots, shown in figure 8, are the power spectral density for two trials. From the two trials, the frequency peaks do show variation from trial to trial. This may be caused by the human motion data collection. However from trials, there exist three major frequency peaks in the PSD. Although the peaks are shifting, they all concentrate below normalized frequency 1. If there exists features for the slow bending motion, we can say that from the four trials that most of the power is concentrated below a normalized frequency of 0.5.

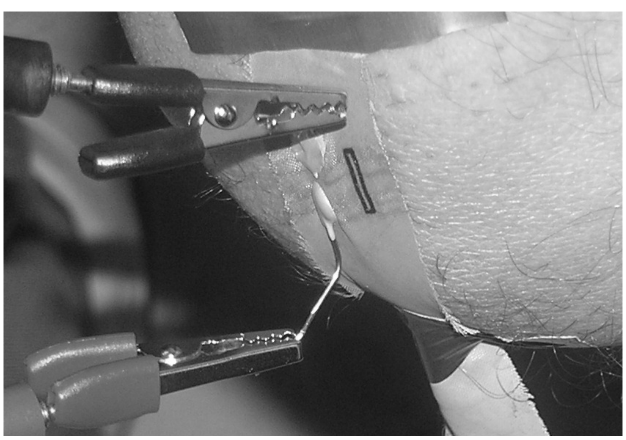

Figure 5 Sensor for bending of knee

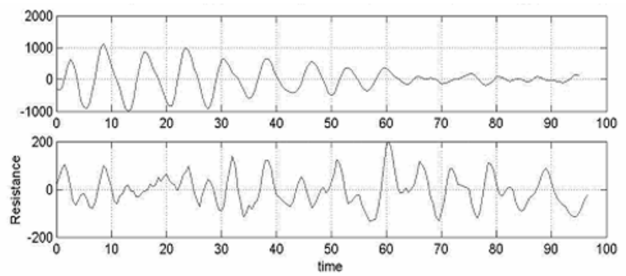

Figure 6 Sensor resistance during knee bending after removing running average and 2nd mean filtering. 2 trials.

From the analysis including four trials from slow knee bending motion as well as four trials from slow wrist twisting motion, we were able to identify and trace down some distinguishable features in both the time domain and frequency domain.

In the time domain, in general, there were approximate 7 pseudo-sinusoidal cycles contained in 50 sec for slow knee bending motion. For slow wrist twisting motion, approximate 12 pseudo-sinusoidal cycles were contained in 50 sec.

In the frequency domain, one can set up a threshold for the power ratio to distinguish the bending and twisting motion in the fixed slow speed. Based on the eight trials, the power ratio threshold was set at 0.5.

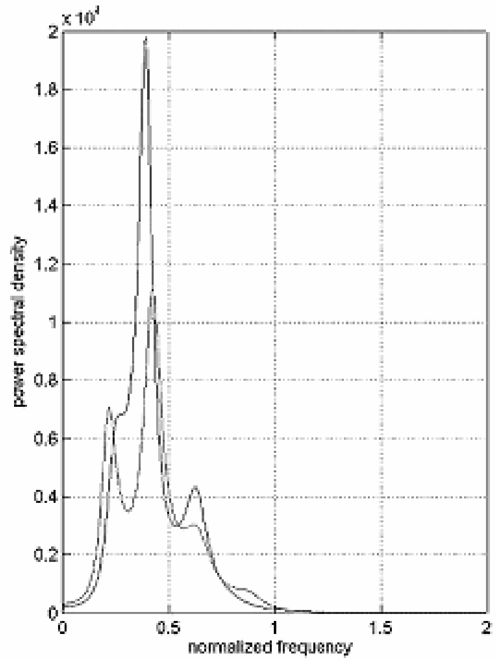

Figure 7 Data from figure 7 shown as a power spectrum.

In the time domain, the periodicity from the smoothed signals was used to separate the two motions. For fast twisting motion (wrist) the period was approximately 8 to 9 sec. per cycle, and for fast bending motion (knee) the period was about 3 sec. per cycle.

In frequency domain, the peaks in each trial were not fixed and also the power ratio method did not work with the fast motion.

4. Conclusions

Printed conducting polymer piezoresistive strain sensors on fabrics can give a high negative gauge factor and so high sensitivity to small strains. Good performance derives from the polymer embedded within the yarn, while the surface layer cracks and becomes ineffective after one cycle of strain. The details of the sensing mechanism are unclear but it depends on improved fiber-to-fiber contact during tensile strain of the twisted yarns.

5. Acknowledgement

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Biography

Paul Calvert is department chair and Prabir Patra is research fellow and Amit Sawhney, Animesh Agrawal and Deepak Duggal are a graduate students in the Department of Materials and Textiles at University of Massachusetts Dartmouth.