ORGANIC SEMICONDUCTOR THIN FILMS FOR INTEGRATED PHOTONICS APPLICATIONS

I. Maqueira Albo(1), M. Caironi (2), F. Morichetti(2)

(1) Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano, 20133 Milano, Italy
(2) Center for Nano Science and Technology, Istituto Italiano di
Tecnologia, Via Pascoli 70/3 – 20133 – Milano (Italy)
francesco.morichetti@polimi.it

Abstract

In this work, we investigate the optical properties of solution processable organic semiconductors that are widely employed in the field of large-area, flexible and portable electronics. The refractive index and extinction coefficient of an n-type organic semiconductor (P(NDI2OD-T2)) were measured in the visible and near infrared range by means of spectroscopic ellipsometry. We also demonstrated integration of P(NDI2OD-T2) as a coating film of low-loss silicon oxynixtride waveguides (SiON). Results suggest the possibility to integrate printed electronics devices on photonic integrated circuits and to realize organic transistors on photonic platforms.

Index Terms – Organic semiconductors, Integrated optics materials, Optical waveguides, Photonic integrated circuits

I. INTRODUCTION

As photonics integrated circuits evolve toward complex on-chip architectures, integration of photonic devices with electronics is becoming mandatory to implement more sophisticated control and read-out operations. Organic molecular materials, offering flexibility and low-cost fabrication, can enrich conventional photonics platforms with new functionalities in order to develop next-generation photonic devices [1].

Solution processable organic semiconductors have been widely studied in the field of large-area, flexible and portable electronics [2] These compounds together with soluble conductors and dielectrics enables the fabrication of complex organic devices solely through solution-based methods. Among these materials, poly{[N, N′-bis(2-octyldodecyl)-naphthalene-1,4,5,8-bis(dicarboximide)-2,6-diyl]-alt-5,5′-(2,2′-bithiophene)} (P(NDI2OD-T2)) is a notable example of n-channel type polymeric semiconductor with high electron mobility in the order of 0.1 – 0.96 $cm^2v^{-1}s^{-1}$. [3]. However, few works report on the optical performance of fully printed organic semiconductors, and the integration itself of printed organic electronic devices, such as organic transistors, on a photonic chip has still to be demonstrated.

In this work we characterized the optical properties of P(NDI2OD-T2) in the visible and near infrared range and we integrated this material as a coating layer of silicon oxynitride (SiON) waveguides. Results suggest the possibility to use P(NDI2OD-T2) as a an organic semiconductor material for the realization of printed electronic circuits integrated on an optical platform.

II. FILM DEPOSITION AND OPTICAL CHARACTERIZATION

P(NDI2OD-T2 thin films were deposited by spin-coating from a 5mg/ml toluene solution on a glass substrate for ellipsometric analysis. The film was then annealed in air at 80 °C for 15 min in order to evaporate the solvent and the final thickness determined by Atomic Force Microscopy (AFM) was of 60 nm. Consequent studies by AFM reveals the random orientation of the polymer fibril structures with the presence of elongated rod-like features and a surface roughness of 0.6 nm rms (Fig. 1b), which is well in line with the requirements of optical applications.

Spectroscopic ellipsometry was performed on P(NDI2OD-T2) thin films (Fig. 1c) in the range between 400 nm to 1650 nm taking into account the anisotropic nature of the material. The absorption P(NDI2OD-T2) spectra in the UV-Vis range is characterized by two spectral features, one high energy peak around 390 attributed to the π−π* transition and a broader and lower energy band between 600 to 800 nm, depending on the solvent employed in the solution, attributed to the charge-transfer

