Flexible Lightweight Films-based Physical Sensors with Wireless Data Transmission

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Abstract— **This article is addressed to the development of flexible lightweight physical sensors suitable for body sensing technology. The polycarbonate films were covered with different organic molecular conductors to fabricate flexible strain and temperature sensing materials. The resulting surface-modified films were fully characterized by different microscopic and spectroscopic techniques and their electric transport and electromechanical properties were studied as well. The investigations demonstrated that the electrical responses of these films suffice to measure very small pressure or temperature changes. Prototypes of strain and temperature sensors with wireless data transmission are under development.**

Keywords-flexible strain sensor; temperature sensing material; organic molecular conductors; electrical detection principle; wireless data transmission.

I. INTRODUCTION

The application of flexible lightweight sensors in electronics is a key point in the development of novel high-tech [1-4]. Engineering flexible all-organic sensing materials with electrical detection principle brings great opportunities in the field of physical sensors for their applications in intelligent textiles, robotic interfaces and body sensing devices [1-3]. A simple covering process of polymeric films with highly strain sensitive, piezoresistive, micro- or nano-crystals of BEDT-TTF-based molecular conductors has been developed previosly; BEDT-TTF = bis (ethylenedithio)tetrathiafulvalene, Fig. 1 [4, 5].

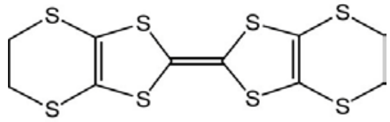

Figure 1. Skeletal formula of BEDT-TTF

We have shown that these bi layer (BL) films may have a great interest in sensor engineering due to important material properties, such as conductivity, high strain (pressure) and temperature sensitivity, excellent elasticity, weightless and biocompatibility [6]. Since the ultimate goal of our studies is to use the developed BL films in body sensing technology the biocompatibility of the BL film has been tested. Haematoxylin-Eosin staining of the tissues adjacent to the sensing BL film and to the silicon band showed the less inflammatory reaction to BL film samples as compared with the reaction to a silicone band [6]. So, the developed sensing BL films have a higher biocompatibility than standard silicone-based materials used in surgery.

The processing characteristics of polycarbonate films, covered with the layer of a BEDT-TTF–based organic molecular conductor, make them potentially useful for electronic applications where conductivity, lightweight, large or small area coverage and flexibility are required [4]. Recently, we have reported on the integration of polycarbonate films metalized with the highly strain sensitive β-$(BEDT\text{-}TTF)_2I_3$ metal in a polyester textile, that permits to demonstrate that the strain sensing properties of this unique organic molecular metal can be completely transferred on the fabric [7]. This result prompted us to develop a temperature sensing material that also uses the electrical detection principle. For this purpose we suggested to cover polycarbonate films with the highly temperature sensitive α'- $(BEDT\text{-}TTF)_2I_xBr_{3-x}$ conductor [8]. Noteworthy also is that the BL film-based sensors have to be equipped for some particular applications especially in biomedicine with some electronic circuit to measure, amplify and transmit the deformation or temperature data.

Here, we present flexible, lightweight sensing BL films whose electrical resistance significantly responses to deformation (piezoresistive) or temperature changes (pyroresistive) depending on the type of molecular conductor used for covering the polycarbonate film. This article also demonstrated a system that can measure strain and temperature and a possibility to transmit the measured data to a data acquisition (DAQ) system. Prototypes of strain and temperature sensors with wireless data transmission being under development will be presented as well.

