Electrochemical Sensor Based on Molybdenum Oxide Nanoparticles for Detection of Dopamine

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Abstract Water nanocolloids of molybdenum oxide were synthesized by using a laser writing of a solid molybdenum target by a focused picosecond pulsed laser beam. The molybdenum oxide nanoparticles are then used to fabricate modified screen-printed carbon paste electrode. Morphology and compositional-structural properties of the samples were investigated by Scanning Transmission Electron Microscopy and X-ray diffraction spectroscopy. The sensors tested show enhanced electro-catalytic behavior for dopamine detection (also in presence of KCl, NaCl, glucose, uric acid, ascorbic acid and folic acid), in phosphate buffered saline (pH = 7). Under the optimal conditions, the peak current of dopamine increases linearly with the concentration in the 10–500 μM range, with the lowest detection limit of 43 nM. All these data indicate an excellent selectivity of this type of sensor towards main interferents, made it as a potential candidate for the detection of dopamine in pharmaceutical and clinical preparations.

Keywords Molybdenum oxide nanoparticles · Pulsed laser ablation Electrochemical sensors · Dopamine

1 Introduction

Nanotechnology involves the creation and manipulation of materials at the nanoscale to obtain innovative products able to exhibit unique properties. In particular, new type of analytical tools for biotechnology and medical field involving the use of metal

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oxide nanomaterials, have received huge attention in recent times [1]. For these applications, the choice of green techniques is much appreciated to grant the production of contaminant free nanoparticles. Over the last decade, pulsed laser ablation in liquid (PLAL) is gradually becoming an irreplaceable technique to synthesize metal oxide nanostructures which represent a new type of analytical tools for biotechnology and life science [2]. This green technique ensures the control of physical-chemical properties of the synthesized nanostructures by changing ablation parameters and the absence of by-products, very useful issues in biological applications.

Dopamine (DA) is a neurotransmitter located in the ventral tegmental area of the midbrain, the substantia nigra pars compacta, and the arcuate nucleus of the hypothalamus of the human brain. Its detection is important in understanding neural behavior and in developing therapeutic intervention technologies for neurological disorders. Monitoring of extracellular DA concentration can serve as a clinically relevant biomarker for specific diseases states as well as a gateway to monitor treatment efficacy [3]. Among other analytical techniques used in biomedical diagnostics, electrochemical sensors show some advantages such as low cost, ease of operation and fast response with high accuracy and sensitivity. In Parkinson's disease for example, electrochemical sensors can be integrated with therapeutic interventions such as deep brain stimulation systems, to enhance the ability to continuously monitor DA and other neurotransmitters that are prone to fluctuations. Despite the advantages, there are some drawbacks limiting the widespread use of DA electrochemical sensors, such as the overlap of voltammetric responses due to several interfering substances present in biological systems and the formation of a passivating polymeric film on the electrode surface [4]. Recently, modified electrodes with assembled monolayers, polymer or metal oxides/graphene composites were developed to overcome the above limitations [5]. In this contest, the nanostructured molybdenum oxide particles could act as efficient electron redox mediators. Being characterized by three oxidation states and a high chemical stability, they can readily participate in redox reactions, contributing to the electrochemical sensing of some biological compounds such as DA. Their application in bio-sensing and specifically for DA sensing is still limited.

In this work, molybdenum oxide nanocolloids different in shape and size distribution as well as in surface chemical bonding coordinations were analyzed. Their electrochemical response was tested. Then, a systematic study was made on the sample with the best performance, ultimately proposing an electrochemical sensor based on a MoO_2 nanocomposite synthesized at room temperature (RT) in water using a picosecond pulsed laser source. The electrochemical sensor proposed enables the determination of DA level without any "engineered" electron transfer mediator, being the molybdenum oxide nanoparticles directly deposited on commercial carbon electrodes. The potentiality lies in the intrinsic properties of the molybdenum oxide nanostructures such as the high surface to volume ratio and the participation to surface oxidation processes.