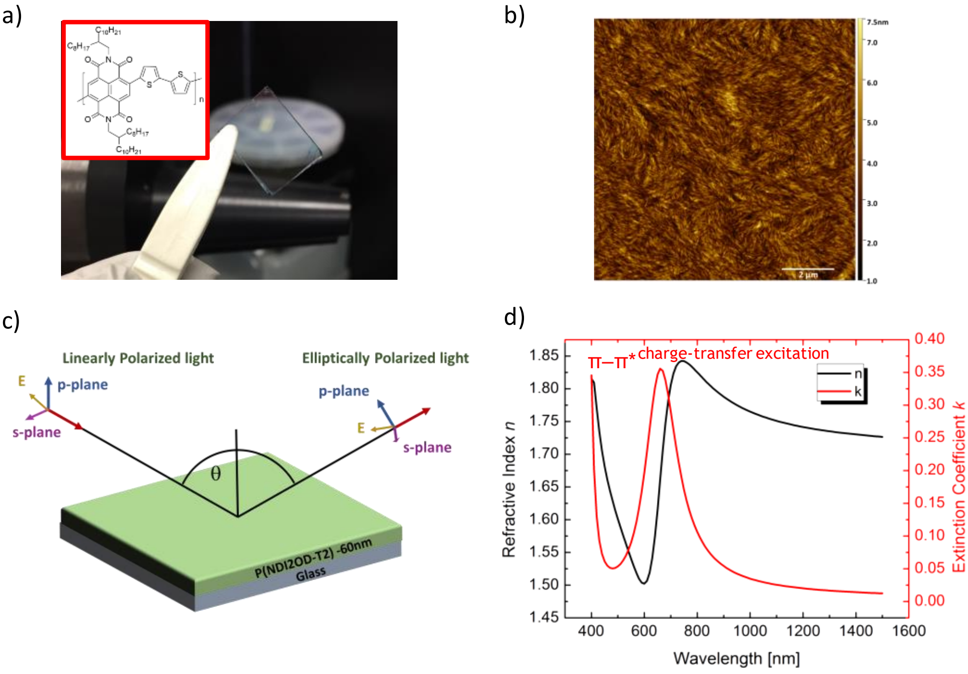

FIG. 1 – (a) P(NDI2OD-T2) molecular structure (inset) and thin film photograph after spin-coating on a glass substrate. (b) AFM topography of the polymer film, exhibiting random orientation of the fibril structures. (c) Schematic representation of the film stack used for the ellipsometric measurements. (d) Refractive index n and extinction coefficient k in the wavelength range between 400 and 1600 nm of the P(NDI2OD -T2) determined by spectroscopy ellipsometry.

(CT) transition. For the ellipsometric data modelling were used two Lorentz oscillators at 390 nm and 660 nm. In the visible range, the refractive index of P(NDI2OD-T2) presents a minimum value of 1.5 at 600 nm and maximum value of 1.84 at 800 nm, which is in agreement with results reported in the literature [4]. At λ > 1300 nm, the refractive index is around 1.7 and the extinction coefficient *k* was found to be lower than the accuracy provided by the experimental setup ($<10^{-2}$) (Fig.1d).

III. P(NDI2OD-T2)-COATED SILICON OXYNITRIDE WAVEGUIDES

In order to accurately evaluate the transparency of P(NDI2OD-T2) in the near NIR range, a thin film of this material was used as coating material of optical waveguides. To this aim, we employed SiON rib waveguides with a cross-sectional geometry as shown in Fig. 2a. A 2.2-µm-thick SiON core layer with a refractive index of 1.497 was deposited by plasma enhanced chemical vapour deposition (PECVD) on a SiO_2 surface and was than etched by 500 nm by reactive-ion etching. The resulting waveguide index contrast is about 3.6 %. A solution of P(NDI2OD-T2) was then spin-coated on top the waveguides. Figure 2b shows the cross-sectional SEM image of one of the fabricated waveguides, where the 60-nm-thick P(NDI2OD-T2) films well follows the waveguide profile, demonstrating the

