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VAN DER PAUW METHOD FOR MEASURING THE ELECTRICAL CONDUCTIVITY OF SMART TEXTILES

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The electrical properties of conductive textile fabrics are investigated using the Van der Pauw method. The dependences of the change in the electrical resistance of conductive knitted fabrics under tension perpendicular to the warp direction, as well as at a particular angle to the warp direction of the fabric, are obtained. The data obtained are intended for use in the design of textile electronics, as well as "smart" and highly functional clothing made based on it.

Researchers have been especially interested in conductive textiles due to the wide range of their potential application, including the manufacture of "smart" clothing with additional functionality [1-3]. Conductive fabrics, often referred to by specialists as "electronic textiles" (e-textiles), can be made by weaving (fabric), knitting (knitwear), netting (mesh), and nonwoven interconnecting (nonwoven fabric), by embroidery with conductive threads [4] or printing with conductive ink [5]. Electronic fabrics are light, flexible, stretchy, durable [6], resistant to washing and other cleaning methods [7], are cost-effective, environmentally friendly [8], and are less noticeable compared to their solid functional counterparts [9].

Conductive textile structures are created both at the yarn level [11] and at the fabric level [12]. The conductive component may be the fibers, yarn, fabric, embroidery, or even the finish, including polymer coating [13]. Electrically conductive threads can be introduced into the fabric structure during its production [8] or attached to its surface with the help of embroidery or zigzag stitches, ensuring sufficient stretchability of the textile [10]. The advantage of the formation of electrical conductivity at the level of the canvas is the ease of its integration into casual clothing [8].

To form the electrical conductivity, inorganic and organic current-conducting components are introduced into the structure of textiles in microstructured and nanostructured forms [11], which include:

– *conductive polymers*; for finishing the textiles, organic conductive doped polymers are used that differ in environmental stability under external conditions, such as polyacetylene [12], polypyrrole (PPy) [13, 14], polyaniline (PANI) [15], polythiophene in the form of poly-3,4-ethylenedioxythiophene (PEDOT) [8]; when textiles are coated with a fluoropolymer, they become desensitized to contamination, moisture or oiliness on direct contact with human skin due to the isolation of the triboelectric effect of conductive elements [16]; when a knitted fabric is coated with a conductive silicone elastomer, it is possible to record the change in the shape of the material [8]; with an increase in the rigidity of polymer composites used [10], a proportional decrease in the conductivity of the conductive fabric occurs [17, 18];

– *particles and alloys of silver* [19], for example, incorporated by precipitating silver nanoparticles from silver nitrate solutions of various concentrations [18] or by silver coating weft yarns in jacquard fabric [4];

– *modified carbon* [20] used to increase the conductivity of textiles by coating silk with graphene nanostructures [21] or by precipitating a dispersion of graphene oxide on cotton fabric by vacuum filtration [10];

– *silicon* in the form of long nanowires [22] or silica gel [23];

– *copper* [22], including in the form of brass [16];

– *nickel* [22], including in the form of super-elastic NiTi alloy, acting as the textile yarn core and used for shape memory of the fabric surface and its recovery after crushing [24];

– *aluminum* [16];

– *stainless steel* [22].

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New generation textile sensors allow to perceive mechanical, thermal, chemical, electrical, magnetic and optical changes in their environment [16]. Sensors can be described as “devices that detect physical perturbation and convert it into a signal that can be measured or recorded” [7]. The functionality of the sensors depends on the level of integration of the conductive elements into the structure of the textile substrate due to its internal or external modifications [24]. For the development of textile-based sensors, two measuring technologies are mainly used: resistive [8, 22] and capacitive [25], which provide a fast response time, which is important for the use of sensors in real conditions. The overall conductivity of the sensor with repeated load [8] depends on the degree of conductivity of the material.

