Coplanar Micro-Strips/Electrospun sensor system to Measure the Electronics Properties of the Polyethylene Oxide (PEO) Electrospun

Carlos Fuhrhop and *Anthimos Georgiadis*
Institute for Product and Process Innovation
Leuphana University
Lüneburg, Germany
cfuhrhop@leuphana.de, georgiadis@leuphana.de

Abstract— **In the literature we found different kind of film conducting polymers, as Polyaniline (PANI) or Polypyrrole (PPY), used as sensor element integrated in a Field Effect Transistor (FET) for the detection of gas or photogenes. In this work we proposed a sensor system prototype based on the combination of a coplanar micro strip (CPµS) waveguide and polymer nanofibers met (electrospun) called, CPµS/PNW sensor system, for target element (bio element or gas) detection. The detection idea is based on the impedance change measurement in the frequency range. The first step toward to develop the sensor is to investigate and understand the low frequency (0.1 to 1 MHz) electrodynamics response properties of the CPµS waveguide with (CPµS/PNW) and without nanofibers. We develop a transmission line mathematical model to describe the CPµS/PNW sensor system, the mathematical model was simulated with Scilab and the results were compared with the CPµS/PNW experimental data to see the degree of agreement between model and experiment. The impedance curves obtained from the experimental data show a good agreement with the model, which predict CPµS/PNW (CPµS + electrospun) impedance curve lower than the CPµS impedance curve. The electronics property (impedance) of the PEO electrospun was calculated from the difference between both impedance curves, this difference represent the polymer nanofibers mat impedance. The curves exhibited approximately a sub-linear power law decrease with frequency, which is consistent with the behavior found in polymers. The polymer nanofibers mat was produced by electrospinning method, where the diameter of the nanofibers obtained are in the range of 100 nm and 900 nm.**

Keywords—coplanar µ-Strip; transmission line; impedance spectrsocopy; polymer electrospun; electrospinning

I. INTRODUCTION

In the literature we found research focusing in the investigation of the low and high frequency properties of conducting film polymer for gas and bio sensors applications [1, 2, 3]. In [4] it is reported of a transistor field effect (FET) as sensor based on silicon nanowire (SNW), here the nanowire (NW) is the sensor element where the NW is the gate of the FET and this amplifies the conductance change in the NW when the target is attached nanowire surface, this is basically the detection method using the FET as an amplifier, [5]. The sensitivity of the DC electrical properties of silicon nanowire to molecules adsorbed (Biosensor) on their surfaces, shown by [4], also raises the question of whether similar AC conductance changes (or another similar method) exist and can be exploited using instead silicon NW a conductive or non conductive polymer NW (nanofibers) for Biosensor purposes [5, 6, 7]. As the first goal we present sensor prototype for the measurement of the electrical properties of polyethylene oxide (PEO) electrospun (non conductive polymer nanofibers net), which was possible using the combination of the coplanar micro strip (CPµS) waveguide with the PEO electrospun as an all system. We called this system as the "CPµS/PNW sensor system". We investigate the electrodynamics response properties of PEO electrospun for the low frequency of [0.1–1MHz]. For the "CPµS/PNW sensor system" we developed a mathematical model based on the transmission line theory where the nanofibers electrospun impedance is modeled by a conductance and capacitance in parallel with the transmission line model of the sensor system, Fig. 1 and 2. The model was simulated with the software Scilab and the simulation results were compared with the experimental data of the CPµS to see the agreement of the model, Fig. 4. To measure the PEO electrospun impedance, first the impedance characteristic of the CPµS without electrospun is measured and then the impedance characteristic of the CPµS/PNW system was measured, where the electrospun was deposited by electrospinning on the surface of the CPµS. From the measurements (experimental data) we obtained two curves, one for the CPµS without electrospun and one for the CPµS/ PNW system, Fig. 10, using the difference between curves we calculate the impedance difference (ΔZ), equivalent to the PEO electrospun impedance. Furthermore the impedance vs. frequency curve exhibited approximately a sub-linear power law decrease with frequency which is consistent with the behavior founded in disordered system as polymer [9]. In the literature we found many research on polymer film DC electrical properties, but a few research about its frequency properties, and a few published papers about the electrical properties of polymer electropsun. One reason for this is due the large impedance of the polymer compare with semiconductor and because of the individual polymer nanowire, the component of the electrospun, which have typically high impedance in the order of 10 MΩ or even more. Compared this high impedance to the 50 Ω impedance of all microwave test equipment and the 377 Ω impedance of free space, and if we take into account that the interaction between the nanowire net and the electromagnetic field is very small (signal below instrumental background), we see that the measurement of the electrospun impedance is a difficult task. To overcome this limitation we have develop the CPμS/PNW system to measure the electrospun impedance. This allowed us to accurately extract the impedance value for the PEO electrospun, and is also possible to extract the conductance and the capacitance. The nanofibers net or electrospun is produced by electrospinning method [8], which is a cost-effective and versatile process to fabricate nanofibers from a wide range of materials at room temperature and atmospheric pressure, of which the diameter ranges from tens of nanometers to a few micrometers, Fig. 5 and 7. The paper is organized as follow: (I) present the introduction, (II-A) the transmission line model for the CPμS, (II-B) the simulation of the CPμS, (III-A) the electrospinning method, (III-B) the impedance measurement and equipment, (IV) the results and (V) the conclusion.

