ORIGINAL PAPER

ELECTRICAL CHARACTERIZATION OF TRANSPARENT CONDUCTING MATERIALS

ANDREI CHILIAN[1], IULIAN BANCUTA[2], OANA ROXANA BANCUTA[1], RODICA MARIANA ION[3,4], RADU SETNESCU[5,6], TANTA SETNESCU[5,6]

Manuscript received: 16.03.2017; Accepted paper: 17.07.2017;

Abstract. *Transparent conducting materials (or Transparent conducting oxides, TCO) are essential elements in the construction of dye-sensitized solar cells (DSSC). They must have a small electrical resistance and a good optical transmittance. By electrical characterization of these materials, it can identify the possible structural defects that can adversely affect the yield of sunlight conversion into electricity in dye-sensitized solar cells (DSSC).*

Keywords: *TCO, structural defects, DSSC, Van der Pauw method, electrical resistance measurement.*

1. INTRODUCTION

Identification of conductive surface defects is an important aspect of these materials study [1], that are used for manufacture of dye-sensitized solar cells (DSSC) [2]. There are various possibilities for their identification:

- by comparing electrical parameters in different parts of surface;
- by comparing the chemical composition in different parts of surface;
- by comparing the surface structure in different parts of surface;
- by comparing the transmittance in the different areas of surface [3].

Electrical characterization of transparent conductive materials is very important because too much electrical resistance in some parts of the material can lead to loss of electricity and thus decreases conversion yield of sunlight into electricity [4].

To characterize electrically the material, in this study it has been used two methods:

- measurement of material surface resistance by multimeter in 2 points;
- measurement of material surface resistance by 2 multimeters in 4 points (Van der Pauw method).

---

[1] The Water Company from Targoviste, 130055, Targoviste, Romania.

[2] Valahia University of Targoviste, Institute of Multidisciplinary Research for Science and Technology, 130004 Targoviste, Romania. E-mail: iulian_bancuta@yahoo.com

[3] National Research & Development Institute for Chemistry - ICECHIM, 060021 Bucharest, Romania.

[4] Valahia University of Targoviste, Faculty of Materials Engineering and Mechanics, 130004 Targoviste, Romania.

[5] Valahia University of Targoviste, Faculty of Sciences and Arts, 130082 Targoviste, Romania.

[6] R&D Institute for Electrical Engineering, Department for Advanced Materials, 030138 Bucharest, Romania.

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. Materials for determination of sheet electrical resistance by Van der Pauw method

For determination it is necessary: a voltmeter, an ammeter, a direct current source (ex. A battery) and connectors.

2.1.2. Materials for determination of electrical resistance by multimeter in 2 points

For determination of the electric resistance by this method, it was used a multimeter with possibility of electrical resistance measurement.

2.2. METHODS

2.2.1. Determination of sheet electrical resistance by Van der Pauw method

Determination of sheet electrical resistance of the surface (R_s) provides an overview on the electrode.

By Van der Pauw method it can determine sheet electrical resistance (R_s). Knowing the electrical resistance and thickness of the deposited conductor layer, it can easily determine its resistivity (ρ) and conductivity (σ).

This method has several major advantages:

- It can be applied for resistivity measurements, even for samples with unknown geometry;
- It can be applied for determining the resistivity of semiconducting materials, but also of the superconductors.

By using this method, it must be considered some very important recommendations [5]:

- The contacts are mounted on the edge of sample. Depending on the thickness of sample, the contacts are arranged so as to include as much as possible the thickness of the deposited layer;
- The contacts must be sufficiently small, ideally as a point and must have a negligible section;
- The sample must be fairly homogeneous in section;
- The surface should be fairly uniform, without cracks and holes.

The procedure of sheet electrical resistance determination by Van der Pauw method. Procedure of sheet electrical resistance determination by Van der Pauw method is relatively simple [6,7]:

- Assemble the circuit as shown in Fig. 1, by using materials indicated in *Section 2.1.1.*;
- The voltage U_{AB} is read at the same time with the intensity I_{CD};
- Repeat the measurement by changing contacts:
  - U_{BC} is read simultaneously with I_{DA};
  - U_{CD} is read simultaneously with I_{AB};
  - U_{DA} is read simultaneously with I_{BC}.

For more accurate measurements at calculation of sheet electrical resistance of material, it will be done additional measurements by reversing the polarity:

- U_{BC} is read simultaneously with I_{AD};
- U_{DA} is read simultaneously with I_{CB};
- U_{BA} is read simultaneously with I_{CD};
- U_{AB} is read simultaneously with I_{DC}.

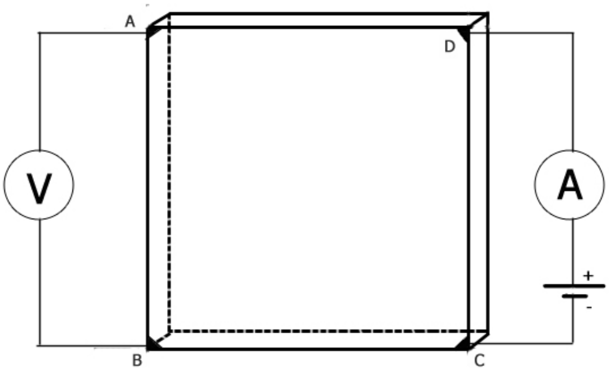

Figure 1. The assembly of the circuit for determining the sheet electrical resistance by Van der Pauw method.