Textile sensors are distinguished by ease of calibration and adjustment of parameters of the measuring system, low cost, subtlety, tensile properties, light weight, suitability for water treatment, robustness, ease of use, performance, durability, good friction properties, ability for interactive mobile transmission of electronic signals [26]. For example, strain gauges knitted from viscose and polyether fibers and with a polythiophene-based coating, change their electrical properties when elongated by 5-50%, making them usable as a measuring tool with excellent performance characteristics [13].

Textile sensors show great potential for use in biomedicine, robotics, automotive and wearable electronics [26]. Due to the effectiveness of obtaining useful information about health, conductive textile sensors are used as a clinical tool for diagnostics, rehabilitation, and sports activity [27]. Since clothes are in direct contact with almost 90% of the human skin surface, the use of non-invasive textile sensors improves comfort and safety for home and outpatient health monitoring, and helps prevent diseases [28].

“Smart” clothing as a system is a textile product that can perceive biomechanical signals, transform them into an electrical signal for wireless data transmission using computer equipment and software [29]. Intelligent systems based on wearable conductive textile sensors and a special algorithm for remote processing the data from each sensor [30], allow to determine the change in biometric, biophysiological characteristics of a person [31] and environmental conditions, including:

– heart rate to monitor the physical state of the body [4, 9, 20, 32];

– respiratory rate to monitor the physiological and psychological state of patients [12, 22, 33];

– skin temperature of the human body for its clinical diagnosis [34] or temperature fluctuations of the environment [26];

– humidity [23, 24];

– pressure [35];

– the presence of chemicals in the environment [28, 36];

– body composition, determined by analyzing the amount of fat, fluid, muscle and bone mass in the human body [37];

– the nature and effectiveness of the movements of the human body, limbs and individual joints for medical, sports and social monitoring [10, 18, 22, 38, 39];

– features of gait [40], including kinematics, kinetics of movements of the lower extremities and electromyography, for disease diagnosis and rehabilitation [32]; identification of excessive pronation and supination during walking and running to prevent injuries such as ankle sprain, Achilles tendonitis, etc., which is important for injury prevention not only in professional athletes, but also in the general population [40];

– the location of the user [13].

According to the degree of intellectualization, “smart” textiles are divided into three groups [13]: 1) “passive-smart” materials that sense environmental changes; 2) “active-smart” materials that respond to environmental changes; 3) “intelligent” materials that can adapt their reaction to the environment [13]. Smart textiles make it possible to transfer data obtained using textile sensors to a control unit and then to a PC or mobile phone using wireless technology without any distortion of the output signal [41].

Currently, smart textile fabrics are used:

– for continuous reading and *measuring the temperature* on the surface of the human body for long periods in stationary and dynamic conditions, which is valuable for clinical diagnostics [42];

– to ensure *antibacterial and cytotoxic activity* of materials (for example, against *S. aureus* and *E. coli*) [18];

– to *protect against electromagnetic fields* [16, 28, 43];

– to create *wearable electronic devices*, including flexible optoelectronics and displays [26].

Clothing is a daily and individual environment for each person, which is convenient to use almost anywhere and at any time. Increasing the intellectualization of this everyday environment makes it possible to receive many additional personalized services by responding to thermal, mechanical, physicochemical, and other signals [13]. The use of “smart” electronic fabrics for the manufacture of tight-fitting clothing makes it possible to read meaningful information from the human body without interfering with normal life activity [11]. The following types of tight-fitting products made from conductive textile fabrics can be distinguished as promising areas of application:

– suits, T-shirts, leotards, socks and gloves for wireless monitoring of the physiological state and movements of a person, thus avoiding additional interference with patients' daily routines for medical monitoring and physical rehabilitation [12, 24, 44];

– "smart" tight-fitting shirts with a pattern of conductive ink in the chest area, which allows to measure the change in the ECG signal during walking, running and other intense physical activity [44];

– "smart" clothing for monitoring cardiovascular activity during sleep, tested with microgravity in space flight conditions [45];

– wireless suit for children with sensors integrated in its belt to monitor the cardiovascular and respiratory activity of the body of children in the hospital [41];