II. COPLANAR MICRO STRIP MODEL

A. CPμS mathematical model based on transmission line.

Equations (1) show the total model for the impedance output of the CPμS. We assume an open line, therefore the load impedance (*Z_L*) goes to infinity and the total impedance model is reduced to (2). The impedance model is composed by the characteristic impedance *Z_0* (3) and the propagation constant γ (4) which are composed by *R, L, C* and *G*. The capacitance is described by (5) and (6) where *C_a* is the air capacitance and *C_{su}* the substrate capacitance. The conductance is described by (7) and the total resistance by (10). The Fig. 1 show the transmission line model for the distributed element *R, L, C* and *G,* which are distributed along the CPμS.

1) Total impedance

$$Z_t = Z_0 \cdot \frac{Z_L + Z_0 \tanh \gamma l}{Z_0 + Z_L \tanh \gamma l} \tag{1}$$

At the end of the CPμS the line is open, therefore we have:

$$Z_L \to \infty \quad \Longrightarrow \quad Z_t = \frac{Z_0}{\tanh \gamma l} \tag{2}$$

where:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{3}$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{4}$$

Z_0: Characteristic impedance of the sensor (CPμS)
γ : Propagation constant of the sensor (CPμS)

2) Capacitance

$$C_{total} = C_a + C_{su} \tag{5}$$

$$C_{total} = \varepsilon_0 \frac{(\varepsilon_a + \varepsilon_{su})}{2} \cdot \frac{k\left[\left(1 - \left(\frac{a}{a + 2w}\right)^2\right)^{1/2}\right]}{k\left[\frac{a}{a + 2w}\right]} \tag{6}$$

where:
k[x]: Complete elliptic integral of the first order
ε_a: Air dielectric constant
ε_{su}: Substrate dielectric constant
ε_0: Electric permittivity of free space
C_a: Air capacitance
C_{su}: Substrate capacitance
C_{total}: Total capacitance
w: strip width and *a*: distance between strips, Fig. 3

3) Conductance

$$G_s = \frac{\sqrt{\varepsilon_{eff_1}}}{120\pi} \frac{k\left[\frac{a}{a + w}\right]}{k\left[\left(1 - \left(\frac{a}{a + w}\right)^2\right)^{1/2}\right]} \tag{7}$$

where:
ε_{eff1} : effective dielectric of the CPμS

4) Inductance

$$L = \mu_0 \varepsilon_0 \frac{1}{C_a} \tag{8}$$

where:
μ_0: Magnetic permeability of free space.
C_a: Total capacitances calculate by (6) when al dielectric materials are assumed to be replacing by air.