R value is calculated according to Ohm's law, using the values of electric voltage and intensity:

$$R_{AB,CD} = \frac{U_{AB}}{I_{CD}} \tag{1}$$

$$R_{BC,DA} = \frac{U_{BC}}{I_{DA}} \tag{2}$$

$$R_{CD,AB} = \frac{U_{CD}}{I_{AB}} \tag{3}$$

$$R_{DA,BC} = \frac{U_{DA}}{I_{BC}} \tag{4}$$

For more accurate determinations, it will be calculated:

$$R_{BA,CD} = \frac{U_{BA}}{I_{CD}} \tag{5}$$

$$R_{AB,DC} = \frac{U_{AB}}{I_{DC}} \tag{6}$$

$$R_{BC,AD} = \frac{U_{BC}}{I_{AD}} \tag{7}$$

$$R_{DA,CB} = \frac{U_{DA}}{I_{CB}} \tag{8}$$

$R_{horizontal}$ and $R_{vertical}$ are determined from formula:

$$R_{horizontal} = \frac{R_{AB,CD} + R_{CD,AB}}{2} \tag{9}$$

$$R_{vertical} = \frac{R_{BC,DA} + R_{DA,BC}}{2} \tag{10}$$

For more precise values of $R_{horizontal}$ and $R_{vertical}$, these indices are determined from:

$$R_{horizontal} = \frac{R_{AB,CD} + R_{CD,AB} + R_{BA,CD} + R_{AB,DC}}{4} \tag{11}$$

$$R_{vertical} = \frac{R_{BC,DA} + R_{DA,BC} + R_{BC,AD} + R_{DA,CB}}{4} \tag{12}$$

The electrical resistance of the surface will be determined from formula:

$$e^{-\frac{\pi R_{vertical}}{R_s}} + e^{-\frac{\pi R_{horizontal}}{R_s}} = 1 \tag{13}$$

Because the analyzed surface of body has quadratic form, it can be concluded that $R_{horizontal} = R_{vertical} = R_m$, but for a better approximation it is applied the equation (14):

$$R_m = \frac{R_{horizontal} + R_{vertical}}{2} \tag{14}$$

$$e^{-\frac{\pi R_m}{R_s}} + e^{-\frac{\pi R_m}{R_s}} = 1 \tag{15}$$

$$2e^{-\frac{\pi R_m}{R_s}} = 1 \tag{16}$$

From this equation it can be deduced:

$$e^{-\frac{\pi R_m}{R_s}} = \frac{1}{2} \tag{17}$$

$$\ln e^{-\frac{\pi R_m}{R_s}} = \ln 2^{-1} \tag{18}$$

$$-\frac{\pi R_m}{R_s} = -\ln 2 \tag{19}$$

Final relationship for sheet electrical resistance:

$$R_s = \frac{\pi R_m}{\ln 2} \tag{20}$$

2.2.2. Determination of electrical resistance by multimeter in 2 points

This method provides a better image on detecting surface defects by comparison with Van der Pauw method that provides only information about total surface electrical resistance.

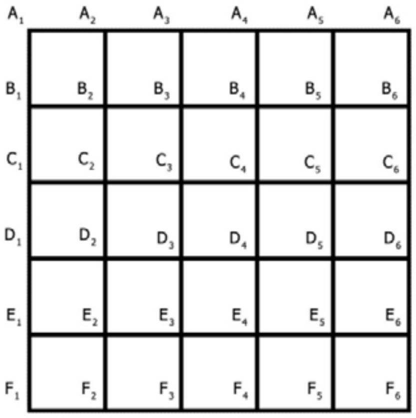

Figure 2. Scheme of points where have been made measurements of the surface electrical resistance.

Determination of electrical resistance was made between each two points (between A_1 and A_2, between A_1 and A_3, ... between F_5 and F_6) as shown in Fig. 2, by using materials indicated in *Section 2.1.2*. The same type of determination was applied to each plate of SnO_2:F, resulting 630 determinations for each sample.

To illustrate the variation of electrical resistance on the surface, they were represented graphically data on its electrical resistance between each two points located at 1 cm distance. Thus, possible structural defects have been observed.

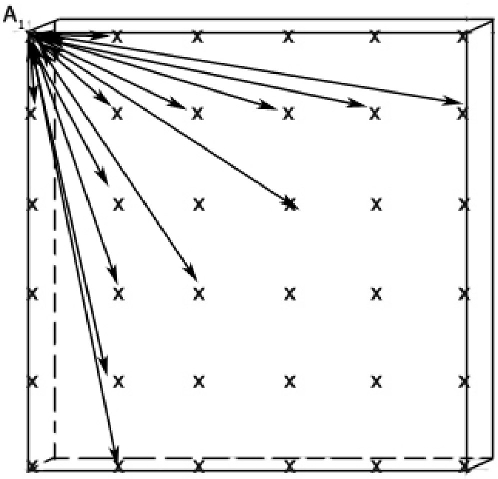

Figure 3. Determination method of electrical resistance between the point A1 and the other points of the material surface (A_2, A_3, ..., F_5, F_6).

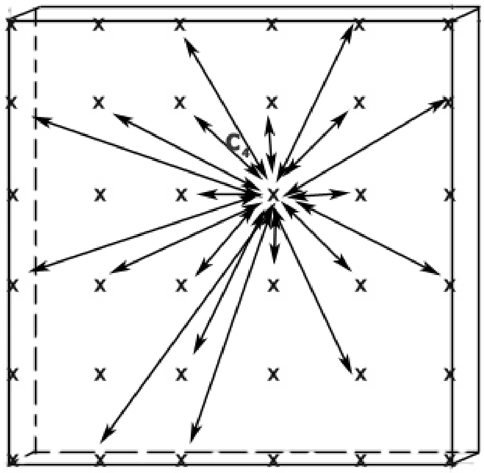

Figure 4. Determination method of electrical resistance between the point C4 and the other points of the material surface (A_1, A_2, ..., C_2, C_3, C_5, C_6,…, F_5, F_6).

The generated images, after electrical resistance values processing measured between each two points located at 1 cm distance, provides a very good interpretation of surface electrical situation.

For a better study of these materials, it has been applied, also, other models of electrical resistance determination:

- between point A_1 and any other point (Fig. 3);
- between point C_4 and any other point (Fig. 4).

2.2.3 Statistical and graphical investigations

For statistical measurements they were used the software Microsoft Excel and IBM SPSS Statistics, and for graphical representation – software Surfer.

Interpretation of the results was performed using Pearson correlations, principal component analysis (PCA) and Student t-test.

3. RESULTS AND DISCUSSION

3.1. RESULTS

3.1.1. Determination of sheet electrical resistance of transparent conducting materials based on SnO_2: F by Van der Pauw method

By Van der Pauw method were characterized 4 plates of SnO_2:F, purchased commercially. Manufacturer's warranty on the sheet electrical resistance of these materials is 7 Ω/area. Experimentally, it was observed that the sheet electrical resistance (R_s) for these plates is much smaller (max. 2.930 Ω/area for FTO 2, Table 1).

Table 1. The electrical characteristics of the transparent conductive materials on the basis of SnO_2: F, determined by the Van der Pauw method.

