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Evaluation of flexible organic transistor stability in harsh conditions

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***Abstract*—Characterizing the degradation of organic electronics is fundamental for the exploitation of this technology in different scenarios, including aerospace and biomedical applications. In this paper, flexible printed organic transistors were exposed to controlled environmental conditions that may resemble those for the above-mentioned applications, including thermal and radiation stresses. The effect of encapsulation layers in enhancing the device reliability is discussed.**

Keywords— Organic field-effect transistor; Flexible printed electronics; UV radiation; Thermal stability.

I. INTRODUCTION

Recently, the growing interest and the continuos progress in organic electronics have extended potentialities of Organic Field-Effect Transistors (OFETs) towards a variety of new applications. At the state of the art, OFETs are mainly employed for the development of cost-effective devices and circuits by means of low-temperature processes over large area and flexible substrates. Moreover, some peculiar OFETs characteristics, such as low voltage operation and biocompatibility, have opened the door to different innovative applications, ranging from smart personal devices to biosensors. Despite all these advances, a significant gap still exists between organic flexible transistors technology and inorganic devices for operation in harsh environments. Indeed, in some interesting applications, like aerospace or peculiar medical procedures, electronic devices can be exposed to extreme temperatures, electrical or mechanical shocks, and even to ionizing radiation. Since organic materials are very subjected to these extreme conditions, reliability of OTFTs for rugged electronics applications has been poorly explored. For example, in space applications, electronics must withstand several degradation stresses such as cycling temperature, high energy radiations, vibrations, vacuum, atomic oxygen and debris impact [1], depending on where the devices operate. Similarly, if organic transistors have to be integrated in medical devices, they must be able to withstand the exposure to extreme temperatures, e.g. in sterilization conditions. Only a few studies show the influence of temperatures on the physical and electrical properties of poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) [2-5]. Radiation hardness is another key parameter to be evaluated for electronics operating in space environment but also in biomedical applications. A wide spectrum of radiations can affect the performances of electronit cs in space: in literature, some works reported results on specific tests through gamma-ray irradiation and high-energy protons [6, 7]. For OTFTs, the near ultraviolet (NUV) radiation (180-400 nm) might represent a serious concern [8, 9]. These aspects sum with the well-known environmental instability of organic materials' electrical performances, mainly due to humidity and oxygen in atmospheric conditions [10, 11], which often brings to the employment of encapsulation layers [12]. In this work, thermal and radiation hardness of OFETs is discussed as a preliminary reliability assessment for their exploitation in harsh environments. Flexible OFETs have been fabricated by large area processes, such as inkjet printing, and exposed to stress conditions, including different temperature values ranging from -20°C to +120°C, and to broad- and wide-band UV radiation at fixed energy. In both tests, single stresses were chosen not to induce multiple failure mechanisms that can generally interact and compete in real applications, but are more challenging to interpret. The aim was to recognize the failure mechanism that really dominates the degradation process induced by each stress.

II. EXPERIMENTAL

A. *OFET Structure and fabrication*

Bottom-gate bottom-contact OFETs were fabricated with interdigitated source and drain electrodes (10 channels with single width W = 1 mm, and length L = 150 µm). As a substrate, 125-µm-thick polyethylene naphthalate (PEN) was employed. Gate, source and drain electrodes are made of poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS). Specifically, all electrodes were patterned by inkjet-printing employing a Dimatix Materials Printer DMP283 (Fujifilm Dimatix). Gate electrodes were inkjet-printed directly on the PEN substrate using three nozzles with a firing voltage of 30 V, a drop spacing of 15 µm and the temperature of the printer platen maintained at 60°C. The gate insulator is a 250-nm-thick Parylene C film, deposited by chemical vapor deposition (CVD) with a PDS 2010 Labcoater 2 (Specialty Coating System). Source and drain were inkjet-printed directly on the Parylene C surface employing a single nozzle of the same PEDOT:PSS-filled cartridge ink and the same printing parameter of gate pattering. Finally, a 6,13-Bis(triisopropylsilylethynyl) pentacene (TIPS pentacene, Sigma Aldrich) solution (1.5% in anisole) was drop-casted on the transistor channels, resulting in a 100 nm thick layer. The structure of a set of devices was completed with an encapsulation layer, consisting of a 40 µm-thick polydimethylsiloxane (PDMS, Sylgard 186®, Dow Inc.) film, and of a 2 µm-thick Parylene C capping layer subsequently deposited by CVD.