5) *Resistance*

$$R_{total} = R_1 + R_2 \tag{9}$$

where:

R_{total}: Total resistance; R_1: strip1 resistance;
R_2: Strip2 resistance.

$$R_1 = R_2 = R = R_{DC} + \frac{\sqrt{\rho\mu\pi f}}{w}$$

$$R = \frac{\rho}{w\,h} + \frac{\rho}{w\delta_{skin}} \;; \quad R_{DC} = \frac{\rho}{w\,h}$$

$$\Longrightarrow \quad R = R_{DC}\left(1 + h\sqrt{\frac{\mu\pi f}{\rho}}\right)$$

then the total resistance is:

$$R_{total} = 2R = 2R_{DC}\left(1 + h\sqrt{\frac{\mu\pi f}{\rho}}\right) \tag{10}$$

where:

ρ: Strip resistivity; w: strip width; h: strip high
μ: Strip permeability; $\mu = \mu_0\,\mu_r$
μ_0: Free space magnetic permeability
μ_r: Relative permeability
δ_{skin}: Skin effect

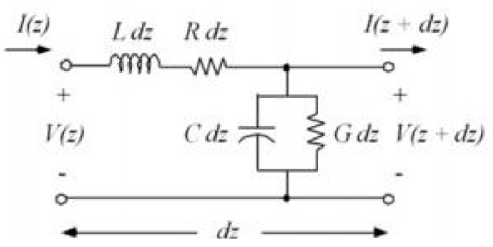

Fig. 1. Transmission line model for the CPµS. Where *L, R, C* and *G* are element distrbuted through the line.

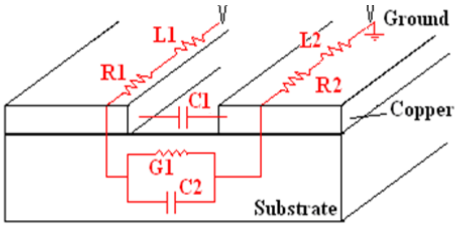

Fig. 2. Schema of the CPµS with its equivalent distribution circuit model.

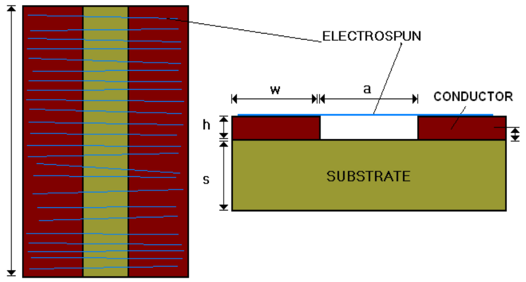

Fig. 3. Schema of the CPµS/electrospun sensor system. Where w and h are the width and high of the strip, a is the distance between strip, s substrate high and l the length.

B. *Simulations of the CPµS impedance*

The sensor system model described in II was programmed and simulated using the open source software Scilab (www.scilab.org). From the simulation we obtained the total impedance vs. frequency curve for the CPµS defined by (1). The frequency simulation was in the low frequency (0.1 to 1MHz) range. The Fig. 4 show the simulation results for the CPµS in the frequency range [0.6–1.0 MHz]. For the simulation in Scilab we used the size parameters and the physical constant showed in the Table. 1. The size parameters were measured by the CLSM in the 3D mode, Fig. 6. And the Fig. 7 shows the fiber's diameter distribution measured by CLSM in 2D mode.

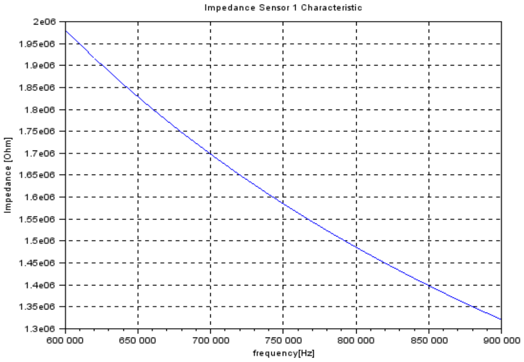

Fig. 4. Simulation curve of Impedance vs. frequency for the CPµS, sensor 1.

TABLE I. VALUE OF THE DIMENSIONS OF THE SENSOR S1 BY CLSM AND THE PHYSICAL CONSTANT USED TO CALCULTE THE IMPEDANCE.

Size Parameter	**Value [mm]**	**Physical Constant**	**Value**
s	1,6	ε_0	$8{,}85\cdot10^{-12}$ [F/m]
h	0,144	ε_a	1,00058986
w	0,54	μ_0	$4\pi\cdot10^{-7}$ [H/m]
a	2,02	ρ_{Al}	$1{,}72\cdot10^{-8}$ [Ωm]
l	13000	----	----

III. EXPERIMENT AND EQUIPMENT

A. *Electrospining Process*

The nanofiber is produced by electrospinning method, which is a cost-effective and versatile process to fabricate nanofibers from a wide range of materials at room temperature and atmospheric pressure, of which the diameter ranges from tens of nanometers to a few micrometers. We called electrospun the net of fibers collected during the electrospinning process, Fig. 5. The equipment is composed by a Harvard syringe pump, high voltage device and two metal electrodes in a vertical orientation, the electrode at the bottom is the collector. The solution used for the electrospinning is composed by 4% PEO (900000 Mw) and 96 % distilled-water (solvent).