	FTO 1	FTO 2	FTO 3	FTO 4
Electrical voltage (mV)	U_{AD} = 66,5 U_{AB} = 67,5 U_{BC} = 69,8 U_{DC} = 64,4	U_{AD} = 65,4 U_{AB} = 63,5 U_{BC} = 67,2 U_{DC} = 66,9	U_{AD} = 66,4 U_{AB} = 61,5 U_{BC} = 59,9 U_{DC} = 68,3	U_{AD} = 61,5 U_{AB} = 64,8 U_{BC} = 64,7 U_{DC} = 63,8
Electrical intensity (mA)	I_{BC} = 104 I_{DC} = 105 I_{AD} = 109 I_{AB} = 101	I_{BC} = 99,8 I_{DC} = 102 I_{AD} = 103 I_{AB} = 102	I_{BC} = 101,5 I_{DC} = 96 I_{AD} = 93,5 I_{AB} = 110	I_{BC} = 99 I_{DC} = 100,9 I_{AD} = 100,2 I_{AB} = 99,5
Electrical resistance (Ω)	$R_{DA,BC}$ = 0,639 $R_{AB,CD}$ = 0,643 $R_{BC,DA}$ = 0,640 $R_{CD,AB}$ = 0,638	**$R_{DA,BC}$ = 0,655** $R_{AB,CD}$ = 0,623 **$R_{BC,DA}$ = 0,652** **$R_{CD,AB}$ = 0,656**	**$R_{DA,BC}$ = 0,654** $R_{AB,CD}$ = 0,641 $R_{BC,DA}$ = 0,641 $R_{CD,AB}$ = 0,621	$R_{DA,BC}$ = 0,621 $R_{AB,CD}$ = 0,642 $R_{BC,DA}$ = 0,646 $R_{CD,AB}$ = 0,641
Horizontal electrical resistance, $R_{horizontal}$ (Ω)	$R_{horizontal}$ = 0,640	$R_{horizontal}$ = 0,639	$R_{horizontal}$ = 0,631	$R_{horizontal}$ = 0,642
Vertical electrical resistance, $R_{vertical}$ (Ω)	$R_{vertical}$ = 0,640	$R_{vertical}$ = 0,654	$R_{vertical}$ = 0,647	$R_{vertical}$ = 0,633
Surface electrical resistance, R_s (Ω/area)	R_s = 2,901	R_s = 2,930	R_s = 2,897	R_s = 2,890

Because of the similarity between the recorded values, it can be mentioned that these materials were obtained by the same technique and possibly be from the same batch.

Table 2. Student t-test applied to the sheet electrical resistance values obtained on 4 plates of SnO_2: F

	Degrees of freedom	Average R_S (Ω/area)	Minimum R_S for a probability of 95 % (Ω/area)	Maximum R_S for a probability of 95 % (Ω/area)
R_S	3	2.90450	2.8765	2.9325

As shown by Student t-test (Table 2), all sheet electrical resistance values enter in the confidence interval for a probability of 95%. This can signify that the all SnO_2:F plates have the same provenience.

Considering the fact that SnO_2:F plates have the same origin and the same geometry (perfect squares with area 5 x 5 cm^2), it is acceptable that the samples should have similar values for measured horizontal ($R_{horizontal}$) and the vertical resistances ($R_{vertical}$). Because these values are calculated from the measured resistance values in various points, they should be very similar.

Table 3. Student's t-test applied on the electric resistance values measured in 4 positions on the 4 plates of SnO_2: F

	Degrees of freedom	$R_{average}$ (Ω)	R_{min} for a probability of 95 % (Ω)	R_{max} for a probability of 95 % (Ω)
R	15	0,64081	0,6348	0,6468

After processing the resistance values ($R_{DA,BC}$, $R_{AB,CD}$, $R_{BC,DA}$; $R_{CD,AB}$) for 4 plates of SnO_2:F (Table 3), it was observed that FTO 2 has the higher values of this indicator (3 high resistance values from 4), which can be correlated with higher surface electrical resistance compared to other samples (2.930 Ω/area). Only values which are greater than R_{max} for a probability of 95% are of interest, the smallest vales of electrical resistance that R_{min} for a probability of 95 % are not interesting because a lower electrical resistance of the material increases the efficiency of DSSC. The values that are greater than R_{max} for a probability of 95% are bold in Table 1.

3.1.2. Electrical resistance measurement of material surface with multimeter in 2 points

Plate 1 of SnO_2:F (FTO 1)

On the basis of these determinations on plate FTO 1, it is able to identify several areas of electrical resistance variation (Fig. 5). Relating to the fact that analyzed objects have surfaces of perfect squares (5 x 5 cm^2) is easy to see that zone A stands out with less resistance (< 14 Ω between 2 points at 1 cm distance), which can be caused by a better uniformity of the material in this area or its greater thickness in this region. The same observation can be made for zone D (< 14 Ω between 2 points at 1 cm distance), which is characterized by a lower electrical resistance. Zones B and C, characterized by higher electrical resistance compared with zones A and D (< 15 Ω between 2 points at 1 cm distance), suggest that these areas have structural defects that worsen the electrical conductivity or that this layer of SnO_2:F in this area is thinner.

Generally, the plate edges are characterized by a higher electrical resistance (> 23 Ω between 2 points at 1 cm distance) compared with other parts of the plate (zones E, F and H), but zone G still seems to have the electrical resistance much lower compared to other corners of the plate (< 19.5 Ω between 2 points at 1 cm distance).

From Fig. 6 characteristic for FTO 1, it can be seen that by changing the measurement mode of electrical resistance, some areas no longer visible, and others become more easily for examination. Areas B and C can no longer distinguish (where it has been observed a higher electrical resistance). Zone D shows fairly uniform in terms of electrical resistance by reference to A_1 point (24 - 25 Ω from the point A_1). Zones F and H, in terms of symmetry, being at the same distance from the point A_1, would have to have the same values of electrical resistance by reference to A_1, however, it can be seen that zone F has up to 37 Ω by reference to A_1, and region H does not reach to 35 Ω by reference to A1.