II. FABRICATING FLEXIBLE STRAIN AND TEMPERATURE SENSING FILMS WITH ELECTRICAL DETECTION PRINCIPLE

In line with the early reported method, [9] we first prepared a 25 μm thick polycarbonate (PC) films that contain a 2 wt. % of BEDT-TTF that is a precursor for various organic molecular metals. The films were cast on glass supports at 130 ^{o}C from a 1,2-dichlorobenzene solution of PC and BEDT-TTF. In order to cover the film with the layer of a BEDT-TTF-based conductor we exposed the film surface to the vapors of a solution of either iodine or IBr in dichloromethane. The surface of a polycarbonate film easily swells under its exposure to dichloromethane vapors; this swelling facilitates a migration of BEDT-TTF molecules from the film bulk to the swollen film surface where the part of donor molecules are oxidized to radical cations by halogen, which penetrates in the film surface together with dichloromethane vapors. This redox process induces the rapid nucleation of highly insoluble the (BEDT-TTF)$^{+\bullet}$(halogen)$_n^-$ conductor and the facing layer of an organic molecular conductor is formed. It should be stressed that the treatment of the film surface with iodine/dichloromethane vapors resulted in the formation of the covering layer of the α- phase of (BEDT-TTF)$_2$I$_3$; gauge factor (GF) is equal to 10 [4]. On the other hand, we have shown that PC films covered with the layer of the beta-phase of (BEDT-TTF)$_2$I$_3$ demonstrate GF being equal to 20 [4]. Taking into account that the highly piezoresistive layer of β-(BEDT-TTF)$_2$I$_3$ may be formed via a thermo-activated $\alpha \rightarrow \beta$ phase transition that occurs at T>100 ^{o}C [9], the BL film with the layer of α-(BEDT-TTF)$_2$I$_3$ was annealed at 150^{o}C during 30 min. The formation of the both covering layers based on either the strain sensing β-(BEDT-TTF)$_2$I$_3$ metal or the highly temperature sensing α´-(BEDT-TTF)$_2$I$_x$Br$_{(3-x)}$ conductor was confirmed by the X-ray diffraction patterns. Referring to Figures 2(left) and 3 (left), both patterns demonstrate only (00*l*) reflections that are characteristic of conducting layers formed by oriented crystals: the *c** axis of the crystals is perpendicular to the film surface and, consequently, their molecular *ab* conducting layers are parallel to it. The surface analysis on a micro scale, performed using “Quanta FEI 200 FEG-ESEM” scanning electron microscope (SEM), showed that the crystallites of the both types of sensitive covering layers are of submicro sizes (Fig. 2, right and 3, right).

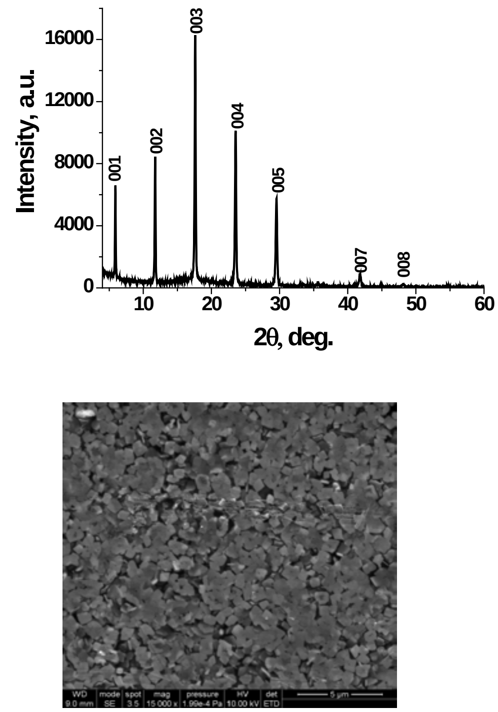

Figure 2. X–ray powder diffractogram (top) and SEM image (bottom) of the piezoresistive covering layer of β-(BEDT)$_2$I$_3$.

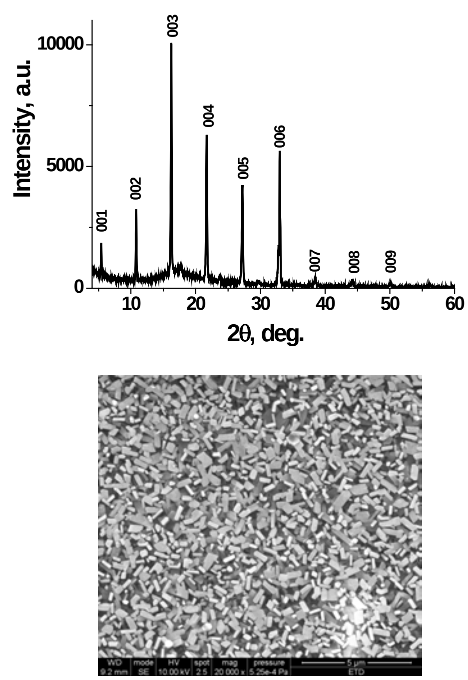

Figure 3. X–ray powder difractogram (left) and SEM image (right) of the covering layer of α´-(BEDT-TTF)$_2$I$_x$Br$_{(3-x)}$ whose electrical resistance highly sensitive to temperature changes.