B. *Electrical and optical characterization*

Electrical characterizations were carried out with a Keithley® 2636 SourceMeter and a custom-made Matlab® software, in ambient conditions and at room temperature. The optical irradiation tests were performed by using Laser-driven Xenon lamp (EQ-99X) with a bandwidth of about 1 nm and average optical power of 1 mW/nm. Band pass filters were utilized to define the excitation wavelength: Hg01-254-25 (Semrock Inc), 10BPF310 (Newport) and10BPF360 (Newport) for emission at 254, 310 and 360 nm, respectively. Broad band UV irradiation has been performed with an ultra-high vacuum Mercury lamp (Model 6285, 500 W). The optical light intensity has been monitored with a 1918-C-Newport Optical Power Meters. All tests were conducted with irradiation coming from above the encapsulating layer.

III. RESULTS

A. *Electrical characterization*

A complete electrical characterization was performed on the flexible printed transistors. Specifically, transfer characteristics ($V_{GS} = [-4 : +4]$ V, $V_{DS} = -5$ V) were recorded in order to evaluate electrical performances of encapsulated and non-encapsulated devices. Average and 1-σ values of threshold voltage and mobility have been evaluated in a set of 15 pristine encapsulated and 15 pristine non-encapsulated OFETs. More in detail, a threshold voltage of (0.98±0.08) V was obtained for non-encapsulated transistors and an average of (1.9±0.1) V for the encapsulated ones. This shift is due to the addition of the encapsulation layer, but it does not compromise device performance. As regards charge carrier mobility, average values of (0.13±0.01) $cm^2V^{-1}s^{-1}$ and (0.19±0.02) $cm^2V^{-1}s^{-1}$ were evaluated for non-encapsulated and encapsulated devices, respectively.

B. *Temperature stress test*

In order to study functionality and endurance of flexible printed OFETs over a temperature range representative for the operation in harsh conditions, temperature stress tests in the range [-20 : +125] °C have been performed. Device electrical characteristics have been acquired before the exposure, 1 hour after the temperature was imposed for 90 minutes, and after 24 hours in order to verify irreversible degradation of device performances. Fig. 1 (a) depicts the average absolute variation of the threshold voltage $\Delta V_{TH} = V_{TH,i} - V_{TH,0}$, where $V_{TH,i}$ is the threshold voltage after 1 or 24 hours from the temperature exposition, while $V_{TH,0}$ is the one extrapolated before the stress test. Specifically, for non-encapsulated OFETs, a decrease of the threshold voltage has been obtained at lower temperatures (<25°C), while an increase has been observed for temperatures in the range [+25 : +100] °C. These variations persist also after 24 hours from the temperature exposition. In the case of encapsulated OFETs, a general increase of the threshold voltage until a breaking temperature of about 100°C has been obtained. Moreover, transistors underwent to a dramatic variation of the threshold voltage for higher temperatures, probably because of a PDMS degassing, which partially dissolves the semiconductor film, or a release of residual solvent in the PDMS. Nonetheless, variations are in general smaller than the one observed in non-encapsulated devices (in a range of 400 mV), and they are substantially recovered within 24 hours for temperature values below 50°C. Fig. 1 (b) shows the relative mobility variation $\Delta\mu/\mu = (\mu_i - \mu_0)/\mu_0$, where μ_i is the mobility after 1 or 24 hours of settling time, and μ_0 is the mobility before the temperature exposition. In details, for non-encapsulated devices there is a relevant decrease of the mobility for low temperature, but for temperature exceeding 0°C it is not possible to observe a clear dependence on applied temperature. Moreover, the mobility reduction obtained for temperatures lower than 0°C is kept after 24 hours, while a general mobility decrease is observed for other temperatures. As regards encapsulated OFETs, mobility shows a lower variability with variations within a tolerance range of maximum 7% until the breaking temperature of 125°C, which causes a reduction of about 80%, i.e. the device failure.

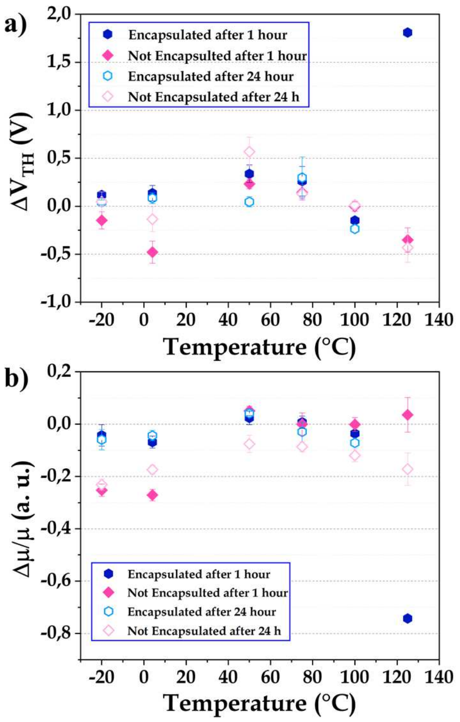

Fig. 1. Temperature stress test for encapsulated and non-encapsulated OFETs: (a) threshold voltage absolute variation and (b) mobility relative variation with temperature ranging from -20°C to +125°C.

