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Fabrication of Force Sensor Circuits on Wearable Conductive Textiles

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Abstract

This paper discusses design and fabrication processes in the development of a wearable and flexible conductive resistive sensor. The design and development of the sensor involve the use of Sn-Ag-Cu (SAC) plated Nylon fabric, precision fused deposition modeling (FDM) using silicone and petrolatum for etch-resistant masks using the EnvisionTEC GmbH Bioplotter, and wet etching using Chromium, Ammonium Persulphate, and Salt-Vinegar etching solutions. Preliminary testing with other mask types, development processes, and sensor design approaches for various applications are discussed.

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1. Introduction

Force Resistive Sensors or Conductive Resistive Sensors can be constructed by placing a conductive resistive material between two layers of electrodes. By using a thin sheet of conductive resistive foam and conductive fabrics as electrodes, a sensor is formed that has similar feel and touch to normal everyday fabrics and cushions. This allows the sensor to be easily embedded into apparels, wearable accessories, beddings or mats, while not adding too much weight or causing the user to be overly conscious of the sensor.

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For the sensor to be effective, it requires an electrical current to go across the electrodes and thus there must be an electrical connection in the form of insulated wires or other conductive media. The challenge with using an insulated wire includes forming a robust connection between the hard wires and the soft conductive fabric while not increasing the overall thickness of the sensor. An alternative option to insulated wires, is conductive threads where the conductive thread can be sewn directly onto the fabric. However, the conductive thread needs to be insulated to prevent a short circuit. Encasing the conductive thread like a wire or sewing the thread onto non-conductive fabric can achieve this. In both cases, it adds complexity to the construction process. Furthermore, the conductive thread increases the resistance of the circuit depending on the length used.

One solution for connecting the sensors to input and output sources is to etch a larger piece of conductive fabric such that only the sensor region is conductive with conductive tracks linking it to the input and output source. This essentially creates a fabric printed circuit board (PCB). Circuits on a PCB are normally formed by a thin layer of conducting material deposited, or "printed," on the surface of an insulating board known as the substrate (normally made out of glass fiber reinforced epoxy resin). Circuits are created on the surface of the substrate by "additive" or "subtractive" manufacturing processes. In the additive process, copper is plated, or added, onto the surface of the substrate in the desired pattern, leaving the rest of the surface unplated. In the subtractive process, the entire surface of the substrate is first plated, and then the areas that are not part of the desired pattern are etched away, or subtracted [1]. Most PCB's are fabricated using the additive lithographic process, which involves: (1) a conductive surface on an insulating board (plated substrate); (2) a photoresist; (3) an exposure mask; and (4) electroplating. During the additive lithographic process, the foil surface of the substrate is degreased before a layer of positive photoresist material is vacuum-pressed onto the entire surface of the copper foil on the surface of the substrate. A positive photoresist material is a polymer that becomes more soluble when exposed to ultraviolet light. The desired printed circuit pattern (photomask) is laid on top of the photoresist and the substrate is exposed to intense ultraviolet light. Because the mask is clear in the areas of the printed circuit pattern, the photoresist in those areas is irradiated and becomes very soluble. The mask is then removed, and the surface of the substrate is sprayed with an alkaline developer that dissolves the irradiated photoresist in the areas of the printed circuit pattern, leaving the copper foil exposed on the surface of the substrate. This exposed track on the substrate is then electroplated with copper (the foil on the surface of the substrate acts as the cathode in this process) to a thickness of about 0.025-0.050 mm. The areas still covered with photoresist cannot act as a cathode and are not plated. Tin-lead or another protective coating is plated on top of the copper plating to prevent the copper from oxidizing and as a resist for the next manufacturing step. The photoresist is stripped from the board with a solvent to expose the substrate's copper foil between the plated printed circuit patterns. The board is then sprayed with an acid solution which eats away the copper foil. The copper plating on the printed circuit pattern is protected by the tin-lead coating and is unaffected by the acid [1].

In comparison to PCB manufacturing, the process involved in etching a conductive fabric to create a wearable circuit is much simpler. This paper describes some of the methods used to develop a Conductive Resistive Sensor using a textile as well as methods of mask development for the application. Additionally, DIY materials and techniques are described for the purpose of informing the maker community on cost effective methods of designing and building Conductive Resistive Sensors without the need of specialized equipment.