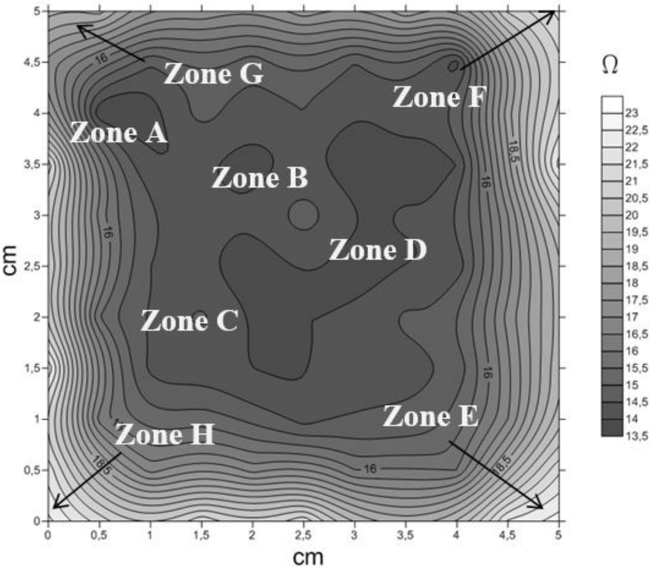

Figure 5. The electrical resistance of the surface (in Ω) measured by multimeter between each two adjacent points at 1 cm distance on FTO 1 as shown in Figure 2.

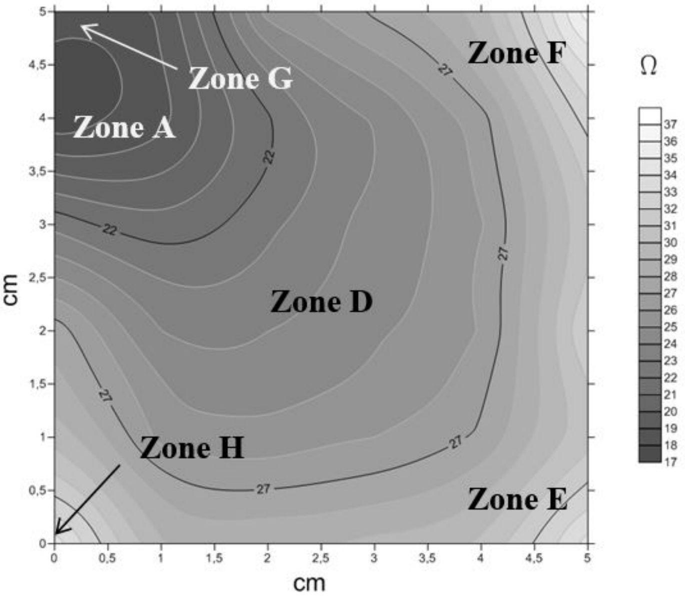

Figure 6. The electrical resistance of the FTO 1 surface (in Ω), measured by multimeter from the point A1 (the point situated on the edge of the plate), and other points, as shown in Figure 3.

Resistance measurement between two points on the material surface, so that a point is near the center of the surface (C_4) and the second point is any other point (Fig. 7), highlights areas E, F, G, H located in the corners of plate, characterized by high electrical resistance (> 24.5 Ω to point C_4). Point C_4 is nearer to the zone F compared to zone G, but the region G has a lower electrical resistance between points, which can be explained in this case that the area F has a higher electrical resistance.

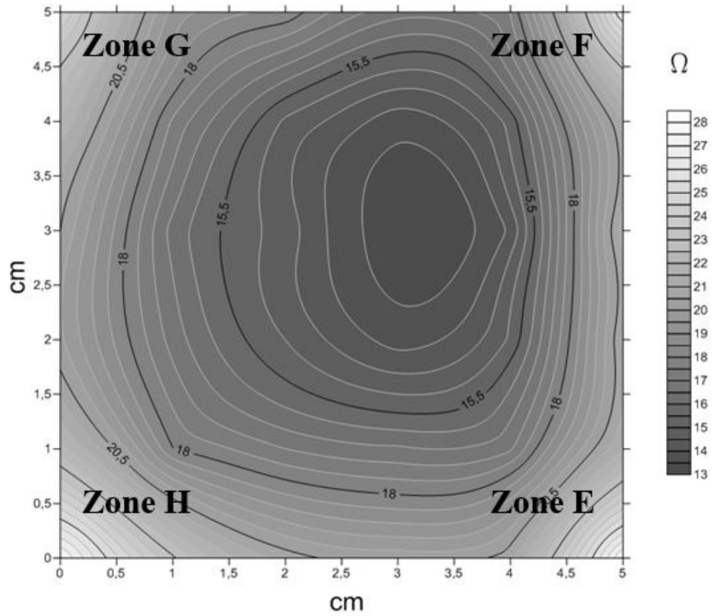

Figure 7. The electrical resistance of the FTO 1 surface (in Ω), measured by multimeter from the point C_4 (the point situated on the edge of the plate), and other points, as shown in Figure 4.

Plate 2 of SnO_2:F (FTO 2)

Applying the same model of study for electrical resistance (electrical resistance values measured between any two random points at 1 cm distance) on the plate 2 of SnO_2:F (FTO 2), some very interesting areas are observed (Fig. 8): Zones A’ and B’ - located in the corners of the plate with high resistance (> 28 Ω between 2 points at 1 cm distance). Although, due to the surface symmetry, areas C’ and D’ should be similar to zones A’ and B’ in terms of electrical resistance, but these areas have much lower values of electrical resistance (> 22.5 Ω between 2 points at 1 cm distance).

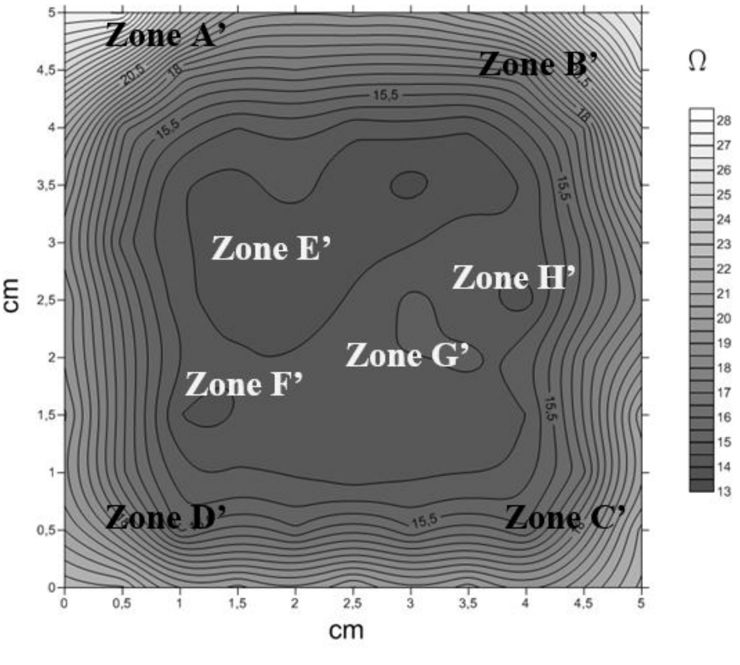

Figure 8. The electrical resistance of the surface (in Ω) measured by multimeter between each two adjacent points at 1 cm distance on FTO 2 as shown in Figure 2.