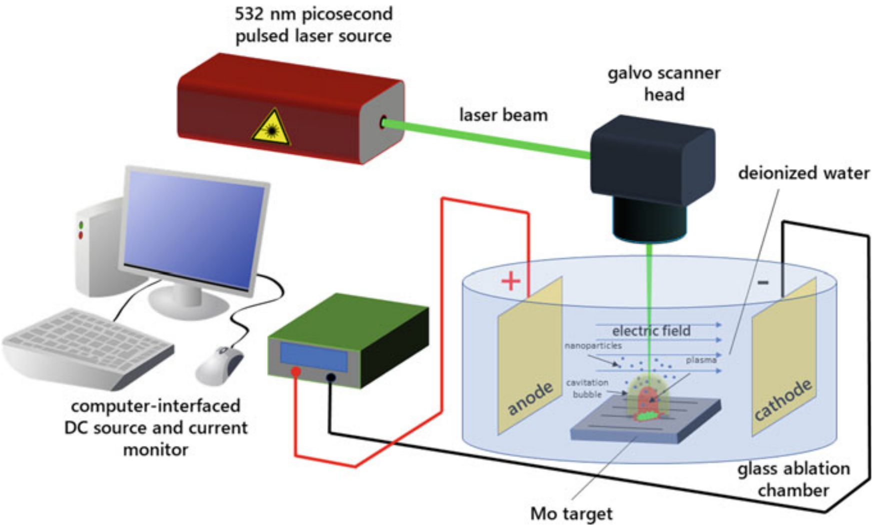

Fig. 1 Scheme of external field-assisted laser ablation setup

2 Materials and Methods

High purity (99.9%) Mo solid target in a 20 mL of deionized water were ablated using the 532 nm line of a laser source, operating at 100 kHz repetition rate with a pulse width of 6–8 ps. The target was irradiated with a typical laser power of 2.5 W and an irradiation time of 30 min. The laser beam was focused to a spot of about 75 µm in diameter on the surface of the target with a galvanometric scanner having a telecentric objective with a focal length of 163 mm. During the ablation process two Pt electrodes were immersed in the liquid in such a way to face their basal planes (see Fig. 1). The two electrodes were polarized by applying a DC potential (20 V/cm) and, between them, the plume was left to develop during the ablation. The experiments were performed at different water temperature (RT and 80 °C) and its values were monitored both before and after the ablation. During the overall process, only a moderate increase was found (less than 10 °C in 30 min), compatible with the thermal energy release due to the ablation phenomena.

Sample morphology was observed through a scanning transmission electron microscope (STEM) operating at 30 kV while chemical environment of the atomic species was analyzed by the X-ray diffraction (XRD) techniques. XRD measurements were performed using the CuK-α radiation (λ = 1.5406 Å) of a Bruker-AXS D5005 diffractometer. The surface Mo chemical bonding fractions was measured by means of X-ray photoelectron spectroscopy (XPS), using a Thermo Scientific spectrometer equipped with a conventional Al-Kα X-ray source (1486.6 eV) and a concentric hemispherical analyzer. The electrochemical sensors were fabricated depositing some drops (10 µL) of the nanocolloids onto commercial screen-printed

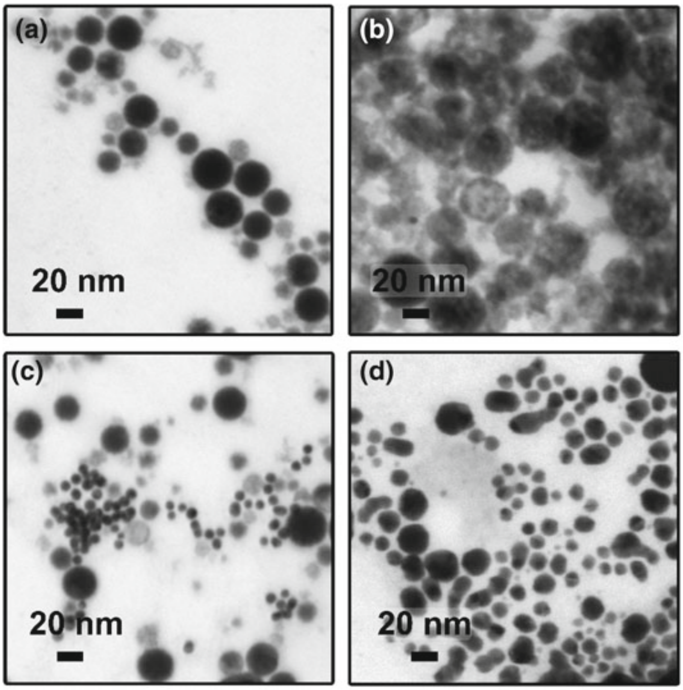

Fig. 2 STEM images of the samples prepared at RT (**a**, **b**) and 80 °C (**c**, **d**) without and applying the electric voltage, respectively

electrodes consisting of carbon working, carbon counter and silver pseudo-reference electrodes. The so prepared samples were dried at RT to obtain the MoO/SPCE (screen printed carbon paste electrodes). Cyclic voltammetry (CV), square wave voltammetry (SWV) and amperometric measurements were carried out in pH 7 Phosphate Buffered Solution (PBS) in presence and in absence of DA.

3 Results and Discussion

Figure 2 shows electron microscopy images of the colloids prepared in water at RT and T = 80 °C, without and by applying an external DC electric voltage.

