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Self-encapsulation of organic thin film transistors by means of ion implantation

P. Cosseddu[a,b,*], B. Fraboni[c], A. Scidà[c], Y.Q. Wang[d], M. Nastasi[e], A. Bonfiglio[a,b]

[a] CNR—Institute of Nanoscience, S3Centre, Via Campi 213A, 41100 Modena, Italy
[b] Dipartimento di Ingegneria Elettrica ed Elettronica, Università di Cagliari, Piazza d'Armi, 09123 Cagliari, Italy
[c] Dipartimento di Fisica e Astronomia, Università di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
[d] Materials Science and Technology Division, Los Alamos National Laboratory, MS-K771, Los Alamos, NM 87545, USA
[e] University of Nebraska-Lincoln, Nebraska Center for Energy Sciences Research, 2200 Vine Street, Lincoln, NE 68583-0857, USA

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ABSTRACT

Long-term stability of devices based on organic materials is still impeding the diffusion of these structures in real applications. In this paper we have investigated the effects of low energy, combined, ion implantation (N and Ne) in the evolution of the electrical performances of pentacene-based Organic Thin Film Transistors (OTFTs) over time by means of current–voltage and photocurrent spectroscopy analyses. We have demonstrated that the selected combination of ions allows reducing the degradation of charge carriers mobility, and also stabilization of the devices threshold voltage over a long time (over 2000 h).

1. Introduction

One of the main open issues in the field of organic electronics is that, generally, the performances of organic semiconductors are severely affected by the exposure to ambient atmosphere [1–6]. In fact, it is well known that oxygen and moisture can interact with the organic semiconductor leading to its local doping or to the oxidation of the organic molecules and thus to a strong degradation of the charge transport properties of the active layer [7–11]. In particular, in the field of Organic Thin Film Transistors (OTFTs), the interaction of the organic active layer with oxygen and moisture is generally correlated with a pronounced increase of the threshold voltage of the devices and by a marked decrease of the carrier mobility. It is well known that the stability of organic semiconductors exposed to ambient oxygen and moisture is related to the distance of the Lowest Unoccupied Molecular Orbital (LUMO) of the semiconductor from the vacuum level [12,13]. However, despite the continuous progress in the synthesis of new, high performing, organic semiconducting compounds, the stability of these molecules in ambient conditions is still a big issue.

A possible, alternative, approach consists in the employment of efficient encapsulating layers for protecting the active film from contamination and degradation. In this sense, several solutions have been proposed such as, the employment of hybrid multilayer barriers [14,15]. However, the majority of proposed approaches have been reported only on devices fabricated on rigid substrates, and would not be suitable for the fabrication of flexible electronics [16–23].

Recently, we have demonstrated on pentacene-based OTFTs, with a nominal pentacene thickness of 300 nm, that by locally changing the chemical/electrical properties of the organic semiconductor film by means of a selective ion implantation process, it is possible to dramatically reduce the mobility degradation and threshold voltage shift due to the exposure to ambient atmosphere [24]. The devices were implanted with two different kinds of ions, nitrogen or neon, and the implantation was made tuning the ion energy and fluence in order to create a local damage only in the upper 250 nm of the pentacene film, so that, under this damaged layer, a pristine semiconductor layer (approx. 50 nm thick) is still preserved and acts as the active channel of the device. We found that the interaction of these two species with pentacene leads to a clear stabilization over time of the most meaningful electrical parameters, such as threshold voltage and carrier mobility. We demonstrated, in both cases, that the implantation induces a local permanent modification of the chemical and physical properties of the pentacene film: in fact, loss of hydrogen and carbonification effects have been observed in the top portion of the implanted layers, by means of Elastic Recoil Detection (ERD) and Fourier Transform Infrared (FTIR) analyses. However,

* Corresponding author. Present addresses: Department of Electrical and Electronic Engineering, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy.
E-mail address: piero.cosseddu@diee.unica.it (P. Cosseddu).

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when neon ions are implanted, a clear stabilization of the carrier mobility over time was noticed, whereas, when nitrogen ions were implanted, a dramatic reduction of the threshold voltage shift was observed. Moreover, nitrogen ions react with the organic hydrocarbon matrix inducing not only lattice damage (as happens for neon) but also the formation of stable, positively charged, groups (not present in pristine pentacene nor in neon implanted films) which, inducing a permanent electrical field, leads to a pinning of the OTFT threshold voltage.

In the present work, we demonstrate that both effects, observed in the previous investigations, may be obtained at the same time, on the same device, in a controlled way, by performing a sequential ion implantation of these two different ions (Ne and N). To this aim, we have investigated the evolution over time of charge carrier mobility and threshold voltage in co-implanted pentacene-based OTFTs, realized with different implantation parameters. The potential of ion implantation as a novel method for effective self-encapsulation of organic devices has thus been assessed, offering a perspective for the elimination of additional barrier/coating layers.

All OTFTs have been fabricated on a heavily doped silicon substrate using a bottom gate, bottom contact configuration (Fig. 1a). The highly doped silicon substrate acts as the bottom gate electrode, on which a 500 nm thick silicon dioxide film was thermally grown. Gold source and drain electrodes have been fabricated using a standard photolithographic process, with a channel width of 5 mm and a channel length of 50 μm. Finally, a 300 nm thick pentacene film was deposited by thermal evaporation.