Also, some areas with lower electrical resistance can be seen toward the center of the material surface: the zones E', F' and H' (< 14 Ω between 2 points at 1 cm distance). Zone G' seems to describe an area with structural defects, having higher electrical resistance compared to surrounding areas (> 14.5 Ω between 2 points at 1 cm distance).

Compared with FTO 1, it can be said that FTO 2 reach higher values of electrical resistance measured between two points at 1 cm distance (28 Ω compared with 23 Ω). This can be associated with fact that total surface resistance of FTO 2 is higher than the total surface resistance of FTO 1 (2.930 Ω/area to 2.901 Ω/area).

Applying the study model of electrical resistance from point A_1 (Fig. 9), it can see a very interesting image: zone E' has lower electrical resistance (< 25 Ω to point A_1). In terms of symmetry, it appears that side between zones A' and B' has a higher resistance. Normally, it should be an area equivalent to the area E' on this side. Zone B' should have the same resistance value to A_1 compared with area D'. However, a difference of 2 Ω exists between resistances values measured from the point A_1. It is clear that this area is characterized by a structure defect or an irregularity related to SnO_2:F layer deposited on the glass.

Zone G' is highlighted as a nearly constant resistance portion to A_1 (< 31 Ω). It can observed easily zone F' with a lower electrical resistance compared with the zone G' (< 30 Ω to A1).

Compared with FTO 1, by studying this model it can be observed higher values of electrical resistance from the point A_1 (< 47 Ω compared to < 38 Ω).

By measuring the electrical resistance between the point C_4 and any other point on the plate (Fig. 10), it can be seen the image of Fig. 4. The variations appear to be quite uniform. Also, it can see zones E' and F' with electric resistance values of < 19 Ω and < 21 Ω compared to point C_4. With this model, also, it can see that FTO 2 has higher resistance against FTO 1 (< 31 Ω compared to < 29 Ω measured from the point C4).

Plate 3 of SnO_2:F (FTO 3)

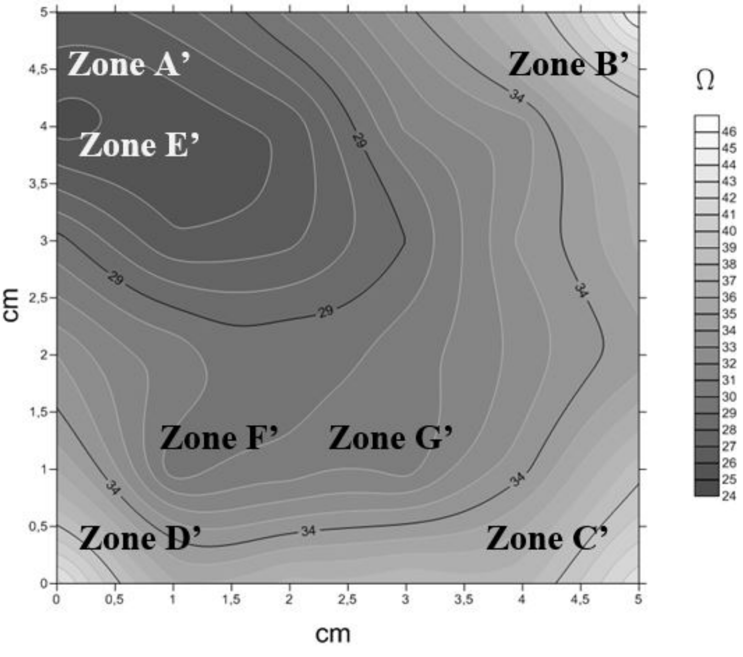

Figure 9. The electrical resistance of the FTO 2 surface (in Ω), measured by multimeter from the point A_1 (the point situated on the edge of the plate), and other points, as shown in Figure 3.

By investigating electrically plate FTO 3 (by measuring the electrical resistance between any two points at 1 cm distance), it can be seen following areas (Fig. 11):

- Zones A'', C'' and D'', characterized by an electrical resistance of < 24 Ω measured between two points at 1 cm distance;
- Zone B'' with an electrical resistance < 28 Ω measured between two points at 1 cm distance;
- Zones E'' and F'', characterized by an electrical resistance of < 14 Ω measured between two points at 1 cm distance;
- Zone G'' with electrical resistance of < 15 Ω measured between two points at 1 cm distance.

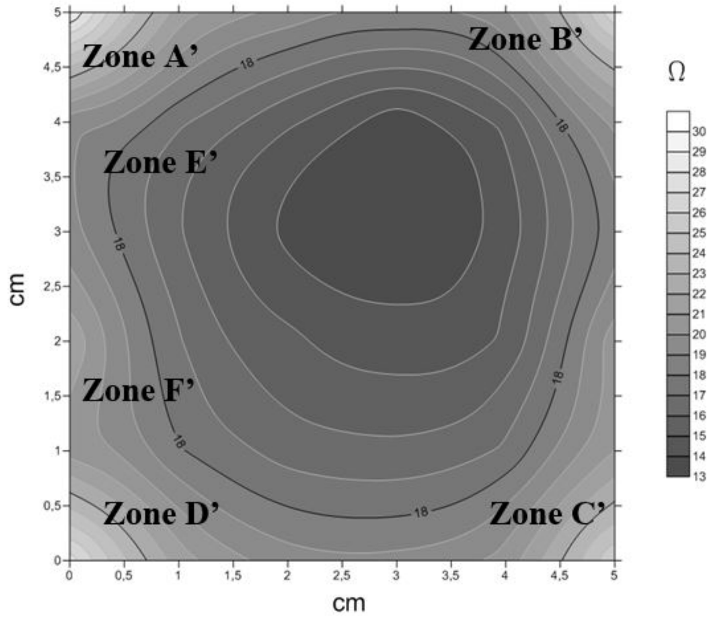

Figure 10. The electrical resistance of the FTO 2 surface (in Ω), measured by multimeter from the point C_4 (the point situated on the edge of the plate), and other points, as shown in Figure 4.