C. *Radiation stress test*

OFETs radiation hardness has been studied performing two different stress tests. Initially, in order to evaluate possible effects of specific wavelengths on transistors performances, tests were performed with radiation at fixed wavelengths in deep UV range (250, 310 and 360 nm). Experiments were carried out with an exposure period of 30 minutes and a power density fixed to 0.1 $mWcm^{-2}$. In particular, each transistor was measured before and 24 hours after the exposure to a given wavelength. Results of these tests are shown in Fig. 2. It is possible to observe that a radiation of 250 nm (with the higher ionization capability) induces a failure in the case of non-encapsulated OFETs: a large threshold voltage variation and variability (6.7±1.0 V) and a reduction of charge carrier mobility larger than 90% were recorded. Interestingly, the same radiation causes a permanent variation of encapsulated transistor threshold voltage, even if with a lower extent (1.2±0.5 V), and with less significant variation of the mobility (1%). This result demonstrates that the encapsulation layer prevents ionizing species to interact with the organic semiconductor, consequently avoiding failure mechanisms. When the wavelength increases and the energy of the radiation decreases, the difference between encapsulated and non-encapsulated OFETs is less significant for both threshold voltage and mobility variation, even if a significantly larger variability of these two parameters has been recorded for non-encapsulated devices. A second kind of radiation stress test has been performed employing radiation with a broader spectrum in the UV range and at fixed power density (0.1 $mWcm^{-2}$), which is more representative of real applications. In particular, experiments were carried out for different exposure time (30, 60 and 90 minutes). Results are shown in Fig. 3: in this case, a less relevant difference between encapsulated and non-encapsulated devices OFETs can be

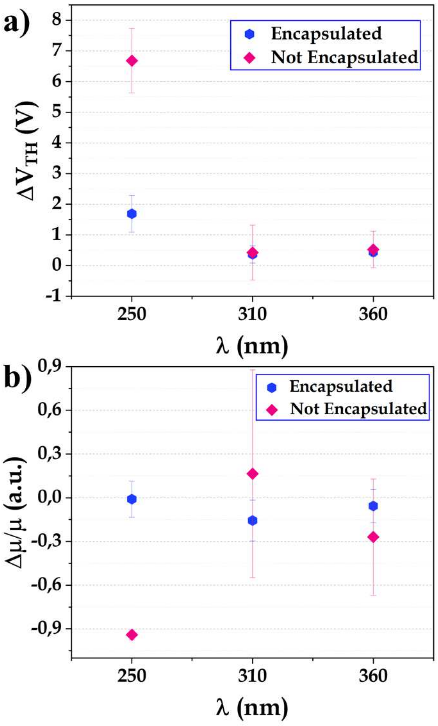

Fig. 3. Radiation stress test for encapsulated and non-encapsulated OFETs: threshold voltage absolute variation (a) and mobility relative variation (b) with radiation.

noticed for the exposure to monochromatic radiations. In general, threshold voltage increases, demonstrating that electrons trapping mechanisms are activated. Moreover, a negligible decrease in mobility can be observed. However, the variability between different non-encapsulated transistor is significantly larger than the one obtained for encapsulated ones. Therefore, the employment of an encapsulation layer enhances the reliability of OFET performances.

IV. CONCLUSIONS

The stability of flexible Organic Field-Effect Transistors exposed to extreme temperatures and UV radiation intervals is investigated in this work. Obtained results show that encapsulation plays an important role in reducing the variability of electrical performances and to mitigate the device degradation with thermal and UV stress. This is correlated with the protection of the organic semiconductor to environmental conditions, preventing charge trapping and oxidation mechanisms. The encapsulation preserves the electrical performance for temperature as high as 100°C. After this point, it seems to contribute to the final degradation process. Moreover, it protects the devices, assuring in particular better and more stable performances at higher ionization radiation. Even if these results are not conclusive, the stability and degradation of the device and its materials retain their significance, and this work paves the way to a detailed reliability evaluation of flexible organic electronics operating in severe conditions.

