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PROOF-OF-CONCEPT EXPERIMENT REPORT

ELECTRIC CONDUCTIVITY OF NON-WOVEN FABRIC

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Proof-of-Concept experiment details

Received samples:

Two representative pieces of non-woven fabric of approximately 0.5m x 0.5m. Thickness of the fabric is below 1mm.

Description by proposer:

One of our products is a semiconductive non-woven fabric. The electric conductivity of this product is an important parameter, which needs to satisfy predetermined value within certain tolerance. The electric conductivity is measured in the direction through the fabric.

We plan to optimize quality control of semiconductive non-woven fabric. We want to verify if transport measurement are suitable for this purpose. In particular, we want to measure electric conductivity in lateral direction of the fabric, and compare the measured conductivity with the electric conductivity in the direction through the fabric.

Planned analysis:

Measure electric conductivity in the plane of the fabric. Measure electric conductivity through the plane of the fabric. Compare results.

Main aim of the proposal:

Test correlation between in-plane and through-plane electric conductivity of non-woven fabric.

Experimental method

Six pieces were cut out of each piece of fabric. All together there were twelve pieces. The pieces were sampled uniformly as presented in Figure 1. Each piece was carefully shaped into a circular form of the diameter of 20mm.

Tape 1 **Tape 2**

Figure 1: Photograph of two non-woven tapes of approximately 0.5m x 0.5m.Left tape was labeled Tape 1 and right tape was labeled Tape 2. Empty gaps represent missing pieces, which were further shaped and electrically characterized.

Resistance measurement through fabric:

For the purpose of electrical resistance measurement through fabric, the piece was mounted between two gold-coated discs as presented in Figure 2. The two discs were used as a top and a bottom electrode. The bottom electrode was placed onto a chunk of the probe station (FormFactor EPS150Triax). The top electrode was pressed down using three probes with needles as presented in Figure 2. Left two needles are low sense and low force connections to a current-voltage measuring device (Keysight B2912A). The chunk was connected to high sense and high force of the same measuring device. The right needle is electrically not connected and is used to apply uniform pressure to the sample under investigation.

For each piece we measured current-voltage (I-V) characteristics. The applied voltage was in the range between -10V and 10V in pulsed mode. The duration of voltage pulses was of 4ms. Using this method, the I-V characteristics exhibited purely Ohmic behaviour. For longer voltage pulses, the I-V characteristics started to show space-charging effects. The resistance (R) was estimated from the slope of current-voltage (I-V) dependence using Ohms law and linear regression:

$$R = {}^{V}\!/_{I} \tag{1}$$

where *R* is the resistance in the direction through plane. We measured the thickness of the fabric and we calculated the resistivity using equation:

$$\varsigma = \frac{R \cdot A}{d} \tag{2}$$

where *A* is area of the circulary shaped fabrics and *d* is the thickness of the fabrics.

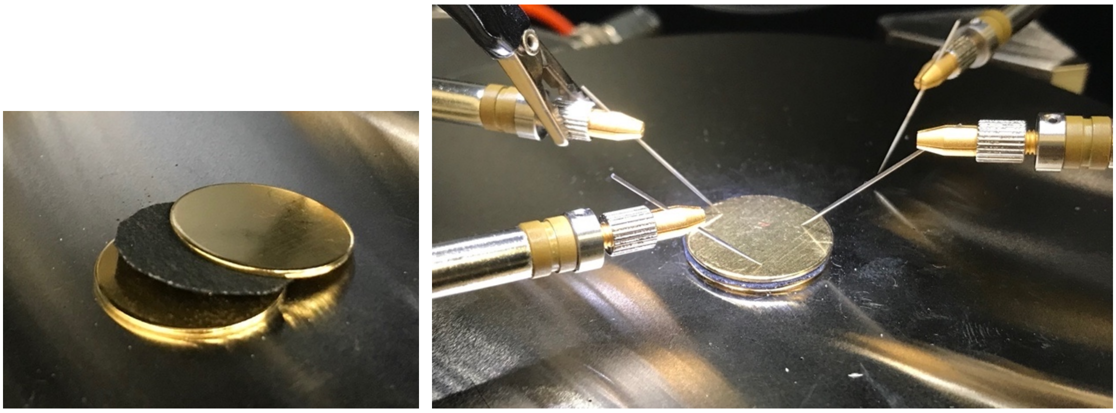


Figure 2: Photograph of (left) assembly of non-woven film between two golden electrodes. And (right) experimental setup of the measurement of electric resistance in the direction through the film. Left two needles are low sense and low force connections. The right needle is electrically not connected and is used to apply uniform pressure to the sample under investigation.