2. Methodology

The conductive fabric used in this experiment was high conductivity plated Nylon Fabric (Zell) from Shieldex-U.S. The Zell fabric is a Rip-Stop woven Nylon fabric containing 3 metalized layers, Tin/Copper over Silver (Sn/Ag/Cu); this composition is commonly referred to as a SAC alloy. Table 1 presents the manufacturer's technical specifications data sheet.

Current applications of the Zell fabric include garment, gaskets, shielded room, EMI shielding, and cable shielding applications. Various types of conducting textiles with different compositions and special properties [2, 3] are increasingly being made available as the maker community grows and finds new and innovative uses for smart textiles [3].

Table 1. Conductive Metallized Nylon Fabric (Zell) technical data sheet. Adopted from [2].

Property	Value
Surface Resistance	< 0.02 Ohms/square
Shielding Effectiveness	Average 85 db from 30Mhz to 10Ghz
Abrasion Resistance	500,000 Cycles
Temperature Range	-40°C to 90°C
Total Thickness	0.003" (0.1mm) nominal
Number of Splices	1/100M nominal
Roll Widths	52" (1.3M) nominal
Master Roll Lengths	144yds-250yds (100M-200M)

The fabrication of the wearable circuit described in this paper, involves two main steps: (1) mask deposition, and (2) etching. The main fabrication considerations when using conductive fabric as the base material are:

- Ensuring accurate masking.
- Ensuring quality of the textile after etching as etchant chemicals may compromise durability of the fabric depending on the textile's composition.
- Ensuring the mask can be removed properly after etching without damaging the conductivity continuity of the circuit.

2.1. Experimental Design

Five samples (A-E) of the enclosed $100 \times 50 \text{ mm}^2$ circuit were masked on top and bottom and etched according to the parameters shown in Table 2. Figure 1 shows the geometry of the circuit with numbered panels and conductive traces.

Table 2. Etching parameters for Zell Fabric circuit shown in Figure 1.

Sample ID	Etchant	Mask Top	Mask Bottom
A	Sigma-Aldrich 651826 Standard Etchant	Silicone	Masking Tape
B	Sigma-Aldrich 651826 Standard Etchant	Silicone	Clear Tape
C	Jaycar Ammonium Persulphate (PCB) @70C ½ solution Etchant	Silicone	Masking Tape
D	Sigma-Aldrich 651826 Standard Etchant	Vaseline	Masking Tape
E	1/7 Salt and vinegar solution	Vaseline	Masking Tape

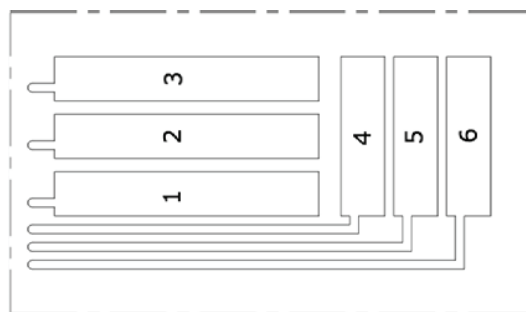


Figure 1. Conductive panels and connecting traces.

2.2. Top Mask Deposition Using a 3D Biplotter

The EnvisionTEC GmbH Biplotter is a rapid prototyping system [4] for processing a great variety of biomaterials within the process of computer aided printing from 3D CAD models to the physical 3D objects with a designed and defined outer form and an open inner structure. The EnvisionTEC GmbH Biplotter works on the principle of Fused

Deposition Modeling (FDM), which is an additive manufacturing technology commonly used for modeling, prototyping, and production applications. FDM works on an "additive" principle by depositing multiple material in layers forming a three dimensional object using pressure. Materials can range from viscous pastes to liquids, and are inserted using syringes moving in three dimensions. Pressure is applied to syringes, which then deposit a strand of materials for the length of movement, and the time that the pressure is applied. Parallel strands are printed in one layer. For the following layer, the direction of the strands is turned to the centre of the object, creating a mesh with good mechanical properties, and mathematically defined porosity. The features of the system include 3-axis positioning system with high movement accuracy, cell printing with up to five types of cells per object, high flexibility in the choice of materials, fast printing speed, a large building volume, and flexible inner structure design. The operating parameters of the Bioplotter were determined through EnvisionTEC's procedure [4]. In order to successfully mask the fabric sample, the following procedure was followed:

- Mask one entire side of the fabric with tape; a 100×100 mm² fabric square is used for each sample to allow for securing in the printer's squared build area
- Place and secure the sample on the bioplotter for deposition of the top mask
- Load the mask geometry into the Bioplotter RP software
- Select the appropriate build area and material: 100×100 mm², and 400 µm layer height for Vaseline and Silicone
- Reposition the model into a location where it can be successfully printed
- Slice the model into layers with the appropriate thickness
- Export to the Visual Machine plotting software
- Turn on the Bioplotter and assign the appropriate material to the part
- Assign the appropriate internal pattern to the part and save the part
- Insert the material cartridge and the needle tip into the printing head
- Assign the appropriate material and needle tip to the print head in the Visual Machine software
- Calibrate the print head
- Purge and clean the print head
- Start the build

Table 3 shows the devised operating parameters for printing the Vaseline and Silicone masks for the wearable circuit shown in Figure 2.

Table 3. Bioplotter settings for printing Vaseline and Silicone.

Material	Plastic tip size	Speed	Pressure	Temperature	Pre-flow delay	Post-flow delay
Vaseline	400 µm	15.5 mm/s	0.6 bar	20°C	0.00 s	0.00 s
Silicone	250 µm	30 mm/s	3.5 bar	20°C	0.05 s	-0.05 s

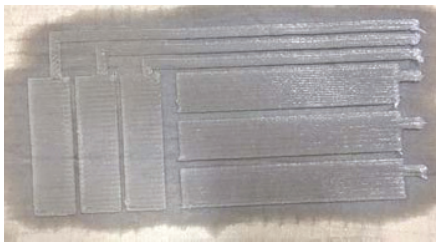


Figure 2. Top Masks printed using a Bioplotter. Vaseline (left) and Silicone (right).

The accuracy of the deposited geometry was satisfactory ensuring consistent isolated paths through the circuit layout. The mix of material volume and deposition speed allowed for circuit design to be produced rapidly (<20 min. per circuit design) while still allowing for a reliable bonding between the layers.

2.3. Preliminary Etching Process

Two square $3 \times 3 \text{ cm}^2$ pieces of the Zell fabric were used to investigate the etching performance of the following two etchants: Sigma-Aldrich 651826 Standard Etchant and Jaycar Ammonium Persulphate Printed Circuit Board Etchant. In a ventilated hood, each fabric piece was placed into a Petri dish, and adequate amount of the etchant was poured into the Petri dish to well cover the fabric piece. At 15-minute intervals, the pieces were removed from the Petri dishes, and while remaining wet, their resistances in $\text{k}\Omega$ between two points separated by 1 cm on the etched area of the fabric pieces were measured using a standard multimeter. Then, each fabric piece was returned to its relevant Petri dish to continue another 15 minutes of etching. At the end of the experiment, the fabric pieces were rinsed with deionized water and dried.

The Sigma-Aldrich etchant can etch Al, Cr, Cu, Ni, GaAs. Surface oxidizes Si, Ta/TaN. It was used at room temperature. The Jaycar etchant was mixed at a ratio of about 40 grams to about 125 mL of water at room temperature. The chemical dissolved quickly and formed a clear liquid. It is recommended to mix this etchant with water at 70 degrees celsius, however, to prevent melting of the nylon fabric in boiling water, water at room temperature was used instead which degraded the etching performance of the etchant. The square samples used the masking method as shown in Table 4.

Table 4. Square samples mask.

Sample ID	Etchant	Mask Top	Mask Bottom
SA	Sigma-Aldrich 651826 Standard Etchant	Nail Polish	Masking Tape
SB	Jaycar Ammonium Persulphate (PCB) @RT $\frac{1}{2}$ solution	Nail Polish	Masking Tape

The etching process for the wearable circuit samples took place after mask completion set up accordingly to parameters previously mentioned shown in Table 2. The set up for the etching process involved is shown in Fig 3.