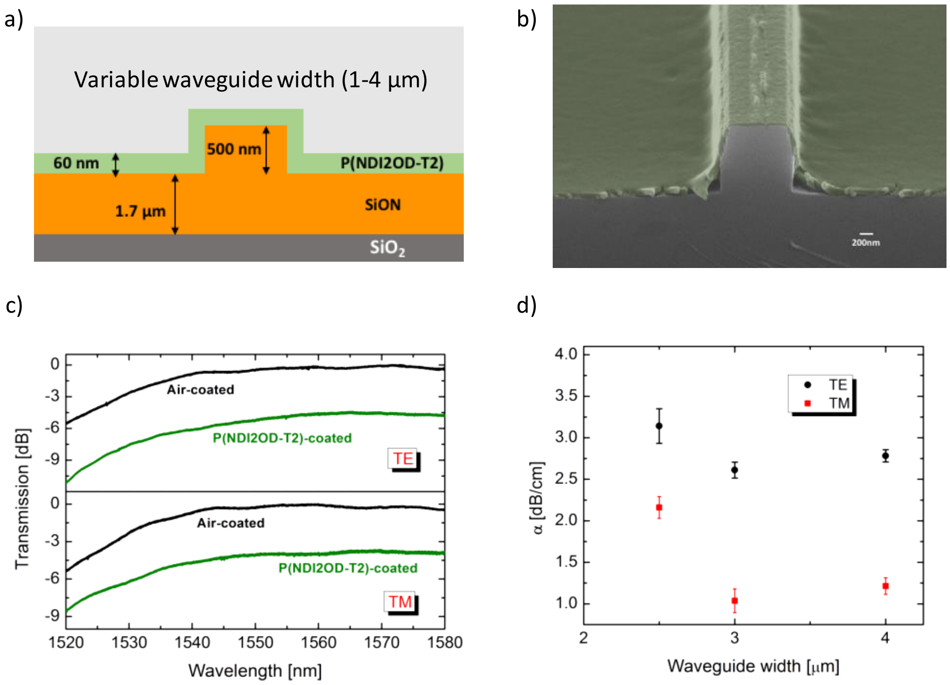

Fig. 2 - (a) Schematic of the SiON waveguide covered by a thin film of P(NDI2OD-T2). (b) SEM cross-sectional image of a SiON rib waveguide after the deposition of a 60-nm-thick P(NDI2OD-T2) coating. (c) Normalized transmission of 1 cm long SiON waveguide before (black curve) and after (green curve) the deposition of the polymer upper cladding. (d) Attenuation of the P(NDI2OD-T2) film integrated in the SiON waveguide versus the waveguide width for TE (black circles) and TM (red squares) polarization.

effectiveness of the solution process deposition method for optical waveguide applications.

Figure 2c shows the transmission of a 1-cm-long waveguide with a width of 2.5-μm for TE and TM input polarization, before (black line) and after (green line) the deposition of the P(NDI2OD-T2) coating. A wavelength-independent loss increase by about 2 dB and 3 dB was observed for TE and TM polarizations, respectively. Taking into account the confinement factor of the TE and TM guided modes in the P(NDI2OD-T2), amounting to about 0.4% and 0.6%, respectively, the extinction coefficient k of the material was found to be around $1.5 \cdot 10^{-3}$. This low k value was confirmed by transmission measurements performed in the 1550 nm wavelength range on SiON waveguides with a different width (Fig. 2d). Results suggests that across the typical length of organic transistors (in the order of 100-μm), optical loss would be almost negligible (<0.03 dB), thus demonstrating the possibility to integration printed electronics devices directly on top of optical waveguides.

IV. CONCLUSION

The optical properties of P(NDI2OD-T2) organic-semiconductor were measured by spectroscopic ellipsometry in the 400 nm - 1600 nm wavelength range. The refractive index n presents a minimum value of 1.5 at 600 nm and maximum value of 1.84 at 800 nm. In the NIR $n = 1.7$ and the extinction coefficient k is less than 10^{-2}. SiON waveguides covered with a P(NDI2OD-T2) thin film show losses in the order of 3 dB/cm, corresponding to an extinction coefficient $k = 1.5 \cdot 10^{-3}$. Results suggest the possibility to employ solution processable P(NDI2OD-T2) as an organic semiconductor to realize printed electronic devices, such as organic transistors, on a photonic chip.

V. ACKNOWLEDGEMENT

This work was supported by Fondazione Cariplo Project “Advanced Control Technologies for Integrated Optics (ACTIO)” – Rif. 2016-0881. This work was performed at Polifab, the micro- and nanofabrication facility of Politecnico di Milano.

VI. REFERENCES

[1] Zhang, C.; Zou, C.-L.; Zhao, Y.; Dong, C.-H.; Wei, C.; Wang, H.; Liu, Y.; Guo, G.-C.; Yao, J.; Zhao, Y. S., Organic printed photonics: From microring lasers to integrated circuits. Science Advances 1 (2015).

[2] Large Area and Flexible Electronics. Wiley-VCH, Verlag GmbH &Co. KGaA: Boschstr. 12, 69469 Weinheim, Germany, 2015.

[3] Luzio A.; Criante L.; D'Innocenzo V.; Caironi M., Control of charge transport in a semiconducting copolymer by solvent-induced long-range order. Scientific Reports 3, 3425 (2013).

[4] R. A. DeCrescent, et al., "Model-blind characterization of thin-film optical constants with momentum-resolved reflectometry," Opt. Express 24, 28842 (2016).