– underwear for children for measuring the respiratory rhythm of babies using miniature woven sensors integrated into it [38];

– "smart" sportswear [5, 36] to monitor the movements of a person [12, 32] by detailed virtual recording of the features of movement of individual joints during various physical activities [7], including the prevention of falls in patients [30];

– "smart" socks with five built-in pressure sensors to assess the degree of pronation and supination of the gait by monitoring the pressure on different parts of the foot, allowing to characterize specificities of the steps [28];

– "smart" shirts, swimsuits and gloves that read and describe the pose and movements of a dressed person, used in the field of art, sports and multimedia [16, 29];

– knitted clothing for lonely elderly people (in Japan), functioning as a system for monitoring daily life activity by analyzing movements of their torso and limbs [33];

– "smart" professional and casual wear designed for controlled protection from the environment [41];

– "smart" electronic clothing that automatically recognizes the activity and behavioral status of the user, as well as his environment to use this information for tuning the configuration and functionality of the system of his life activity [10];

– jackets and gloves ("Levi Strauss Europe") with integrated wearable electronics ("Philips Research") that have electrodes activated by contact with the skin of the wearer's palm through the fabric [46];

– "smart" functional clothing for the military, intended for specialized activities [13, 28];

– garments intended for conducting anthropometric studies in dynamics [41, 42] and for measuring the pressure of clothing on the human body [39].

The functionality of "smart" textiles depends on the degree of its electrical conductivity, which determines the speed, volume and range of transmitted electronic information [13]. The basic principle of designing conductive textile fabrics is minimization of signal loss during reception and reflection [33], and fast response time is important for application of sensors in real conditions [7]. The electrical conductivity of textile elements is significantly influenced by the width, thickness, and surface resistance of the conductive paths, the distance between them [27], and the type of weave connecting the fabric threads [33].

Studies of the electrical conductivity of textile fabrics carried out by domestic scientists [47] consisted in directly measuring the electrical resistance of a textile fabric and often had unstable results, since the measurement methods used were primarily intended for conductive materials with considerable thickness and isotropy of properties. On the contrary, woven and knitted fabrics have an insignificant thickness in the range of 0.05–2 mm; therefore, it is proposed to treat the conductive textile fabric as a thin conductive film.

Textile materials are characterized by heterogeneity of structure [6], therefore the properties of conductive textiles can be either isotropic or have flat and normal anisotropy [48], which causes a different manifestation of their electrical properties depending on testing directionality [49]. To determine the electrical properties of materials, methods for measuring the specific surface and volume resistance of samples are employed. The electrical resistance of a textile material depends on its raw material composition, geometrical dimensions and internal structure of the sample [50], as well as on the number and placement of the electrodes used, the contact area between the electrode and the sample [5]. It is known that the electrical resistance of conductive filaments and materials produced in different ways remains constant when elongated to 100%, although electrical performance of materials decreases as a result of cyclic stretching or wetting [23].

Table 1. Structural Characteristics of the Conductive Knitted Fabric

Fabric parameters	Parameter values
Material composition	90% cotton + 7% lycra + 3% silver
Thickness, mm	0.253
Number of loop rows, pcs	130
Number of loop columns, pcs.	100
Surface density, g/m^2	145

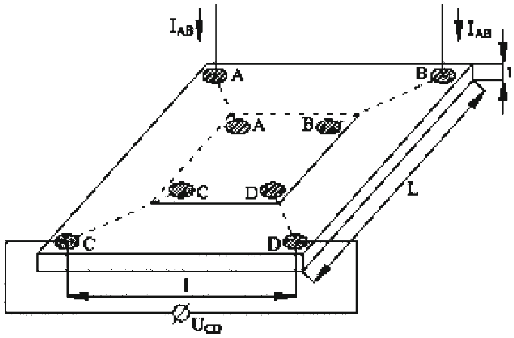

Fig. 1. Layout of Ohmic contacts on the sample.