All the electrical characterizations were carried out at room temperature in air and in dark with an Agilent HP 4155 Semiconductor Parameter Analyzer. For all devices, both mobility and threshold voltage were determined from the transfer characteristics in the saturation regime. After implantation all the devices have been stored in dark in ambient atmosphere, with a temperature ranging around 22–25 °C and humidity around 60%.

Ion implantation was performed on a Varian CF-3000 ion implanter at Ion Beam Materials Laboratory in Los Alamos National Laboratory. The implantation was performed at room temperature with two different ion species (N and Ne) with various fluences. The beam flux was kept at a fixed value so that the flux effect is not a concern. Monte Carlo SRIM code was used to estimate ion beam parameters producing the required damage thickness and ion profile in the pentacene layer. The maximum ion energy was chosen so as not to completely damage the pentacene layer.

The thickness of the implanted samples has been measured by XRD analyses and with an Atomic Force Microscope and no significant modification has been observed after co-implantation.

Three different co-implantation combinations, labelled I, II and III (see Table 1) have been carried out on several batches of samples to induce a controlled and different ion penetration and damage-depth distribution within the pentacene layer (Fig. 1b–e). Considering the preliminary results obtained with single implantation [24], energy and fluence were varied in order to assess their role in the stabilization of the OTFT mobility and threshold voltage. In particular:

a) Combinations I and II are exactly the same, with opposite order of the implantation sequence. The goal is to understand if the order plays a role, i.e. if the co-implantation is simply a superposition of the effects of each single ion implantation. Energies and fluences were chosen so as to preserve the integrity of the active channel.

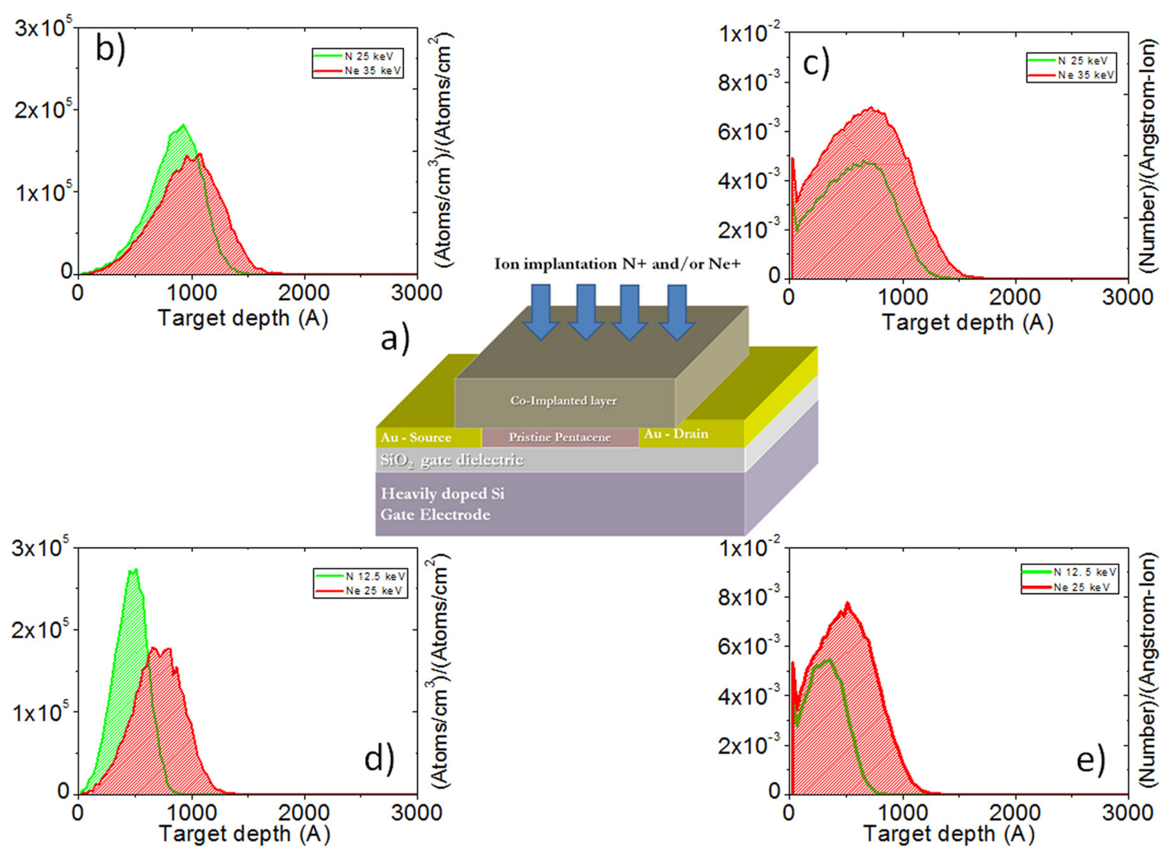

Fig. 1. Schematic representation of the Organic Thin Film Transistor and of the implantation procedure (a) and Monte Carlo SRIM of the ion profile and damage thickness in the pentacene film induced by the implantation of N and Ne ions using the configurations I or II (b and c), and III (d and e).