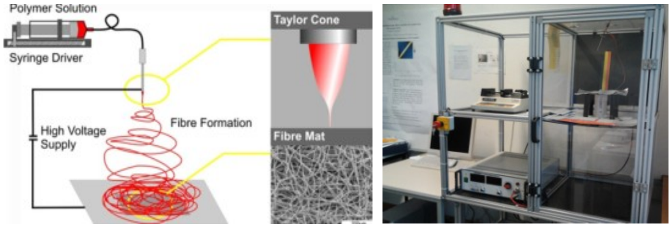

Fig. 5. Electrospinning process schema and Lab-Equipment.

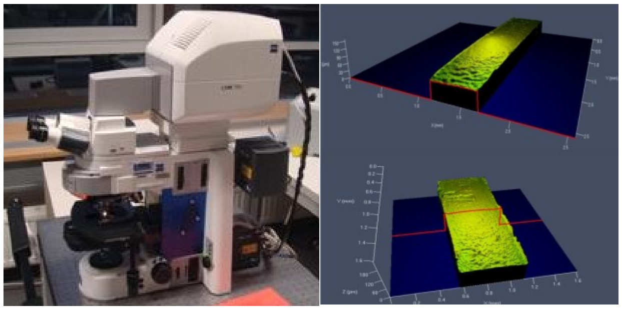

Fig. 6. Confocal Laser Scaning Microscope (CLSM, C. Zeiss) and the 3D image of the strips of the CPμS.

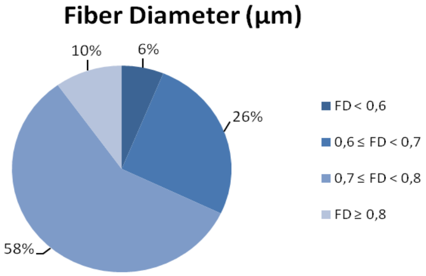

Fig. 7. Circle diagram of the PEO fiber's diameter distribution.

B. *Impedenace measurement*

The impedance vs. frequency of the sensor system with and without PEO electrospun was measured by the HIOKI 3552 LCR spectrometer under ambient condition, T=20.3°C (temperature); Hr=36% (relative Humidity), Fig. 8.

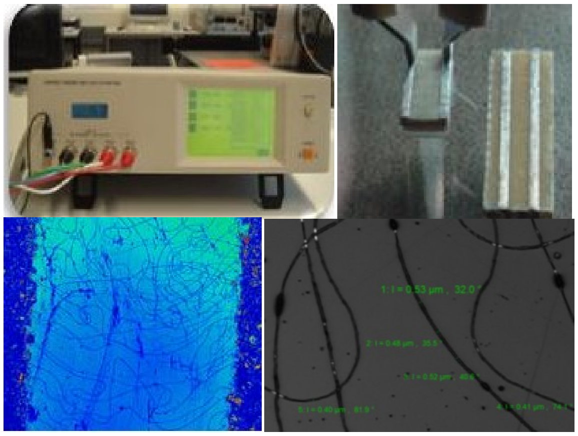

Fig. 8. Up, Hioki LCR device and image of the CPμS/electrospun sensor system S1 and S3 (thin strip and FR2 substrate). Down, CLSM 2D image of the sensor system/electrospun nanofibers (Ag strips and glass substrate) and PEO nanofibers with its diameter measured by ZEN (C. Zeiss Software) .

IV. RESULTS

Two curves were obtained from the experimental data, through the measurement of the impedance spectroscopy of the CPμS/electrospun sensor system without and with electrospun using the Hioki LCR instrument, Fig. 9. The Scilab simulation results are in agreement with the experimental results, which mean, that we have develop a good mathematical and physical model to describe the sensor system, Fig. 2 and 3. Using the difference between both curves we can see that is possible to measure the impedance, conductance and the capacitance of the PEO electrospun. We have found that the complex AC impedance of the polymer electrospun exhibited approximately a sub-linear power law decrease with frequency that is consistent with behavior found in polymer (insulator), Fig. 9. The Fig. 4 shows the simulation curve by Scilab for the CPμS sensor 1 without electrospun. These curves show a similar behavior as the experimental curve.