Resistance measurement in-plane of fabric:

For the purpose of electrical resistance measurement in-plane of fabric, four silver electrodes of a ~1mm diameter were deposited into four corners of the circular piece as presented in Figure 3. Silver electrode coatings were used to improve electric contact between measuring needles and the fabric. Silver electrode contacts were labeled with numbers 1, 2, 3 and 4 in a clock-wise direction. The arrow represents prefered orientation of fibers in the fabric. Silver electrodes 1 and 3 were aligned with the fiber direction, while 2 and 4 were placed perpendicularly. These silver electrodes were approached with the needles of the probe station and connected in a Kelvin mode to a current-voltage measuring device (Keysight B2912A). The fabrics was placed on top of microscope slide.

For each piece we measured current-voltage (I-V) characteristics using Van der Pauw method. Accordingly, for each piece we measured four I-V characteristics, namely I_{12}-V_{34}, I_{23}-V_{41}, I_{34}-V_{12}, and I_{41}-V_{23}, where indexes represents the corresponding connection of the voltmeter and amperemeter of the measuring device. We used pulsed voltage method for the same reasons as explainied before. Using the same Eq.(1), we estimated four resistances: R_{1234}, R_{2341}, R_{3412}, and R_{4123}. Using the Van der Pauw theory, we calculated horizontal (R_H) and vertical (R_V) resistance of the fabrics:

$$R_H = \frac{R_{1234} + R_{3423}}{2} \qquad R_V = \frac{R_{2341} + R_{4123}}{2} \tag{3}$$

These two were used to calculate sheet resistance using Newton-Raphson method and Van der Pauw equation:

$$e^{-\pi R_V / R_S} + e^{-\pi R_H / R_S} = 1 \tag{4}$$

where R_S is the sheet resistance in plane of the fabric.

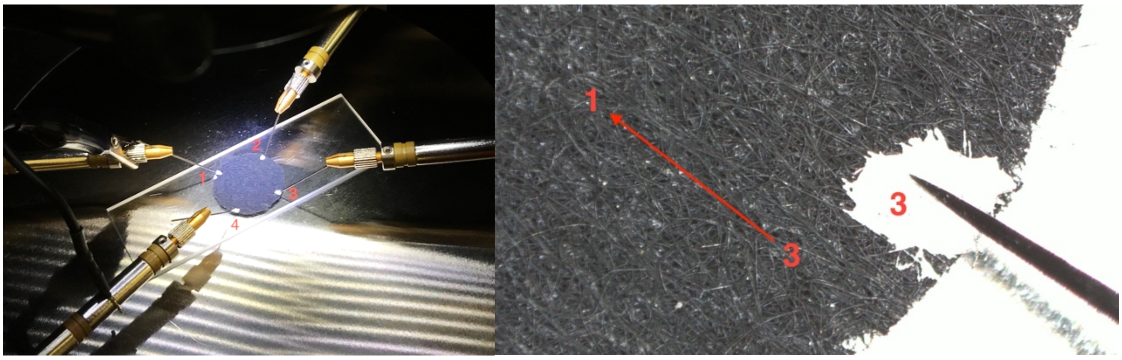


Figure 3: Photograph of experimental setup of the measurement of electric resistance in-plane of the film (left). Opical microscopy of the non-woven film and the silver electode contact, which were used to improve electric contact between measuring needles and the fabric. Silver electrode contacts were labeled with numbers 1, 2, 3 and 4 in a clock-wise direction. The arrow represents prefered orientation of fibers in the fabric. Silver electrodes 1 and 3 were aligned with the fiber direction, while 2 and 4 were placed perpendicularly.