Methods of measuring electrical resistance include: 1) the two-electrode method, designed to measure samples of considerable thickness; 2) three-electrode method, requiring relatively large sizes of flat samples [16]; 3) the four-electrode method [6, 51], in particular, the method proposed by Van der Pauw [52], designed to measure conductive materials of small thickness and to eliminate the influence of contact resistance due to the special arrangement of electrode pairs [53]; 4) a method using more than four electrodes to measure resistance, for example, the Montgomery method [54], which requires 6 to 8 contacts on the upper and lower parts of the sample.

When measuring using the Van der Pauw method, the sample and related components (Ohmic contacts) must meet the following basic requirements:

– the sample should have a flat surface and a small uniform thickness;

– the distance between the four Ohmic contacts (or needle electrodes) should be much larger than the sample thickness;

– Ohmic contacts (or needle electrodes) should be placed at the edges or along the perimeter of the sample;

– the diameter of the Ohmic contacts should be much smaller than the distance between two electrodes, otherwise measurement error is possible;

– the resistivity of the Ohmic contacts should be much lower than the resistivity of the sample.

Using the van der Pauw method, originally intended to determine the resistivity of thin inhomogeneous semiconductors, one can accurately measure the properties of a sample of any arbitrary shape, flat, solid, non-perforated, anisotropic, by placing electrodes around its perimeter [52, 53]. In this case, the resistivity is determined depending on the potential difference, the distance between the electrodes and the current strength. One of the main advantages of the Van der Pauw method is that it is nondestructive, and the material under study after measurement can be used for other purposes without any damage. Since the method of positioning the electrodes on the surface of a flat textile product is important for the result of measuring the sample resistance [50], to assess the electrically conductive properties of the entire surface of the sample, it is desirable to have four electrodes on its sides, but not too close to the sample boundaries [52].

Thus, the *purpose of this work* is to investigate the conductivity of conductive textile fabrics using the Van der Pauw method, as well as to determine the feasibility of its use in research.

Based on the fact that woven fabrics have a less tense and more uniform structure than knitted ones [4], a conductive knitted fabric was selected as the *object of study* (Adafruit, USA). The structural characteristics of the sample are presented in Table 1.

After preparing samples of conductive knitted fabric with dimensions of 200 × 200 mm (sample 1/S1) and 100 × 100 mm (sample 2/S2), 4 round electrodes (Fig. 1) made of steel were attached to the surface. The diameter of the

Table 2. Results of the Study of Conductance of Conductive Knitted Fabrics

Sample type	Tilt from the direction along columns, deg	Resistance, 10^{-2} kΩ						
		loop rows	loop columns	under tension (with stretching)				
				5%	10%	15%	20%	25%
S1	0	99.0±8.7	47.2±8.2	88.4±4.5	80.2±3.4	54.7±3.7	27.4±1.5	22.0±0.8
S2		103.2±9.4	71.1±7.0	64.4±3.2	57.7±2.8	42.5±2.2	26.8±1.3	18.4±1.1
S1	10		47.4±6.5	13.2±0.8	5.0±0.3	5.1±0.3	4.7±0.3	3.5±0.2
S2			60.1±5.8	24.5±1.0	7.3±0.5	6.7±0.8	5.1±0.2	4.1±0.2
S1	20		36.3±4.2	18.1±0.7	8.2±0.3	6.2±0.7	5.4±0.2	4.7±0.3
S2			40.2±5.5	14.3±0.5	7.4±0.2	8.4±0.5	7.0±0.4	5.2±0.2
S1	30		48.5±4.7	18.8±0.9	11.1±0.7	8.7±0.4	5.2±0.3	4.3±0.1
S2			56.2±3.5	23.2±0.7	13.4±0.3	10.2±0.5	7.9±0.4	4.7±0.3
S1	40		59.7±4.8	28.1±0.8	14.7±0.4	8.1±0.2	5.0±0.3	3.4±0.1
S2			66.4±5.3	24.6±0.9	10.2±0.5	8.3±0.4	1.3±0.1	2.2±0.1
S1	50		58.1±7.2	22.5±1.1	12.4±0.7	7.7±0.5	4.2±0.2	2.7±0.2
S2			72.6±6.2	28.3±1.7	12.6±0.8	6.2±0.3	5.7±0.3	3.2±0.1
S1	60		64.0±4.4	26.0±0.9	15.2±0.7	8.0±0.2	5.0±0.2	2.6±0.1
S2			78.4±5.1	24.7±1.2	17.1±0.8	11.9±0.3	10.1±0.4	5.4±0.2
S1	70		71.2±6.3	27.5±1.5	16.8±0.4	10.2±0.2	5.3±0.3	3.3±0.2
S2			79.1±4.8	22.4±0.8	18.2±0.7	13.1±0.4	7.4±0.4	4.2±0.1
S1	80		72.4±5.3	24.1±1.0	15.4±0.6	12.5±0.6	6.6±0.3	4.0±0.3
S2			82.6±7.5	24.4±0.7	22.0±1.1	14.7±0.5	13.2±0.6	8.3±0.4