As a final remark to this part, we would like to add that the temperature coefficients of resistance (TCR) were found as 0.3 %/°C and -1.3 %/°C, for the covering β-$(BEDT\text{-}TTF)_2I_3$ and α´-$(BEDT\text{-}TTF)_2I_xBr_{(3\text{-}x)}$ layers, respectively (Fig. 4). The TCR were calculated as a relative resistance change per grade. The room temperature resistance of the films covered with the sensitive α´-$(BEDT\text{-}TTF)_2I_xBr_{(3\text{-}x)}$ layer is equals to 25-30 kΩ. It is evident from the forgoing TCR that the film resistance changes as 320-390 Ω per grad. It is obviously that such sensitivity permits this BL film to control small temperature changes (0.01-0.005 grad) as a well definite electrical signal.

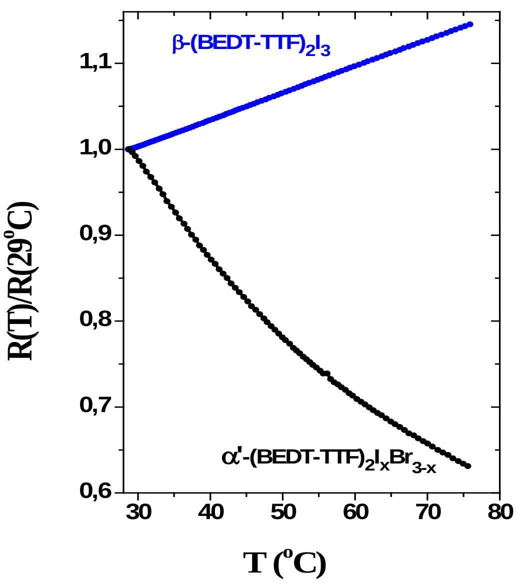

Figure 4. Temperature dependence of the resistance for sensing BL films.

III. Electronic and Electromecanic Measurements – Prototypes

With the aim to study the possibility to apply the highly sensitive BL films as physical sensors, different prototypes have been developed [4, 6, 7].

A. Portable Prototype capable of monitoring deformation induced resistance change displayed in a LED array

A new sensor prototype capable of measuring deformations of the BL-Film manifested in either compression or expansion of the crystalline network has been developed. For this purpose, a BL-Film covered with β-$(BEDT\text{-}TTF)_2I_3$, was mounted on top of a 30 μm thick steel foil (see Figure 5 bottom right). An electronic circuit which includes a Wheatstone bridge, amplifiers and two transistor driven “staircase” light emitting diode (LED) schemes to monitor the deformation is also shown in Figure 5. Upon expansion of the BL-Film the and upon compression the corresponding LEDs turn on sequentially.

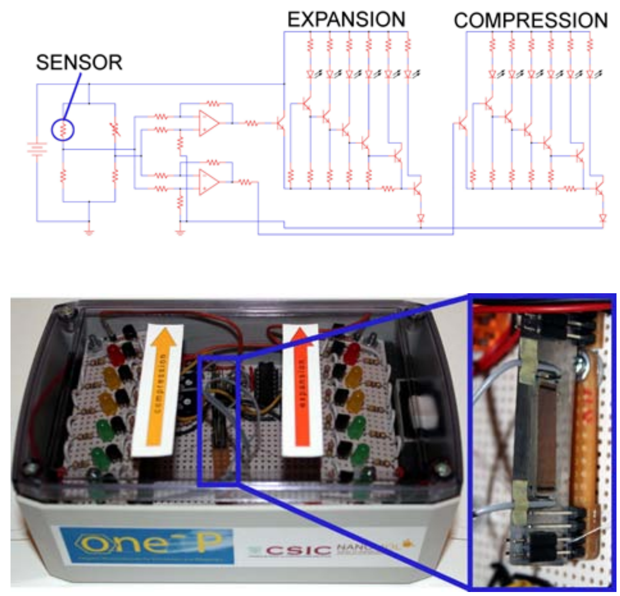

Figure 5. Demonstration proof of concept prototype to monitor the compression and expansion of BL-Film based sensor mounted on a thin steel foil. Electronic scheme (top) and finished prototype box developed at NANOMOL Department (ICMAB-CSIC) with a zoom of the sensor element (right).