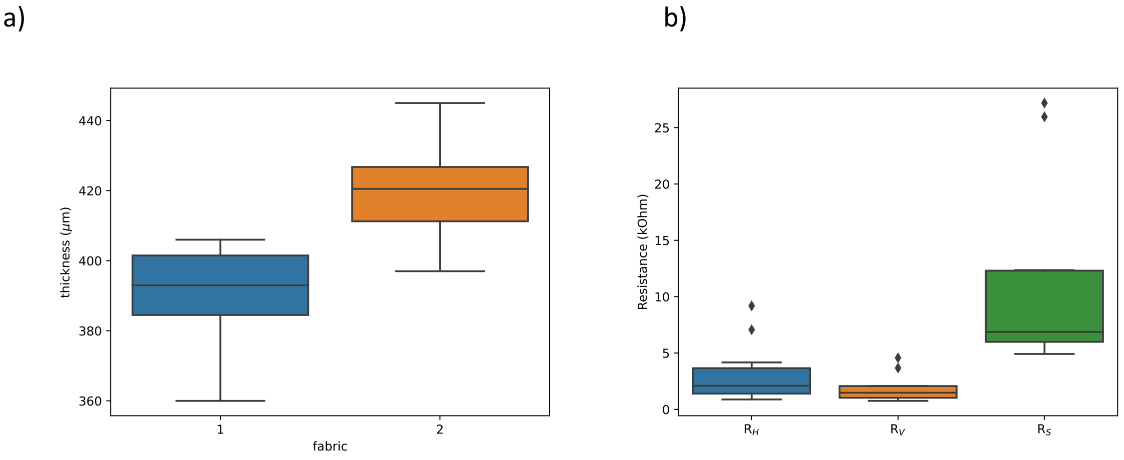


Figure 4: (a) Boxplot of thickness of measured pieces of non-woven fabrics. (b) Horizontal, vertical and sheet resistance of non-woven fabrics.

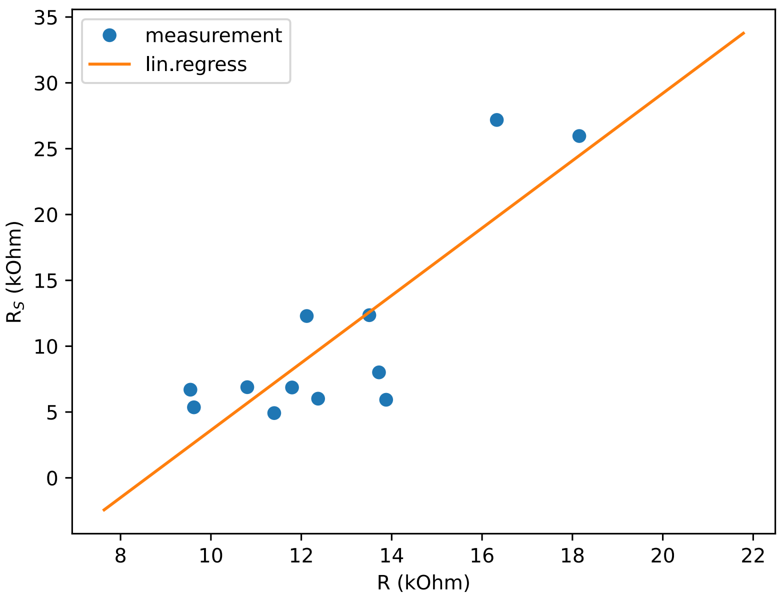


Figure 5: In-plane resistance (R_S) as a function of resistance measured through the fabrics (R).Line represents linear regression of the dependence between the two measured properties.

