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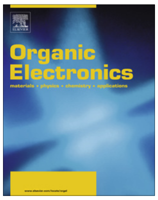

The effect of oxygen content on the performance of low-voltage organic phototransistor memory

Xiaohui Liu [a], Mingjun Zhang [a], Guifang Dong [a,*], Xinyue Zhang [b], Yapei Wang [b], Lian Duan [a], Liduo Wang [a], Yong Qiu [a,*]

[a] Key Lab of Organic Optoelectronics & Molecular Engineering, Department of Chemistry, Tsinghua University, Beijing 100084, PR China
[b] Department of Chemistry, Renmin University of China, Beijing 100872, PR China

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ABSTRACT

Optical writing and electrical erasing organic phototransistor memory (OPTM) is a promising photoelectric device for its novel integration of photosensitive and memory properties. The performance of OPTM can be influenced by the trap density of the gate dielectric layer. Here, we occupy tantalum pentoxide (Ta_2O_5), which is a prospective material in microelectronics field, as the gate dielectric. By increasing the oxygen content from 10% to 50% during the fabrication process of Ta_2O_5, it is found that the mobility and the photoresponsivity of OPTMs are significantly enhanced about 10 times and the retention time is greatly increased to 8.4×10^4 s as well. As far as we know, this is the first example that the modulation of oxygen content can improve the OPTM performance. Furthermore, the change of the oxygen content gives rise to the alteration of the threshold voltage and memory window, of which the absolute values of all the threshold voltage are below 5 V which is low enough to reduce the power consumption. It is found that the oxygen content can influence the surface roughness and surface energy of Ta_2O_5 films, which alter the nucleation and orientation of semiconductor layers, change the contact resistance and modulate the electron trap density in the Ta_2O_5 films.

1. Introduction

Organic phototransistors (OPTs) are special kinds of functional organic thin film transistors (OTFTs). On the basis of OTFTs, OPTs possess a fourth electrode, light, to tune the electrical signal [1–6]. In 2004, Narayan reported an optically induced memory which was the first report of the OPT-based memory (OPTM) [7]. This report attracts great attention and promotes the development of OPTMs during these years [8-14]. OPTMs are advantageous for their low cost, light weight, flexibility and large area applications. There are also some reports demonstrate that OPTMs are novel for its optical writing and electrical erasing processes [15,16].

Our previous researches indicate that the dielectric layer plays key role in the photosensitive and memory properties of OPTMs [15,17]. When poly(4-vinylphenol) (PVP) and poly(methyl methacrylate) (PMMA) are occupied as the gate dielectric materials, devices show little photosensitivity. However, when tantalum pentoxide (Ta_2O_5) substitutes PVP and PMMA as the gate dielectric, the photosensitive and memory properties are enhanced significantly. It is mainly attributed to the trap density at the interface between the organic semiconductor and gate dielectric or in the gate dielectric. To our knowledge, Ta_2O_5 is a high permittivity dielectric with a dielectric constant of 20–27, resulting in large trap density and leakage current

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[*] Corresponding authors. Tel.: +86 10 6278 2287; fax: +86 10 6279 5137.

E-mail addresses: donggf@mail.tsinghua.edu.cn (G. Dong), qiuy@mail.tsinghua.edu.cn (Y. Qiu).

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in Ta_2O_5. The electrons originating from the dissociation of the photogenerated excitons can be trapped by the interface or Ta_2O_5. Therefore, the photosensitive and memory properties could be observed. The Ta_2O_5 layer is usually fabricated by the way of DC magnetron reactive sputtering. The oxygen exposure in the sputtering process has shown positive influence to the film quality or characteristics. Herein, the intent of this work is to study the relationship between the performance of the Ta_2O_5-based OPTMs and the oxygen content during the sputtering process. As a result, we hope to fully understand the role of the oxygen in the OPTMs, thus building up a map to create high-performance OPTMs on demand.

As discussed more detail later, the oxygen content in the sputtering process was precisely controlled, ranging from 10%, 30%, to 50%. It was found that the performance of the OPTM devices was improved greatly with the increase of the oxygen content. The mobility, photoresponsivity and retention time reached a maximum value of 0.3 $cm^2 V^{-1} s^{-1}$, 0.14 $A W^{-1}$ and 8.4×10^4 s, respectively when 50% oxygen was involved during the sputtering process. Furthermore, the on/off current ratio remained at 10^4 regardless of the change of the O_2 ratio. The threshold voltage and memory window were both adjusted by the oxygen content as well. It was noteworthy that the absolute values of all the threshold voltage were below 5 V, which was low enough to reduce the power consumption in practical application. In terms of the mechanisms, the atomic force microscopy, contact angle measurement, contact resistance measurement, Kelvin probe force microscopy and vacuum-ultraviolet spectroscopy were performed to demonstrate that the oxygen content can alter the nucleation and orientation of pentacene and the contact resistance, and modulate the trap density in Ta_2O_5 films. It is beneficial for the understanding of the memory mechanisms and the application of the OPTMs in photosensors, electrical eyes and etc.

