IDEs structures created in the physical vacuum deposition process on textile substrates

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Abstract. The article proposes a method for producing interdigitated electrodes structures on a flexible composite substrate in the physical vacuum deposition process. Ag and Au with a purity of 99.99% were used as deposited metals. The results of impedance measurement of created structures in the range up to 500 kHz are presented. Based on the results of computer simulation, an equivalent circuit for computer simulation of the structures has been proposed based on measurement result. It can be used in the design of sensors built based on IDEs in textronic systems. The very high agreement was obtained between impedance measurements and simulation results up to tens of kilohertz.

1. Introduction

Interdigitated electrodes (IDEs) are typically used in circuits where electrical signals generated by sensing materials are detected via increasing the effective capacitance of the created structure. At the same time increasing the effective active area of the produced sensor is observed. The “fingers” of the IDE structures are interleaved to maximize the capacitance per unit area and as a consequence, through the geometry of so designed structure, they have an impact on increasing the capacity of the entire system. There is a lot of scientific work that addresses these points in regards to sensors e.g. humidity ones [1], gas sensors [2–5], electrochemical sensors [6,7], biosensors used for immunochemical reactions or DNA hybridization processes [8,9], immunosensors [10,11].

However, by increasing the capacitance, the self resonant frequency of the structure decrease. Also, by using an IDEs structure of capacitance character, the sensitivity of the transducer device to external factors increases. The sensing environment affect the capacitance of planar structures. This kind of electrodes are also often used as ultra sensitive electrochemical biosensors [12]. The parameters of electrodes are usually measured either directly as a one port capacitance measurement or indirectly by building the IDEs into an LC tank whose resonance frequency is monitored.

In some research works it is important to create sensors based on impedance changes [8,11,13]. Material which is used for fabricating of interdigitated electrodes is critical for their selectivity and sensitivity. IDEs used for impedance measurement are usually made of metal with good conductivity such as gold (Au) and platinum (Pt) also chromium (Cr), carbon (C), titanium (Ti) and indium tin oxide (ITO) [3,9,14,15]. Such sensors can be used to measure high-frequency changes in the construction of machines such as those presented in the works [7,16]. This is very important in the diagnosis of materials
[17] dynamic mechanical systems and machine tools, where high repeatability of measurement results is required [7,18].

Biological applications, e.g. virus detection, require large arrays of up to 2000 lines as narrow as 250-500 nm. Such fine structures can only be fabricated using advanced lithography techniques, which are costly and complex [12,19-21]. The concept of using a stamp with silver ink to produce desirable structure of bigger dimensions was developed by Chou [22]. The equipment used in this method is much less expensive. The attainable line widths and spacing are dependent on the ink viscosity and resolution of the stamp pattern. Screen printing is another technique used to creating useful IDEs for various sensor applications [3,23]. Additionally it is also possible to find ink jet printing method of creating IDEs [4,5].

In the literature the IDEs structures are created on glass, silicon or aluminum oxide substrate [8,9,13,22,24]. Partel et al in their work [21] demonstrated for the first time a successful implementation of electrodes on polymer substrate. The initial structure was created in hot embossing process [25] and subsequent sputtering deposition processes were not affecting the polymer layers.

The authors of the presented work proposed the IDEs structures produced in physical vacuum deposition process on flexible textile substrate with polymer coating. It is possible to use IDEs in wearable electronics systems due to the usage of a flexible composite substrate on which the desired structures are created. Increased precision in the fabrication of such structures is achievable using laser ablation of the applied metal [26-28].

2. Materials and Methods

2a. Fabrication of IDEs

The interdigitated electrode structures were created in physical vacuum deposition (PVD) process in a Classic 250 chamber of the Pfeiffer Vacuum system by thermal evaporation from a tungsten resistive source. The evaporated material was Ag and Au with 99.99% purity and its quality was guaranteed by the Mint of Poland. Prior to the deposition process, the substrate was conditioned at room temperature 23 °C and 50% humidity, and then cleaned using organic solvents.

As the substrate on which the electrodes were made, a flexible composite textile substrate known under the brand name of Cordura® was used. It is a fabric made of nylon threads with a Polyurethane coating. Coating the thread with a polymer layer is a prerequisite for the PVD method to be able to produce a continuous electroconductive layer. The choice of such a fabric as the substrate is dictated by the very high mechanical strength of Cordura, which is of fundamental importance due to the application of such a structure in the domain of textronics. The IDEs structure was patterned on the substrate with a reusable metallic mask and given the final shape with a laser.

The geometry of the structures created is shown in figure 1.

![Figure 1. The geometry of tested IDEs structure.](image-url)
2b. Method of measurement
The electrical parameters of the sensor were measured in the frequency range from 10 Hz to several
dozens kilohertz using a GW INSTEK LCR-8110G meter. The research was carried out in the range of
frequencies considered as the most common among the published works [3,8,14].

In order to ensure the highest possible accuracy and characterization of the impedance of the
interdigitated electrodes structure, the authors used a digital RLC measurement for impedance that
implements the impedance component processing method. [30]. This instrument monitors the real and
imaginary part of the current (forced by the reference source Uw) flowing through the device under test
and presents the result as values of the components of an equivalent circuit.

The measured impedance Zx is connected via a four-probe connector (Kelvin’s four-probe method)
[2]. Two of them, called current probes, are responsible for the current flow through Zx. The other ones,
called voltage probes, are responsible for measuring the voltage drop on Zx (figure 2). The four-electrode
method provides accurate and reliable results for measuring resistances less than 100 Ω. Current
terminals must always be located outside the voltage terminals, giving the lowest measuring errors.
Voltage terminals must be connected exactly at the points where the impedance should be measured.