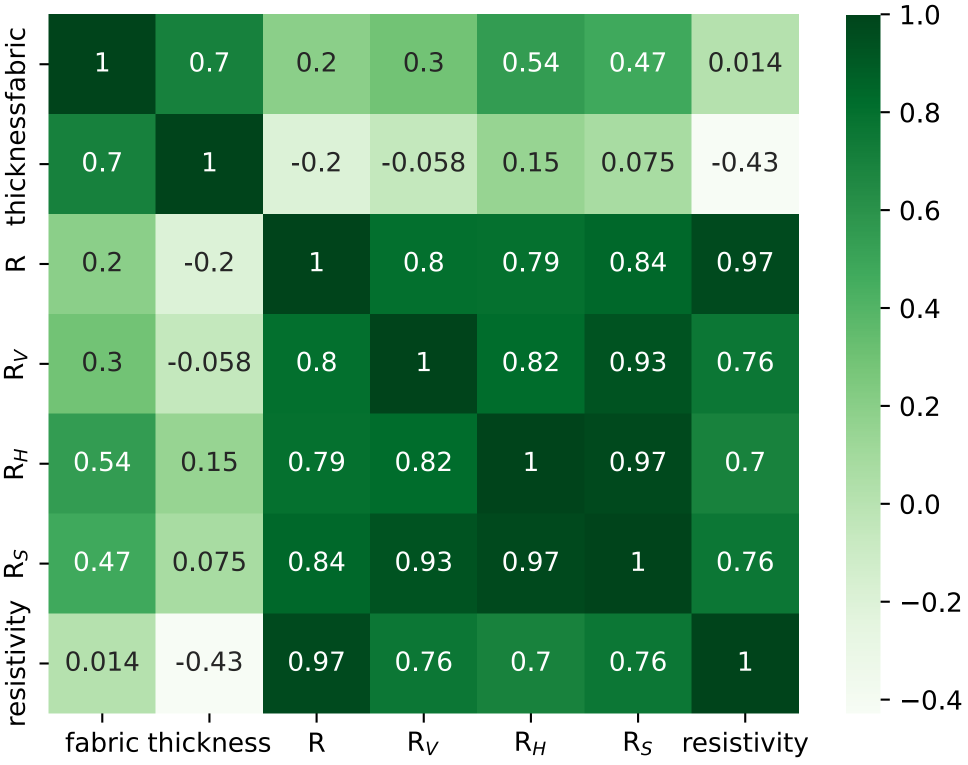
Results

The thickness of fabric pieces varied as presented in Figure 4a. The thickness of the first fabric (360µm - 410µm) was approximately 30 µm thinner than the second fabric (395µm - 445µm).

Figure 4b represents in-plane resistance obtained by Eqs.(3-4). We note that the in-plane resistance is anisotropic. Horizontal in-plane resistance is exhibiting higher values compared to vertical in-plane resistance. Presumably, lower vertical in-plane resistance hints that the in-plane conductivity is higher in the direction of fiber alignment (see Figure 3). In-plane sheet resistance (RS) is obtained by Eq.(4) and stands for the in-plane resistance.

Symbols in Figure 5 represent in-plane resistance (R_S) as a function of resistance measured through the fabrics (R). The measured datapoints are scattered in two groups. Majority of datapoints are distributed in relatively random manner. In addition to the main group, there are two datapoints with higher resistances. We performed linear regression analysis in order to estimate correlation between the two resistances. Line represents linear regression of the dependence between the R_S and R. The correlation coefficient R was of 0.84, the power of the test was $6.5x10^{-4}$. Based on these results, we can conclude there is positive correlation between R_S and R.

Correlation was tested also between other parameters and is summarized in Figure 6. The correlations between R_S, R_V, R_H and resistivity are high since these parameters were calculated from the same measured resistances as described above. Consequently, these parameters exhibit similar correlation to R_S as R, which was discussed above. The last significant correlation is between thickness and fabric, which was already presented in Figure 4.



	fabric	thickness	R	R_V	R_H	R_S	resistivity
fabric	1	0.7	0.2	0.3	0.54	0.47	0.014
thickness	0.7	1	-0.2	-0.058	0.15	0.075	-0.43
R	0.2	-0.2	1	0.8	0.79	0.84	0.97
R_V	0.3	-0.058	0.8	1	0.82	0.93	0.76
R_H	0.54	0.15	0.79	0.82	1	0.97	0.7
R_S	0.47	0.075	0.84	0.93	0.97	1	0.76
resistivity	0.014	-0.43	0.97	0.76	0.7	0.76	1

Figure 6: Correlation between different measured parameters.

Concluding remarks

In-plane resistance (R_S) exhibits statistically significant correlation to the through-fabric resistance (R). The correlation coefficient is of 0.84. Consequently, the transport measurement of in-plane resistance can potentially be used for quality check purposes.

This report has been written by Egon Pavlica (Ajdovščina, 14 July 2022)