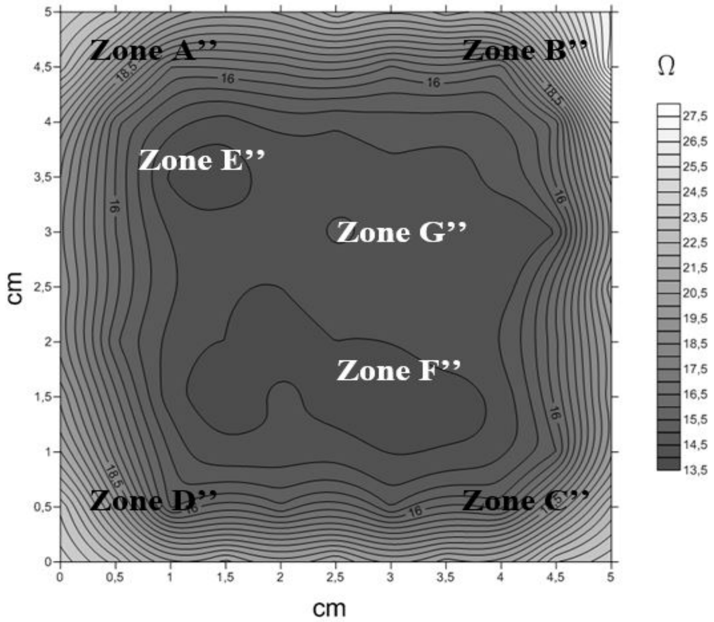

Figure 11. The electrical resistance of the surface (in Ω) measured by multimeter between each two adjacent points at 1 cm distance on FTO 3 as shown in Figure 2.

The values of maximum electrical resistance measured between two points at 1 cm distance is < 28 Ω, which approaches FTO 3 to FTO 2. However it should be noted that FTO 3 has a single electric resistance area close to 28 Ω, compared with the FTO 2, which has two such areas.

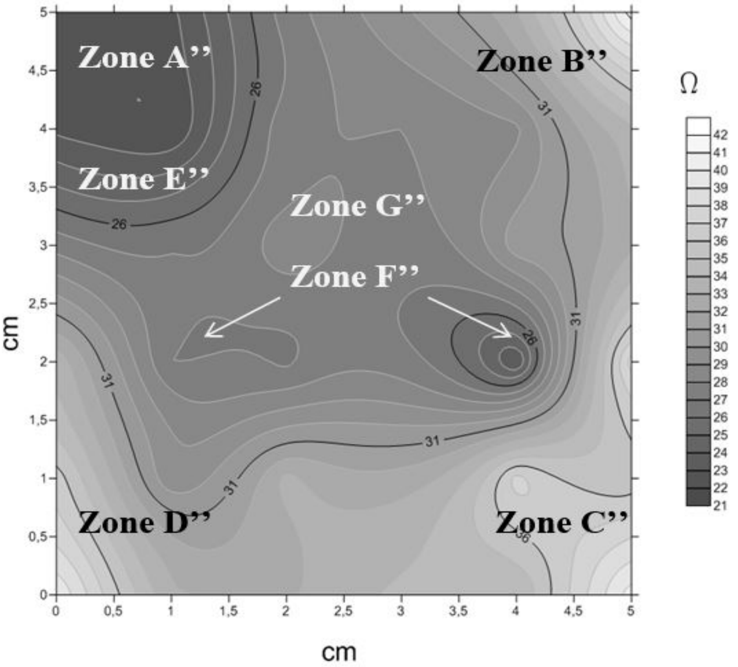

Figure 12. The electrical resistance of the FTO 3 surface (in Ω), measured by multimeter from the point A_1 (the point situated on the edge of the plate), and other points, as shown in Figure 3.

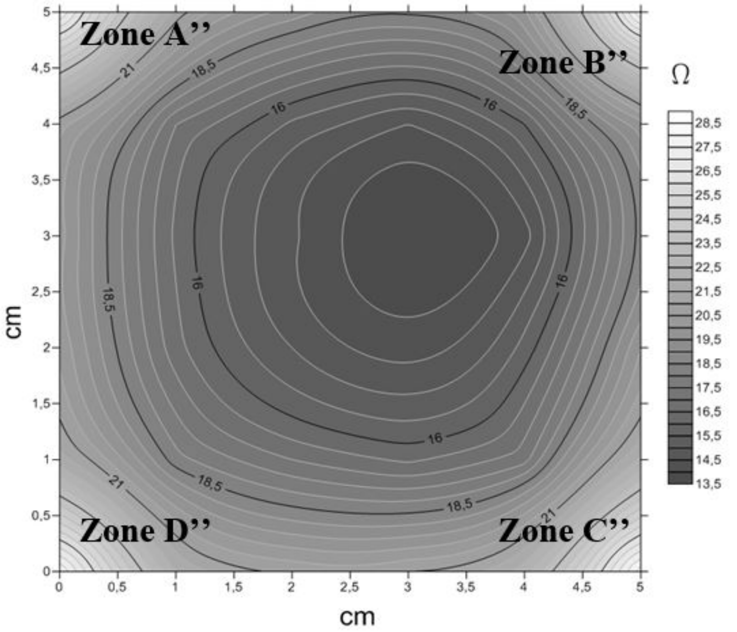

Figure 13. The electrical resistance of the FTO 3 surface (in Ω), measured by multimeter from the point C_4 (the point situated on the edge of the plate), and other points, as shown in Figure 4.

Regarding the experimental model for the measurement of electrical resistance from the point A_1 (Fig. 12), it appears that areas of concern remain visible, emphasizing areas with defects. Zone G'' is visible in this experimental model (having electric resistance to < 29 Ω to point A_1). Zone F’’, fragmented into 2 parts, has very low electrical resistance to the point A1 (< 27 Ω).

With experimental model focused on measuring the electrical resistance between C_4 (located near the center of the area) and other points on the surface (Fig. 13), it is observed a uniformity in terms of electrical resistance (< 29 Ω compared to C_4). The maximum values of electrical resistance, measured in this mode, are very similar with the maximum values observed at FTO 1.