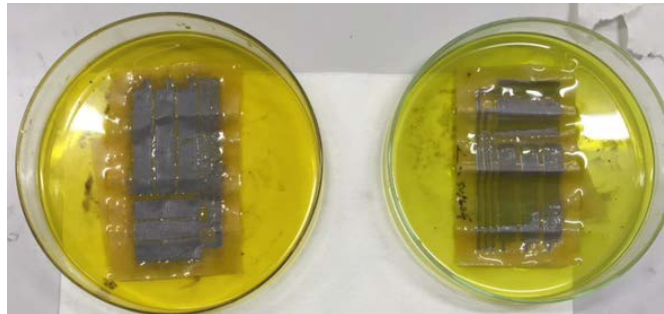


Figure 3. Samples in Chromium etchant Vaseline (left) and silicone (right) at 2 hours of etching.

3. Results

3.1. Preliminary Etching Test – Square Samples

The measured resistances in $\text{k}\Omega$ of the two fabric pieces versus time are shown in Figure 4. The graph in blue represents the resistance changes for the Sigma-Aldrich etchant while the graph in orange shows the resistance changes for the Jaycar etchant. As can be seen in the figure, the Jaycar etchant started etching quicker than the Sigma-Aldrich etchant, and reduced the conductance of the exposed areas significantly after around 30-minute mark. It then continued the etching of the fabric gradually. On the other hand, while the Sigma-Aldrich etchant started the etching slower, after 75-minute mark, it delivered a sharp decrease in the conductance of the exposed areas much faster than that by the Jaycar etchant.

The etched samples are shown in Figure 5. It should be stated that the displayed resistances are not the true resistances of the exposed areas of the fabrics due to the fact that during the measurements the fabrics remained wet

with the etchant. If the fabric pieces had been rinsed and dried before each measurement, much higher resistances would have been observed. Accordingly, while both etchants performed well in etching the unwanted conductive regions of the fabric pieces, the Sigma-Aldrich etchant was found to be more effective and also user friendly than the Jaycar etchant.

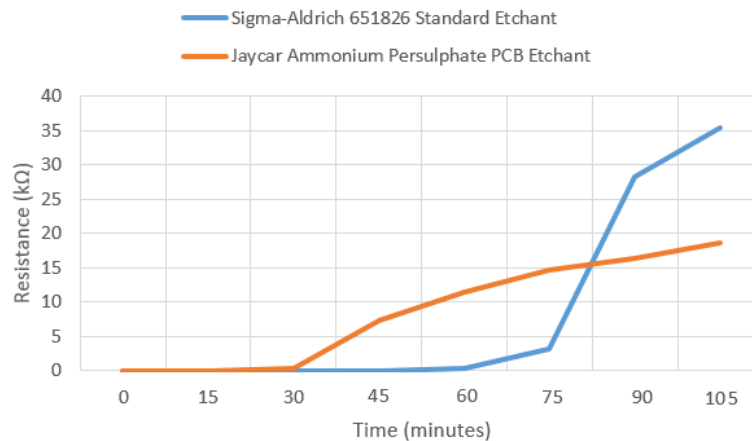


Figure 4. Resistance in kΩ between two points separated by 1 cm on the etched area of the conductive metallized nylon fabric versus time in minutes for Sigma-Aldrich 651826 Standard Etchant (in Blue) and Jaycar Ammonium Persulphate Printed Circuit Board Etchant (in Orange).