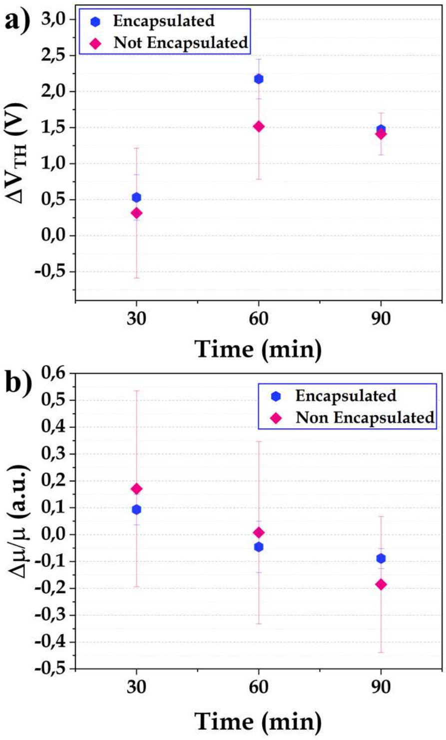

Fig. 2. threshold voltage absolute variation (a) and mobility relative variation (b) with broad spectrum radiation for encapsulated and non-encapsulated transistors for different exposure time.

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REFERENCES

[1] A. Hassan, Y. Savaria and M. Sawan, "Electronics and packaging intended for emerging harsh environment applications: A review," IEEE transactions on very large scale integration (VLSI) systems 26.10, pp. 2085-2098, 2018.

[2] A. Moser, J. Novák, H.-G. Flesch, T. Djuric, O. Werzer, A. Haase, R. Resel, "Temperature stability of the pentacene thin-film phase," Applied Physics Letters 99.22, 221911, 2011.

[3] K. Kuribara, H. Wang, N. Uchiyama, K. Fukuda, T. Yokota, U. Zschieschang, C. Jaye, D. Fischer, H. Klauk, T. Yamamoto, K. Takimiya, M. Ikeda, H. Kuwabara, T. Sekitani, Y.-L. Loo and T. Someya, "Organic transistors with high thermal stability for medical applications," Nat. Commun. 3.1, 723, 2012.

[4] E. Vitoratos, S. Sakkopoulos, E. Dalas, N. Paliatsas, D. Karageorgopoulos, F. Petraki, S. Kennou, S.A. Choulis, "Thermal degradation mechanisms of PEDOT: PSS," Org. Electron. 10.1, pp. 61-66, 2009.

[5] J. Huang, P.F. Miller, J.C. de Mello, A.J. de Mello, D.D.C. Bradley, "Influence of thermal treatment on the conductivity and morphology of PEDOT/PSS films," Synth. Met. 139.3, pp. 569-572, 2003.

[6] L. Basiricò, A. F. Basile, P. Cosseddu, S. Gerardin, T. Cramer, M. Bagatin, A. Ciavatti, A. Paccagnella, A. Bonfiglio and B. Fraboni, "Space environment effects on flexible, low-voltage organic thin-film transistors," ACS Appl. Mater. Interfaces 9.40, pp. 35150-35158, 2017.

[7] L. Cai, T. Hirao, H. Yano, Z. F. Duan, H. Takayanagi, H. Ueki, T. Ohshima, Y. Nishioka, "60Co Gamma–Ray Irradiation Effects on Pentacene-Based Organic Thin-Film Transistors." In: Materials Science Forum Trans. Tech. Publications Ltd 687, pp. 576-579, 2011.

[8] E. Brandon, W. West, L. Zhou, T. Jackson, G. Theriot, R. A.B. Devine, D. Binkley, N. Verma and R. Crawford, "Flexible electronics for space applications," MRS OPL 814, pp. 335–346, 2004.

[9] N. Wrachien, A. Cester, D. Bari, J. Kovac, J. Jakabovic, D. Donoval, G. Meneghesso, “Near-UV irradiation effects on pentacene-based organic thin film transistors,” IEEE Trans. Nucl. Sci. 58.6, pp. 2911-2917, 2011.

[10] Q. Zafar, S. M. Abdullah, M. I. Azmer, M. A. Najeeb, K. W. Qadir, K. Sulaiman, “Influence of relative humidity on the electrical response of PEDOT:PSS based organic field-effect transistor,” Sens. Actuators B Chem. 255, pp. 2652-2656, 2018.

[11] Y. Chen, W. Deng, X. Zhang, M. Wang, J. Jie, “Ambient instability of organic field-effect transistors and their improvement strategies,” J. Phys. D: Appl. Phys. 55, 053001, 2021.

[12] S. H. Kim, W. M. Yoon, M. Jang, H. Yang, J.-J. Park, C. E. Park, “Damage-free hybrid encapsulation of organic field-effect transistors to reduce environmental instability” J. Mater. Chem. 22, pp. 7731-7738, 2012.