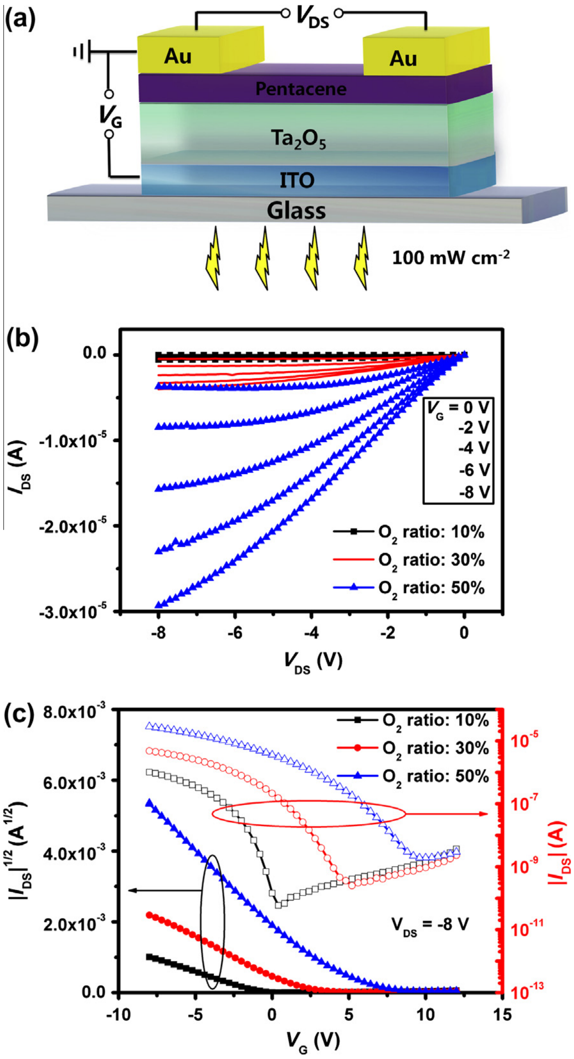

Fig. 1. (a) Schematics of OPTM device structure, (b) the output characteristics of OPTMs and (c) the transfer characteristics of OPTMs.

2. Experimental methods

2.1. Fabrication of OPTM devices

As shown in Fig. 1a, a typical bottom-gate top-contact device structure is adopted. The substrate used here was glass and above it 150 nm indium tin oxide (ITO) was well patterned using photolithography. The ITO served as the gate electrode. The substrate was carefully cleaned in ultrasonic bath and then treated by UV/Ozone for 10 min before use. Next, a 300 nm Ta_2O_5 gate dielectric film was sputtered on the substrate in an Ar/O_2 gas mixture with a total pressure of 0.1 Pa and the O_2 ratio was tuned to be 10%, 30% and 50%, respectively. On the basis of the same sputtering power, the sputtering rate was estimated to be 6.0 Å s^{-1}, 1.8 Å s^{-1} and 0.6 Å s^{-1}, respectively. The size of the target material Ta (General Research Institute for Nonferrous Metals, >99.9%) was Φ101.6 mm × 7 mm. All of the Ta_2O_5 films were not annealed. A pentacene (Sigma–Aldrich, >99%, used as received) film with a thickness of 45 nm was then thermally evaporated at room temperature at a deposition rate of 0.01–0.02 nm s^{-1} under a 1×10^{-4} Pa vacuum. Finally, a 45 nm thick gold layer was deposited through shadow masks to get desired pattern of the source and drain electrodes. The channel length (L) and width (W) were 50 μm and 940 μm, respectively.

2.2. Characterizations

The capacitance per area (C_i) of the gate dielectric was assessed by Agilent 4294A with device structure of ITO/Ta_2O_5/Au. The morphologies of Ta_2O_5 films and pentacene films deposited on the Ta_2O_5 films were discerned under ambient air with a multimode atomic force microscope (AFM, Veeco D3100 instrument) operated in tapping mode. Contact angles of Ta_2O_5 films were measured at room temperature under ambient conditions using an optical contact angle measuring device (OCA 20, Dataphysics Instruments GmbH) by a sessile drop measuring method, which is a static contact angle assessment. The OPTM

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