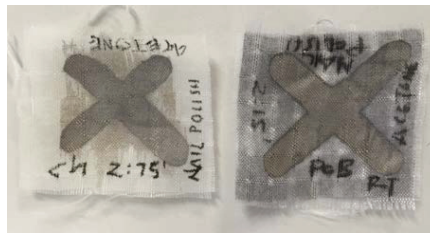


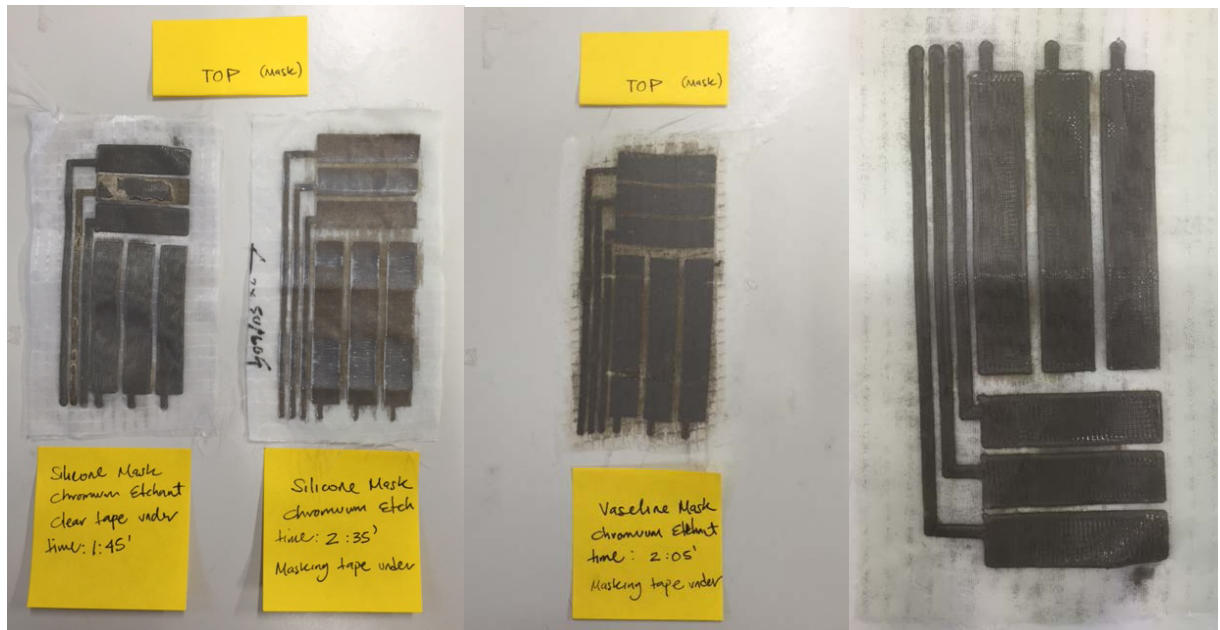
Figure 5. Etched square samples, Sigma-Aldrich 651826 Standard Etchant (left) and Jaycar Ammonium Persulphate Printed Circuit Board Etchant (right)

3.2. Wearable Circuit: Continuity and Separation Tests

Figure 6 shows etched samples results after approximately two hours of etching for the Sigma-Aldrich etchant. The continuity test was performed using a multimeter, and the aim was to test for continuity between each conductive panel (1-6) and its connecting trace. The separation test was basically the same as the continuity test except the aim was to test for non-continuity between the 6 different panels. The five different etching variations tested (Table 5) and etching variant C & E had the best outcome with all 6 panels having continuity with its connecting trace and with each separated from the other 5.

Table 5. Etching parameters for Zell Fabric circuit shown in Figure 1.

Sample ID	Etchant	Top Mask	Bottom Mask	Etch Time (s)	# of panels with continuity	# of panels with separation
A	Sigma-Aldrich 651826 Standard Etchant	Silicone	Masking Tape	2:35'	6	0
B	Sigma-Aldrich 651826 Standard Etchant	Silicone	Clear Tape	2:05'	6	6
C	Jaycar Ammonium Persulphate (PCB)	Silicone	Masking Tape	1:45'	6	0
D	Sigma-Aldrich 651826 Standard Etchant	Vaseline	Masking Tape	16':09"	6	4
E	1/7 Salt and vinegar solution	Vaseline	Masking Tape	72 hours	6	6



a) Mask: Silicon (top). Clear tape mask bottom (left), b) Mask: Vaseline (top). Masking tape bottom. Sigma-Aldrich etchant. c) Mask: Silicone (top). Masking tape bottom clear. Salt and Vinegar solution

Figure 6. Etched results for wearable circuit as per the parameters given in Table 4.

4. Conclusion

This etched conductive fabric design is suitable for building customised wearable pressure sensors using conductive resistive foam. The array of rectangular panels act as positive electrodes, and another piece of conductive fabric of similar size can be used as the negative electrode, with the conductive resistive foam held between the two fabrics. From the experiments, it was found that the combination of Silicone masking, Chromium etchant and clear tape at an etch time of approx. 2 hours was the most successful at etching the conductive fabric. The salt and vinegar solution also was very effective, and utilises cost effective materials. However the etching time needs further optimization

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