Plate 4 of SnO_2:F (FTO 4)

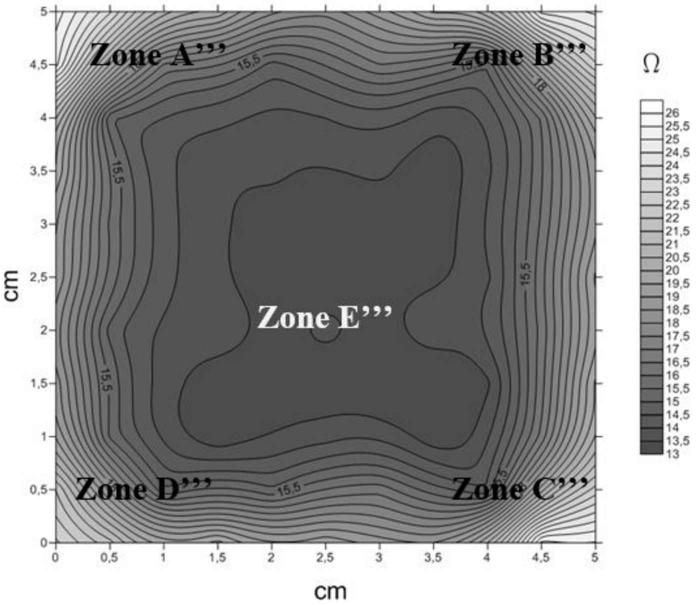

Figure 14. The electrical resistance of the surface (in Ω) measured by multimeter between each two adjacent points at 1 cm distance on FTO 4 as shown in Figure 2.

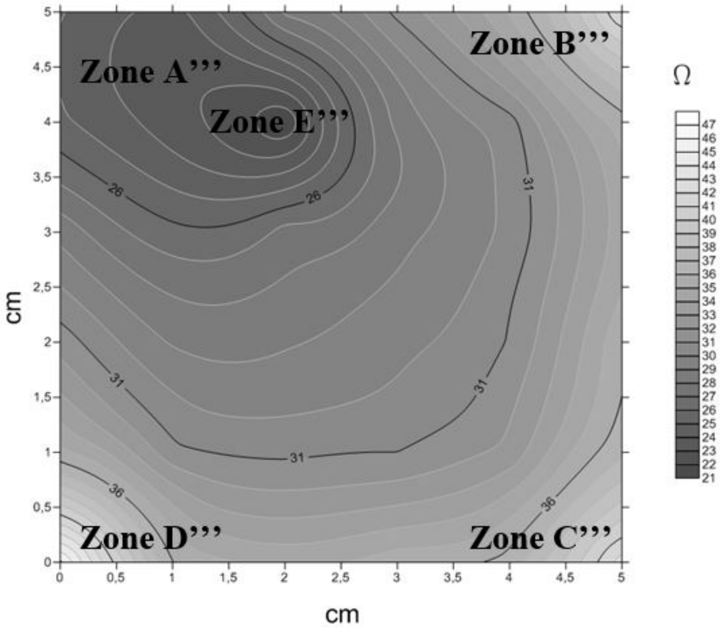

Figure 15. The electrical resistance of the FTO 4 surface (in Ω), measured by multimeter from the point A_1 (the point situated on the edge of the plate), and other points, as shown in Figure 3.

From all studied plates of SnO_2:F it is observed that plate 4 (FTO 4) is uniform in terms of electrical resistance (excluding areas A''', B''' and C''' with electrical resistance > 26 Ω). It is unable to identify other areas than zone E''' with electrical resistance < 13.5 Ω measured between two points at 1 cm distance (Fig. 14).

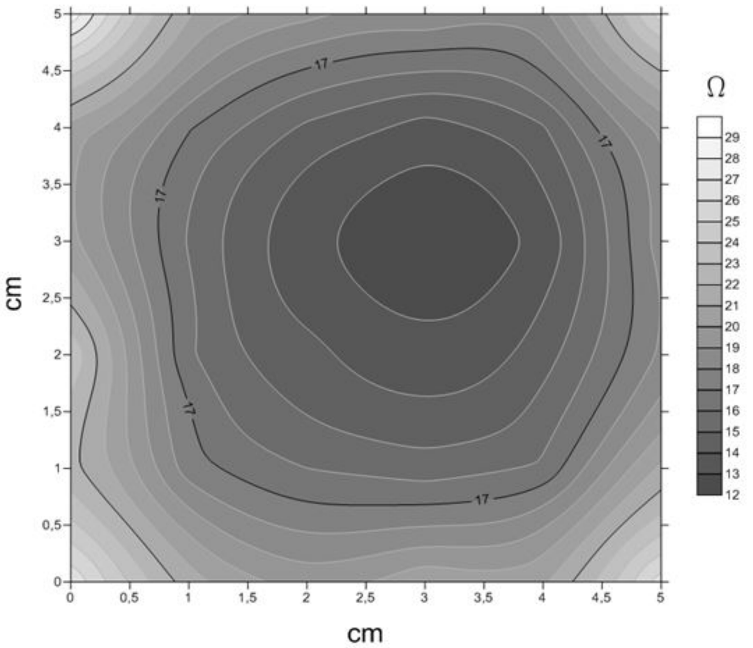

Figure 16. The electrical resistance of the FTO 4 surface (in Ω), measured by multimeter from the point C_4 (the point situated on the edge of the plate), and other points, as shown in Figure 4.

FTO 4, compared with all plates of SnO_2:F, seems to have the most symmetrical distribution of electrical resistance and as shown no visible defects that have higher electrical resistance (Fig. 15).

From Fig. 16, it can see that FTO 4 has electrical resistance values < 13 Ω to C4, which is not observed at other plates of SnO_2:F. Thus, it is quite believable lowest surface resistance value of all investigated plates (Table 1).

3.2. DISCUSSION

To better understand the electrical properties of SnO_2:F plates, electrical resistance values were processed using Pearson correlations.

By Pearson correlations (Table 4) it can be observed that plates FTO 2, FTO 3, FTO 4 correlates closely between them (> 0.965, p <0.01), while with FTO 1, these plates correlates less (< 0.941, p < 0.01). This can be explained from several perspectives. For example, at determination of surface resistance of these plates were observed large differences between Rhorizontal and Rvertical, while at FTO 1, these indicators have similar values.