B. Development of Prototypes based on piezoresistive and pyroresistive BL-Films with wireless data transmission

Our sensor prototypes developed up to know exhibited high sensitivity and reproducibility in the strain measurements; however the sensing unit was connected with an electrical cable to the measurement unit which was further connected to a measurement computer. In many real applications, especially in monitoring vital functions of the human body, sensors connected with the data acquisition (DAQ) system using wires limit the feasibility drastically. An important improvement in this regard is the development of a small measurement unit connected to the sensor element, either piezoresistive or pyroresistive, which than transmits the measured data set to a DAQ system or a computer.

A simple variant of such an electronic scheme includes a Wheatstone bridge for offset compensation and an operational amplifier [10]. Depending on the chemical nature of the BL-Film and the particular application one is interested in, the Wheatstone bridge also allows to include additional to the active strain sensing unit a passive (strain) sensors, which can be used for temperature compensation if needed. The analog electrical signal obtained after the amplifier has to be digitalized (A/D converter), encoded and transmitted. Figure 6 shows a simple block diagram of the complete sensor unit which works for both piezoresistive and pyroelectric sensors.

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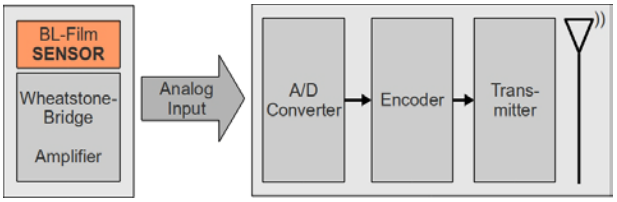

Figure 6. Simple block diagram of the BL-Film based sensor unit (either piezoresistive or pyroresistive), Wheatstone bridge with amplifier and transmitter scheme for wireless data transmission.

On the receiving side of the electrical circuit, the signal has to be decoded and transferred either directly to a DAQ-system (*i.e.*, computer) or back converted to an analog signal (Figure 7).

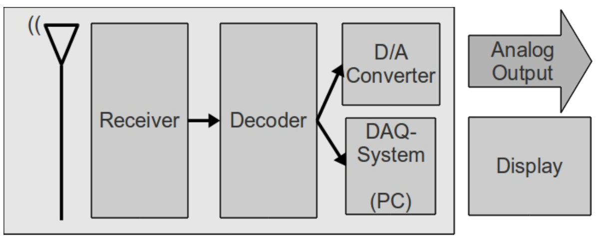

Figure 7. Simple electronic reciever scheme with decoder for either analog output or connected directly to a data aquistition (DAQ) system (*i.e.* Computer).

For the construction of a proof of concept device to measure, transmit and receive the variation of the electrical resistance induced in the BL-Film based sensor a commercial transmitter-receiver unit was purchased at ABACOM Technologies [11]. The transmitter unit (RF-AD-TX) consists of an 8 bit analog to digital converter able to convert a voltage range from 0 to 5 V of up to four independent channels and a corresponding step size of about 20 mV. The transmitter works at a frequency of 433 MHz. The receiver unit (RF-AD-RX) on the other hand consists of an 8 bit digital to analog converter and again for corresponding analog outputs. A schematic representation is shown in Figure 8.

A complete system and a new generation of prototypes including similar schemes described above with wireless data transmission in smaller dimensions is currently under preparation. The development of similar prototype devices including wireless data transmission is desired especially for applications in biomedicine for human healthcare to monitor vital functions.

IV. SUMMARY

It was shown that covering polycarbonate films with the α´-(BEDT-TTF)$_2$I$_x$Br$_{(3-x)}$ conductor makes a good promise of a flexible lightweight temperature sensor.

The small measurement unit connected to the BL film-based sensing elements which is able to transmit the measured data set to a DAQ system or a computer have been designed that permits to develop prototypes of the BL film-based strain and temperature sensors with wireless data transmission.

The preliminary data show that the polycarbonate films covered with molecular BEDT-TTF-based conductors show a considerable promise as flexible wireless physical sensors that are able to take the place of conventional metal-based strain and temperature sensors in biomedical high-tech. It is expected that developed sensing materials may have a large impact in biomedical applications.