We observe that some molybdenum oxide nanoparticles have a mean size of 20 nm when the ablation process was carried out at RT (Fig. 2a, b). However, overlapped spherical nanoparticles are obtained by applying the electric field (Fig. 2b). Nevertheless, smaller nanoparticles (size less than 10 nm) characterize colloids obtained at 80 °C with respect to the ones obtained at RT (Fig. 2c) while nearly oblong nanos-

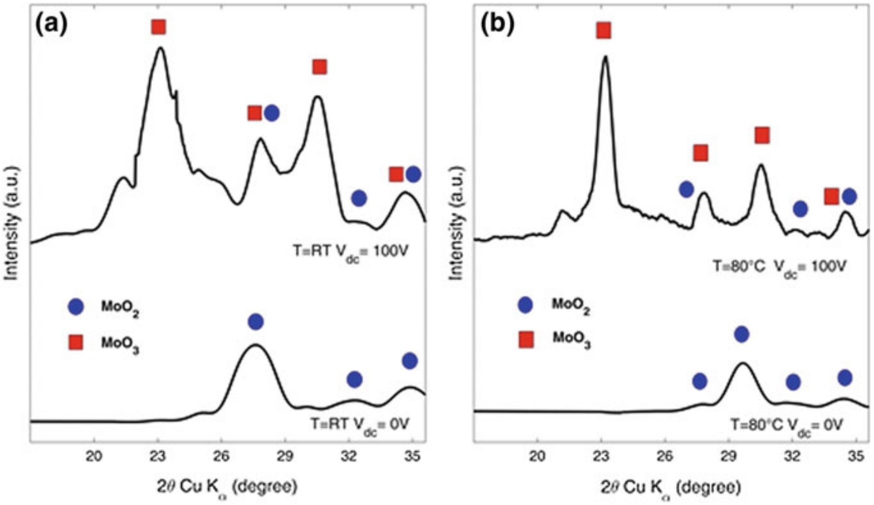

Fig. 3 XRD spectra of the samples prepared at RT (**a**) and 80 °C (**b**) without or applying the electric voltage. All spectra are shifted to highlight spectral differences

tructures mixed with spherical shaped ones are obtained at 80 °C and applying the DC electric field (Fig. 2d).

Figure 3 shows XRD spectra with the proper reflections assignments of the samples prepared at RT and 80 °C, by applying, or not, the electric voltage during the ablation process. XRD patterns show mixed phases which can be attributed to MoO_2 and MoO_3 coordinations. Moreover, the reflections (110), (040), (021), (111), (002) and (112) observed at about 23°, 28° and 30° match with the orthorhombic structure of MoO_3 (International Centre for Diffraction Data, JCPDS file no. 05-0508). In absence of the electric voltage, the samples show only the MoO_2 coordination. On the other hand, in presence of the electric field, the more crystalline MoO_3 phase dominates as indicated by the nearly lack of the reflections due to MoO_2 phase and the narrowing of the main characteristic contributions of MoO_3.

The surface chemical bonding nature of the samples was investigated by studying the modifications, induced by the synthesis parameters, on the Mo 3d X-ray photoemission peak lineshape. It is quite well established that the hot water and the electric voltage induce an increase of the MoO_3 bonding structure while, in RT & 0 V conditions, the sub-stoichiometric coordinations, mainly the MoO_2 configuration, were found (see Table 1).

Figure 4a shows CV responses of 50 μM DA in pH 7 PBS at the bare SPCE and molybdenum oxide modified SPCE. We outline that the modified electrode did not show any response in the absence of DA (not shown). In the CVs, both cathodic and anodic peaks of the modified electrode shifted negatively, relative to those of the screen-printed carbon electrode. The oxidation and reduction currents of DA on all the investigated electrodes were comparable. However, using the molybdenum

Table 1 Mo bonding fractions percentage estimated from XPS fitting procedure

Synthesis parameters	Mo (%)	MoO_2 (%)	MoO_{3-x} ($0 < x < 1$) (%)	MoO_3 (%)
RT & 0 V	0.4	68.7	22.7	8.2
80 °C & 0 V	0.3	60.2	25.5	14.0
RT & 100 V	0.0	58.4	26.2	15.4
80 °C & 100 V	0.0	57.9	28.9	13.2