Table 4. Pearson correlations between the values of electrical resistance measured between any two points, as shown in Fig. 2.

	FTO 1	FTO 2	FTO 3	FTO 4
FTO 1	1	0,919**	0,941**	0,932**
FTO 2	0,919**	1	0,965**	0,968**
FTO 3	0,941**	0,965**	1	0,968**
FTO 4	0,932**	0,968**	0,968**	1
**. p < 0.01 level (2-tailed). N = 630				

Based on the measurement model of the electric resistance shown in Fig. 2, it can be seen that the minimum resistance determined on SnO_2:F plates was measured on the FTO 4 - 13.2 Ω between points D4 – E4, E2 – E3 and E4 – E5 (which is visible in the Fig. 14), this plate, also, have the record for maximum of measured electrical resistance - 46.2 Ω between points A_1 and F_1 (one of plate's diagonals).

Minimum average electrical resistance (the average of about 630 measured resistance values as shown in Fig. 2) was observed at FTO 1. It is possible that this plate has the lowest values for maximum electrical resistance measured between 2 random points (43.0 Ω between B6 and F6, it can be seen from Fig. 5 that the areas of these points have high electrical resistance).

The highest average electrical resistance is characteristic for FTO 2, which has, also, the highest value of surface electrical resistance measured by the Van der Pauw method (2.930 Ω/area, Table 1).

Table 5. Mean, minimum, maximum values and standard deviation of electrical resistance measured between any two points as shown in Fig. 2.

	Determinations per plate	R_{min} (Ω)	R_{max} (Ω)	$R_{average}$ (Ω)	Standard deviation (Ω)	Relative standard deviation (%)
FTO 1	630	13,60	43,00	22,3813	5,25170	23,46472
FTO 2	630	13,40	45,20	23,1286	5,92928	25,63616
FTO 3	630	13,80	43,20	23,1214	5,69452	24,62877
FTO 4	630	13,20	46,20	22,5548	5,68248	25,19416

The sample with the lowest standard deviation compared with the average electrical resistance is observed at FTO 1 (± 5.23 Ω), which has the most uniform structure in terms of electrical resistance (demonstrated by Pearson correlations in Table 4). This plate has minimal differences between Rhorizontal and Rvertical (Table 1).

Also, it can be seen that the higher standard deviation is characteristic for FTO 2 (± 5.93 Ω).

In terms of relative standard deviation, the samples can be placed in ascending order as follows: FTO 1 (23.46%), FTO 3 (24.63%), FTO 4 (25.19%), FTO 2 (25.64%). This order underlines better the uniformity of SnO_2:F plates.

Table 6. Principal components analysis, followed by Varimax rotation method with Kaiser normalization (3 iterations) performed on measured electrical resistance values as shown in Fig. 2.

	Component	
	1	2
FTO1	0,567	0,823
FTO2	0,832	0,538
FTO3	0,772	0,617
FTO4	0,800	0,581

By principal component analysis, following by Varimax rotation method with Kaiser normalization (3 iterations), it can identify two components (Table 6):

- Component 1, characterized by uniformity of samples in terms of electrical resistance. Component 1 samples values are correlated with relative standard deviation values for them;
- Component 2, characterized by the uniformity of the samples in terms of electrical resistance. Sample values for component 2 are in inverse correlation with the standard deviation of electrical resistance values for these materials.

4. CONCLUSIONS

By Van der Pauw method (method used for determination of sheet electrical resistance) and by method of determination of the electrical resistance between the two points, it can be obtained very important information about the electrical properties of SnO_2:F plates.

Van der Pauw method applied on SnO_2:F plates for determination of sheet electrical resistance (R_s) demonstrates very similar results. The lowest value of R_s is 2.890 Ω/area (FTO 4) and the maximum is 2.930 Ω/area (FTO 2). By Student t-test, it can see that all 4 obtained values of R_s enter in confidence range for a probability of 95%. Due to very small differences between values of sheet electrical resistance (R_s) of the 4 plates, it can be admitted that plates are from the same batch.

Data processing was performed, using the Pearson correlations, on electrical resistance values obtained between any two points on plate surface, as shown in Fig. 2. It was observed a great similarity between FTO 2, FTO 3 and FTO 4 (> 0.965, $p < 0.01$, $N = 630$). These plates correlate less with the FTO 1 (< 0.941, $p < 0.01$, $N = 630$).

By principal component analysis (PCA), it can see the same situation. This statistical analysis has identified two components: component 1 characteristic for FTO 1 and component 2 characteristic for FTO 2, FTO 3 and FTO 4.

Differentiation between FTO 1 and other plates can be explained by reduced standard deviation, ± 5.25 Ω (± 5.93 Ω for FTO 2, ± 5.69 Ω - FTO 3, ± 5.68 Ω - FTO 4) and reduced relative standard deviation (± 23.46% compared of ± 25.64% - FTO 2 ± 24.63% - FTO 3 ± 25.19% - FTO 4) compared with other plates.

The graphical representation of the electric resistance as shown in Figs. 2-4 is useful for the location of the local defects. It is observed that by combination of the these 3 patterns of electrical resistance measurement (between any two points at 1 cm distance; between point A_1 and any other point on the surface, between C_4 and any other point on the surface), it is possible to locate areas with different electrical resistance. The areas with greater resistance compared to neighboring areas can prove the presence of structural defects.

REFERENCES

[1] Hwang, J. H., Edwards, D. D., Kammler, D. R., Mason, T. O., *Solid State Ionics*, **129**(1), 135, 2000.

[2] Lee, J. K., Jeong, B. H., Jang, S. I., Yeo, Y. S., Park, S. H., Kim, J. U., Kim, Y.-G., Jang, Y.-W., Kim, M. R., *Journal of Materials Science: Materials in Electronics*, **20**(1), 446, 2009.

[3] Goto, K., Kawashima, T., Tanabe, N., *Solar Energy Materials and Solar Cells*, **90**(18), 3251, 2006.

[4] Coutts, T. J., Young, D. L., Li, X., *MRS Bulletin*, **25**(08), 58, 2000.

[5] Van der Pauw, L. J., *Philips Techical Review*, **20**(8), 220, 1958.

[6] Matsumura, T., Sato, Y., *Journal of Modern Physics*, **1**(05), 340, 2010.

[7] Sun, Y., Shi, J., Meng, Q., *Semiconductor Science and Technology*, **11**(5), 805, 1996.