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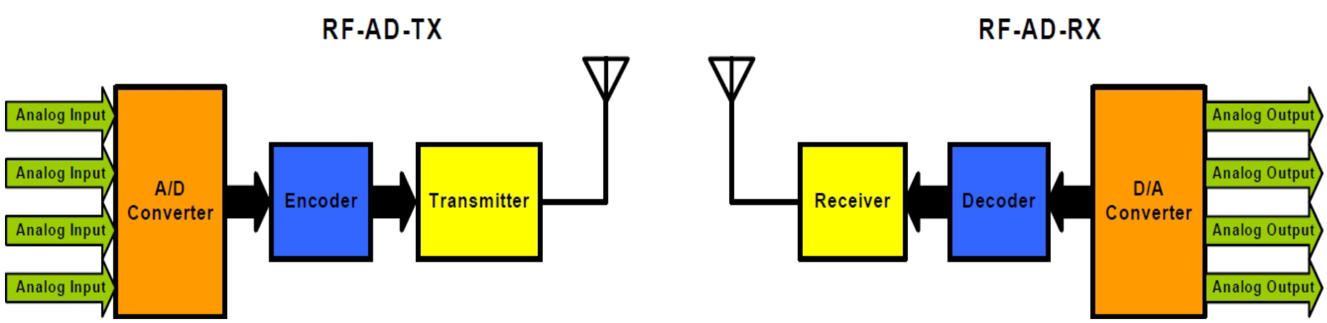

Figure 8. Commercially available analog to digital transmitter (RF-AD-TX) and digital to analog reciever (RF-AD-RX) used to transmit the measured and amplified signal of the BL-Film based sensor (scheme taken from data sheet, 11).

REFERENCES

[1] S. Y. Yurish, N. V. Kirinaki, and I. L. Myshkin, "World Sensors and MEMS Markets: Analysis and Trends", Sensors & Traducers Magazine (S&T e-Digest), vol. 62, Issue 12, pp. 456-461, 2005.

[2] F. Axisa, P. M. Schmitt, C. Gehin, G. Delhomme, E. McAdams, and A. Dittmar, "Flexible technologies and smart clothing for citizen medicine, home healthcare and disease prevention", IEEE Transactions on Information Technology in Biomedicine, vol. 9, No. 3, pp. 325-336, 2005.

[3] B. Adhikari, and S. Majumdar, "Polymers in sensor applications", Progress in Polymer Science, vol. 29, pp. 699-766, 2004.

[4] E. Laukhina, R. Pfattner, L. R. Ferreras, S. Galli, M. Mas-Torrent, N. Masciocchi, V. Laukhin, C. Rovira, and J. Veciana, "Ultrasensitive Piezoresistive All-Organic Flexible Thin films", Adv. Mater., vol. 22, pp. 977-991, 2010.

[5] E. Laukhina, C. Rovira, and J. Ulanski, Organic metals as active components in surface conducting semi- transparent films, Synth. Met., vol. 21, pp. 1407-8, 2001

[6] V. Laukhin, I. Sánchez, A. Moya, E. Laukhina, R. Martin, F. Ussa, C. Rovira, A. Guimera, R. Villa, J. Aguiló, J.-C. Pastor, and J. Veciana, "Prototype for Noninvasive IOP Monitoring with a Nanostructured Polymeric Sensor Embeded in a Contact Lens", Transducers & Sensors, vol. 170, pp. 36– 43, 2011. Patent: ES2330405-A1; WO2009147277-A1.

[7] L. R. Ferreras, R. Pfattner, M. Mas-Torrent, E. Laukhina, L. López, V. Laukhin, C. Rovira, and J. Veciana *J.* "Highly piezoresistive textiles based on a soft conducting charge transfer salt", Mater. Chem**.**, vol. 21, pp. 637- 641, 2011.

[8] E. Laukhina, V. Tkacheva, S. Khasanov, L. Zorina, J. Gomez-Segura, A. Perezdel Pino, J. Veciana, V. Laukhin, and C. Rovira, "Linked Crystallites in the Conducting Topmost Layer of Polymer Bilayer Films Controlled by Temperature: From Micro- to Nanocrystallites", ChemPhysChem, vol. 7 pp. 920 – 923, 2006

[9] E. E. Laukhina, V. A. Merzhanov, S. I. Pesotskii, A. G. Khomenko, E. B. Yagubskii, J. Ulanski, M. Krysezewski, J. and K. Jeszke, "Superconductivity in reticulate doped polycarbonate films containing $(BEDT\text{-}TTF)_2I_3$", Synth. Met., vol 70, pp. 797-800, 1995.

[10] U. Tietze, and C. Schenk, "Halbleiter-Schaltungstechnik", Springer Verlag Berlin-Heidelberg, 1999, ISBN: 3-540-64192-0, pp. 1242-1260.

[11] ABACOM Technologies: http://www.abacom-tech.com [retrieved : 07, 2012].

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