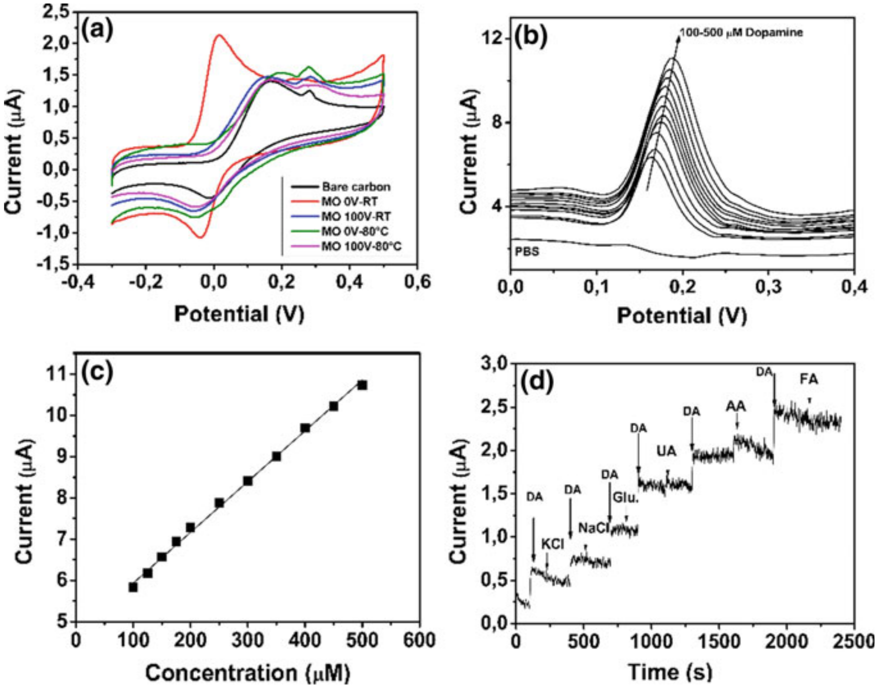

Fig. 4 **a** CV responses of 50 μM dopamine in pH 7 PBS at the bare SPCE and molybdenum oxide modified screen printed carbon paste electrodes; **b** SWVs for different concentration of dopamine; **c** Calibration curve in the range of concentration 100–500 μM of dopamine; **d** Selectivity test

oxide nanocolloids prepared at RT in absence of the electric field, the redox reaction shifted at more negative potentials and a well-defined redox peak corresponding to DA with improved peak current (2.2 μA) is achieved.

This sample shows the biggest nanoparticles mean size (see Fig. 2), i.e. a low surface to volume ratio, that cannot explain the observed CV behaviour. It is more likely that the electrochemical response and selectivity toward DA is affected by the different Mo-O bonding configurations (MoO_2 or MoO_3 phases) as observed by XRD and XPS analyses. It is well known [6] that the oxygen deficient, i.e. sub-stoichiometric MoO_{3-x} films, contain excess metal atoms which act as doping centers.

Generally, stoichiometric MoO_3 is an insulator with a band gap of about 3.1 eV. When the oxide is reduced, by the introduction of impurity donor atoms or by oxygen deficiency, electronic donor levels are created near the bottom of the conduction band and, therefore, the reduced oxides behave as semiconductors. These “doping centers” control the optical and the electrical field response of the nanomaterials by affecting the electronic mobility. As reported in a previous paper [7], our samples prepared at 80 °C have an optical bandgap of approximately 3.0 eV, while the RT prepared colloids exhibit smaller values due to the presence of the occupied gap states within their forbidden gap. Hence, from all the collected data, it seems that the nanoparticles made of MoO_2 configuration might favour the electrons transfer kinetic, then the electrocatalytic reaction of the DA on the electrode [8].

Owing to the best performance obtained for the sample prepared at RT in absence of electrical field, its electrochemical behavior toward detection of DA has been further investigated. Figure 4b shows the SWV recorded for the fabricated sensor in absence and in presence of different concentrations of dopamine ranging from 100 μM to 500 μM in PBS. When DA was present in solution an intense anodic peak was observed which shifted with increasing of concentration. In addition, in the whole investigated range the anodic peak current (i_a) increased linearly with the concentration of DA (c) according to the equation i_a (μA) = 0 0.012 c (μM) + 4.7, $R^2 = 0.996$ (Fig. 4c). The selectivity of the sensor against common interfering species was also investigated by amperometric experiments. Figure 4d shows the chronoamperometric curve recorded at an applied potential of 0.1 V during step increases of 50 μM of dopamine and in the presence of 10 fold excess of K^+, Na^+, glucose, uric acid (UA), ascorbic acid (AA) and folic acid (FA), demonstrating that the molybdenum oxide modified-electrode is also highly selective towards the determination of dopamine in the presence of potential interferents.

4 Summary

Molybdenum oxide NPs with tunable surface physical-chemical properties were synthesized by a picosecond pulsed laser source and then used to fabricate modified screen-printed carbon paste electrodes. A combination of XPS, XRD and STEM analyses has shown that the synthesis parameters influence the nanoparticles size distribution and the Mo-O bonding configurations which, in turn, affects the dopamine electrochemical response of the colloids. The best performance, also in terms of selectivity, was exhibited by the sample prepared at RT in absence of electric voltage. This sample shows nanoparticles with the biggest mean size, i.e. a low surface to volume ratio, made of MoO_2 configuration. On the overall, from the collected data, it emerges that nanoparticles with the MoO_2 surface bonding configuration favour the electrons transfer kinetic and, ultimately, the electrocatalytic reaction of the dopamine on the electrode.

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