electrodes is 15 mm, the specific resistance is $\rho_d = 0.103\text{-}0.137$ Ohm·mm^2/m, which satisfies the requirements for materials for use as an Ohmic contact. The mass of the electrodes was 5.63 g.

Laboratory Element 1502DD (Russia) was used as a power source. The power source (2 A, 0-15 V) is used to supply a small amount of direct current (0.5A) to protect the contacts from overheating, as well as an ammeter to measure the current passing between the two electrodes. A multimeter CEM DT-9969 (Russia) was used as a voltmeter to measure the voltage difference between two Ohmic contacts.

At the first stage of the study of piezoresistive characteristics, the voltage U_{AB} and the current I_{CD} were measured, after which, the values of electrical resistance of the fabric along the loop columns were calculated according to Ohm's law. The voltage U_{AD} and current I_{BC} were measured respectively on the sides along the looped rows. The values of the electrical resistance of the fabric along the looped rows were established according to experimental data. During the experiment, 10 measurements were made for each type of resistance.

According to the Van der Pauw method of calculation, the electrical resistance of the sample, measured in horizontal and vertical directions, should satisfy the following equation:

$$\exp(-\pi d/\rho_1 R_{AB/CD}) + \exp(-\pi d/\rho_1 R_{AC/BD}) = 1, \tag{1}$$

where ρ_1 is the resistivity of an Ohmic contact, Ohm·mm^2/m; d is the distance between Ohmic contacts, mm; $R_{AB/CD}$ is the resistance of the sample measured in the horizontal direction; $R_{AC/BD}$ is the resistance of the sample measured in the vertical direction.

At the next stage, voltage and current were measured placing Ohmic contacts at an angle to the loop columns. The range of deviation from the edge was 10-80° with an interval of 10°.

For the schemes of arrangement of the Ohmic contacts described above, electrical resistance was studied depending on the amount of stretching of the knitted fabric. The range of magnitude of stretching was 5-25% with an interval of 5%. The conditions for carrying out tensile tests of the fabric in width and length were performed in accordance with the regulations GOST 26435-85 [55]. The obtained values of electrical resistance across and along the fabric for two types of samples of conductive elastic fabric are presented in Table 2.

It should be noted that when designing "smart" clothing, especially for athletic purposes, it is important to arrange the patterns of the product design at an angle to the warp of knitted and woven fabrics for cutting. Therefore, additional studies have been conducted of the conductivity of conductive textile fabric samples placed at different angles to the direction of the loop columns in the range of 10-80° with an interval of 10°. The results of the investigation are presented in Table 2.

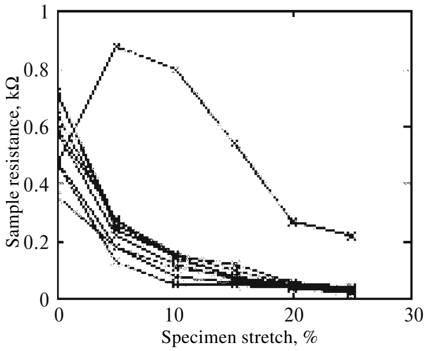

Fig. 2.