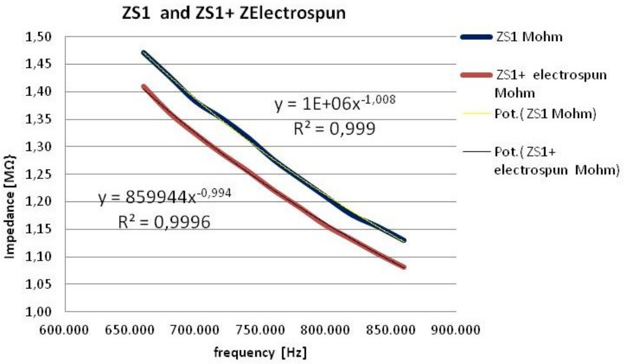

Fig. 9. Experimental and fit curve with its power law function for CPµS/electrospun sensor system S1. The blue line is CPµS without electrospun and the red line is the CPµS with PEO naofibers electropsun.

V. CONCLUSONS

We have found the problem due to the small interaction between the nanofibers and the electromagnetic field (which produces a signal below the instrumental background) was overcome through the CPµS/electrospun system. Therefore CPµS/electrospun system is a good approach to measure the electrodynamics response of the electrospun PEO nanofibers, which means that we can measured the impedance change even if we used non conductive polymer as the PEO. From the obtained curves we can calculate the electronics properties, (impedance, conductance and capacitance) of the PEO nanofibers electrospun. Furthermore the curves show a sub-linear power law which is consistent with the behavior found in polymers and the simulation shows a good agreement with the experiments.

REFERENCES

[1] F. Musio, et al. High-frequency a.c. investigation of conducting polymer gas sensors. Sensors and actuators B, 23 (1995), pp. 223-226.

[2] M. Amrani, et al., High-frequency measurements of conducting polymers: development of a new technique for sensing volatile chemicals. Measurement Science and Technology, Volume 6, Issue 10, pp. 1500-1507 (1995).

[3] M. Gerard. Review - Application of conducting polymers to biosensors. Biosensors & Bioelectronics 17 (2002) 345–359.

[4] F. Patolsky et al., Proc. Natl Acad. Sci. USA 101, pp. 14017–14022, (2004).

[5] C. Fuhrhop et al. Sensoren und Messsysteme 2010. Nürnberg, Germany (18-19.05. 2010). *ISBN* 978-3-8007-3260-9.

[6] C. Fuhrhop, A. Georgiadis. Polyethylene Oxide (PEO) Nanofibers as Sensing-Element in Biosensors. EuroNanoForum 2011. Budapest, Hungary (30.05.2011-01.06.2011).

[7] C. Fuhrhop. Sensor based on Coplanar µ-Strips to Measure the Electronics Properties of the Polyethylene Oxide (PEO) Electrospun. ICSNN2012, Dresden-Germany (July 22-27, 2012).

[8] S. Ramakrishna et al. An Introduction to Electrospinning and Nanofibers. World Scientific Publishing Co. Singapore, 2005.

[9] A. K. Jonscher. The Universal Dielectric Response. Nature Vol. 267, 23 June 1977.

[10] B. Wadell. (1991) Transmission Line Design Handbook. Artech House.

[11] A. A. Talin, L. Hunter, F. Leonard, B. Rokad, Appl. Phys. Lett. 89, 153102 (2006).

[12] J. D. Jackson. (1975) Classical Electrodynamics. Second Edition. John Wiley & Sons.

[13] C. VEYRES a & V. FOUAD HANNA , “Extension of the application of conformal mapping techniques to coplanar lines with finite dimensions,” *International Journal of Electronics*, vol. 48, no. 1, pp. 47–56.

[14] Nir Tessler, Yevgeni Preezant, Noam Rappaport, and Yohai Roichman, “Charge Transport in Disordered Organic Materials and Its Relevance to Thin-Film Devices: A Tutorial Review,” *Adv. Mater,* vol. 21, pp. 241–2761, 2009.