![Figure 2](image)

**Figure 2.** The scheme of four-point impedance measurement method using the Kelvin method.

Due to the shape of the studied structure, measurements were made for equivalent circuit of parallel
impedance Zx and it was possible to apply the voltage and current terminals exactly at the same points.
Thus, the authors used Kelvin clamps with both parts isolated from each other [2]. The measuring system
with the connected structure is shown in figure 3.

![Figure 3](image)

**Figure 3.** Connection of Kelvin clamps to measured impedance.

The current that appears in the voltage lines is negligible. The voltage drop on the voltage terminals
of the meter is then the same as that of the Zx.
2c Modelling

Equivalent circuit model of an IDEs sensor was proposed by [8,15] and another one used in the impedance immunosensor system was described by Wang or Martinez [11,14].

The authors of this paper proposed another equivalent circuit which is appropriate for interdigitated electrode structures created on textile composite substrate. The measured behavior can be modeled using the equivalent circuit presented in figure 4.

![Figure 4. Equivalent circuit of the interdigitated electrode structure.](image)

$C_p$ represents the capacitance between the fingers, $R_p$ – the shunt resistance between them, and $R_l$ – the substrate loss modeled as:

$$R_l = \frac{R_1}{f},$$

(1)

where $R_1$ is a constant and $f$ is the signal frequency. The real and imaginary parts of the IDEs impedance are respectively expressed as

$$R(Z) = \frac{R_{\text{eff}}}{1 + (2\pi f C_p R_{\text{eff}})^2},$$

(2)

$$I(Z) = -\frac{2\pi f C_p R_{\text{eff}}}{1 + (2\pi f C_p R_{\text{eff}})^2},$$

(3)

where the effective shunt resistance is

$$R_{\text{eff}} = \left( \frac{1}{R_p} + \frac{f}{R_l} \right)^{-1}.$$  

(4)

The values of model parameters for interdigitated electrodes made of gold and silver are summarized in Table I.

|                      | Gold   | Silver |
|----------------------|--------|--------|
| $C_p$ [pF]           | 3.37   | 4.82   |
| $R_p$ [GΩ]           | 2.5    | 2.3    |
| $R_l$ [GΩ*kHz]       | 1.30   | 1.07   |

3. Results

3a. Results of measurement

As the result of carried process of applying the electro-conductive metal layer structures were created with finger surface resistance in the order of single ohms per square. This proves the good quality of the produced metal layers [30].

The results of measurements of resistance and capacitance as the components of the IDEs structure impedance are presented in figure 5. Both the effective resistance and capacitance of the system decrease as the signal frequency increases. In the measured frequency range, the IDEs structure shows a capacitive character, which is compatible with the expectations for such electrodes. Electrodes made of Au are characterized by lower resistance values and higher capacitance values in comparison to Ag.
The Q-factor of the entire electrode system depends on the type of applied metal and for Ag reaches a maximum for the frequency of 5kHz and for Au for 7kHz. Due to the achieved maximum values of the systems Q-factor and measurements for the frequencies which are used in the construction of sensors [3,8,24], further frequency increase was not justified. All obtained results are for dry structures.

3b Results of modelling
The results obtained for both interdigitated electrodes structures are presented in figure 6 and 7. The impedances for f < 100 Hz are extremely high, which makes the measurement results unreliable.

Figure 5. The dependence of resistance (a), capacitance (b), impedance (c) and Q-factor (d) on frequency for created Ag and Au interdigitated electrodes.

Figure 6. The real and imaginary parts of the impedance of the gold IDEs. Symbols – measurement, lines – model given by formulas (1)-(4)
The introduction of the frequency-dependent component $R_l$ deserves a comment. In the absence of this component, the real part Re($Z$) of the impedance decreases asymptotically as a quadratic function of the frequency. However, figure 6 b and 7 b show that this roll-off of Re($Z$) slows down at frequencies exceeding several hundred hertz. Several hypotheses have been proposed to explain this behavior. All those hypotheses have been tested with Spice simulations of a distributed representation of the IDEs structure, with each finger modeled as an RLC ladder of one hundred stages. One possible source of the observed behavior is non-negligible series resistance of the metallic paths. However, the previously mentioned values of several ohms per square have no perceptible effect within the analyzed frequency range. In fact, the path resistance can be neglected until it reaches several kilohms per square. The only explanation of such abnormally increased path resistance is skin effect. Simulation shows, however, that skin effect is negligible at frequencies less than tens of kilohertz. Moreover, when skin effect eventually does set in, it abruptly changes the character of the Re($Z$)–$f$ curve from decreasing to gently increasing. Such behavior is not observed. Another hypothesis was linked to parasitic inductance of the connections and/or the metallic paths. The geometry of the IDEs, however, suggest an inductance on the order of single microhenries. Simulation shows that such a value has no effect within the given frequency range.

In view of the above, the only viable explanation of the observed Re($Z$)–$f$ behavior is frequency-dependent loss in the substrate. The model proposed here provides a good fit up to tens of kilohertz.

4. Summary

The article presents the method of manufacturing IDEs structures on a flexible composite substrate in the process of physical vacuum deposition. An equivalent circuit of the developed structures has also been proposed. For the developed equivalent circuit, simulation tests were carried out in the Ngspice software [31], and then their results were compared with the results of laboratory tests. The obtained consistency of results confirms the correctness of the proposed equivalent circuit. Simulation of the behavior of the created structures can provide useful information on the behavior of IDEs depending on the frequency of the supplying signal. Understanding the equivalent circuit of IDEs structures created on flexible composite substrates will allow better use of interdigitated electrodes as sensors in textronic solutions.

Acknowledgements

The work was carried out within the framework of activities financed from statutory funds.

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