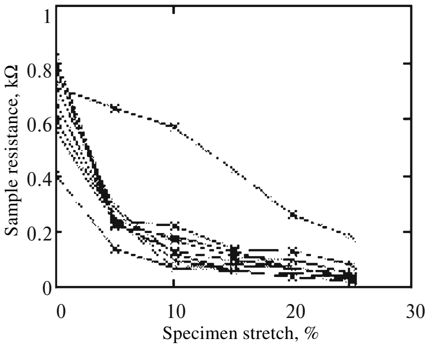

Fig. 3.

Fig. 2. Resistance of a flat sample as a function of the magnitude of the stretch (tension) of the conductive knitted fabric for sample S1.

Fig. 3. Resistance of a flat sample as a function of the magnitude of the tension (stretching) of the conductive knitted fabric for sample S2.

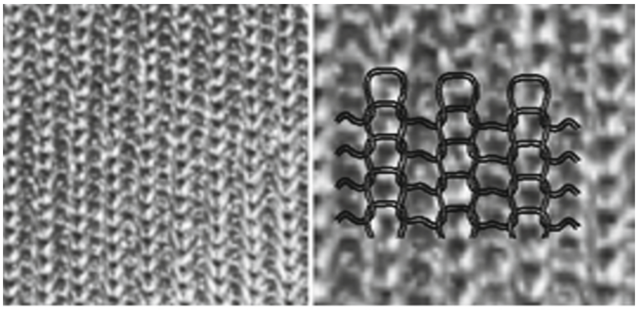

Fig. 4. The structure of the conductive knitted fabric.

Fig. 2 (sample S1) and 3 (sample S2) show the dependences of the resistance of a flat sample on the magnitude of stretch (tension) in the conductive knitted fabric. When analyzing the data obtained, it was found that the value of electrical resistance, as well as the nature of its change when the fabric is stretched, do not depend on the size of the sample under study, which satisfies the basic principles of the Van der Pauw method.

According to the data obtained, the electrical resistance in the transverse direction of the fabric is greater than the analogous value measured in the longitudinal direction. When the knitted fabric is stretched, the resistance decreases throughout the entire measurement cycle. In this case, when stretching across the fabric and at an angle to the longitudinal direction, the nature of change of the resistance differs: in the first case, the change is linear, described by the equation $y = ax + b$, where $a < 0$; in the second case, the pattern is logarithmic and is described by the equation $y = a\ln x + b$, where $a < 0$. This is because when measured at an angle to the longitudinal direction of the fabric, the electrical resistance at any, even slight stretching begins to decrease rapidly.

To determine the possible causes and reliability of the obtained dependencies, a theoretical analysis was performed. Fig. 4 shows the state of the structure of the knitted fabric when conducting tensile studies, as well as when measuring electrical resistance at a certain angle to the direction of the columns of loops.

When the conductive knitted fabric is stretched, the amount of conductive polymer (silver particles) can be represented as $n = kL$, where k is the number of silver particles per unit length of the thread, L is the length of the thread, mm. During tensile testing the length of the thread increases according to the law $L_1 = L_0(1 + m/100)$, where L_0 is the initial length of the thread, mm, m is the amount of stretch, %. The length of the thread along the segment L_0 is L_0^2/L_1 or $(L_0/L_1)L_0$, where $(L_0/L_1) < 1$. The number of silver particles before and after stretching is, respectively, $n_0 = kL_0$ and $n_1 = kL_0(L_0/L_1)$ where $(L_0/L_1) < 1$. Thus, an experimental study showing the decreasing electrical resistance when a conductive knitted fabric is stretched was confirmed by a theoretical conclusion. A significant decrease in resistance at the initial stage of stretching from a state of rest may result from the principle of violation of the interaction between charged particles, the existence of a tunnel effect and other causes.

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