In this work, a self-made dip-coater equipment was developed for the fabrication of thin films. The assembly of the apparatus was carried out using simple mechanical and electronic pieces, recycle parts, and spending an inexpensive budget suitably. The production, software design, and features of the device were focused on the sol-gel dip-coating method, which involves gravitational draining and drying processes, as well as continued condensation reactions. The dip-coater was based on the Arduino microcontroller and a step motor. The immersion speed in the solution, the waiting time, and the withdrawal process were typed by a digital control panel, where the optimal range found for speed was 0.1 – 6.0 mm s\(^{-1}\) without vibration interferences. The total fabrication cost of the fabricated dip coater was less than 100 USD and the assembly process was not complicated. Finally, the performance of the dip-coater was evaluated through the deposit of copper oxide and iron oxide films on fluorine-doped tin oxide glass substrates by layer by layer. The field emission scanning electron microscopy cross-section images confirm the formation of thin films with thickness in the nanoscale range, with good stability and sameness achieved through the control thickness during the dip-coating method under ambient conditions.

Keywords: laboratory equipment; computer-based learning; nanotechnology; materials science.
MATERIALS AND METHODS

Electrical and electronic components

The general construction of a dip-coater is presented in Figure 1. Specifically, in our work, the dip-coater was moved by using an electrical part composed of an inexpensive recycled stepper motor (Epson printer; model LQ-2090) controlled by the electronic part conformed by an Arduino microcontroller (SparkFun Electronics, Mega 2560) and an EasyDriver (Sparkfun, model SX09402). The software used was Arduino IDE 1.8.13. Besides, the other electrical parts used were a Liquid Crystal Display, LCD (Hitachi HD44780 20x4), a regulated Switching Power Supply (Joolonpor, S-60-12 DC 12V 5A), a PCB universal board, some electrical wires, switches, and buttons. Details concerning the materials cost as well as teaching recommendations are presented in the Supplementary Material.

In order to control the maximum height of the path available for the arrangement composed of the wooden support and the standard crocodile clips, a Micro limit switch SPDT (DaierTek, model KW3-0Z) connected to the Arduino was used. When the dip-coater is turned on, the crocodile clips disposition is positioned at the top of the lead screw allowed, labeled as the home position. After that, the user can enter the parameters desired. Figure 1 shows the frontal and inside view of the dip-coater switched on using the electrical and electronic parts described above. Except for the wires, the other parts of the figure were attached through glue on the solid pine wooden frame.

Arduino microcontroller has a role as a signal trigger, which is used for control of the speed and direction of rotation to step motor with a high degree of accuracy. The rotor of a stepper, seated on a series of magnets, is controlled by a series of coils that are charged positively and negatively in sequence, moving it forward or backward in discrete “steps”, one step at a time. The motor moves 1.8 degrees per step, this equals 200 steps for a 360 degrees rotation. On the other hand, the EasyDriver employed a current supply and handled the current regulation required to the step motor to avoid its damage. Based on the rotation of the motor and the input time of the step assigned, the dipping speed can be calculated as follows:

\[
\text{Speed (mm/s)} = 3 \times \frac{n \times 2\pi}{N_{\text{step}} \times t_{\text{step}} (s)}
\]

where speed is expressed in millimeters per second, \(n\) is the number of revolutions of step motor, \(N_{\text{step}}\) is the number of steps for revolution, \(t_{\text{step}}\) is the time between steps, and finally, the number 3 corresponds to the radius of the motor shaft in millimeters. The minimum speed measured for the stepper motor was 0.1 mm s\(^{-1}\), whereas, the maximum speed measured was 6.0 mm s\(^{-1}\) without any vibration of the parts, particularly of the threaded rod, which could disturb the deposition by immersion of the film and the subsequent withdrawal of the substrate from the solution.

Mechanical components

The mechanical part of the dip-coater involves the equipment body that encloses the rest of the device’s components. Each part of the dip-coater body in a real proportion model was drawn and the complete simulation assembly test was developed by using Solidworks 2018 program. Figures 2a and 2b show images of the dip-coater pieces designed employing Solidworks and the image of the dip-coater already fabricated, respectively. It could be mentioned that two substrates, each placed on the different crocodile clips, can be bathed using the dip-coater machine at the same time and with the same settled parameters.

Figure 1. Wiring of the Arduino-based dip coater. The control panel buttons in the frontal view of the dip-coater are shown as an inset

To set the parameters desired of the dip-coater built, an Arduino code was elaborated. The user could enter the values of dip speed, dip duration, dip length, dry duration, and the number of dips, which are displayed on the LCD. After that, the code receives the orders and computes them, adjusting the angle of rotation and waiting for the time until the stepper motor starts again. The Arduino code is available in the Supplementary Material.

TESTING THE DIP-COATER

Performance experiment

In order to determine the system performance, different thin films of copper oxide (CuO) and iron oxide (α-Fe\(_2\)O\(_3\)) were fabricated using precursor solutions prepared by the sol-gel method according to Pastrana et al.\(^{16}\) The films were deposited onto FTO glass conductive plates (Dyesol company, 7.0 cm\(^2\); 2.2 mm thickness) of 3.5 cm x 2 cm of area. The dip-coating parameters were optimized after running a series of experiments. The FTO substrates were dip length 7 cm into the different precursor solutions with a constant entrance speed of...
The film morphologies and cross-sections were investigated by Hitachi SU-8230 field emission scanning electron microscope (FE-SEM) equipped with an energy dispersive X-ray spectrometer (EDX). FE-SEM images of CuO and \( \alpha \)-Fe\(_2\)O\(_3\) thin films are shown in Figures 4a and 4c, respectively. As shown, the average size of quasi-spherical CuO crystals is 53 ± 8 nm (Figure 4a). In the case of \( \alpha \)-Fe\(_2\)O\(_3\), a worm-like morphology was obtained,\(^{11}\) with an estimated diameter of 63 ± 10 nm (Figure 4c), both morphologies were usually reported in previous research.\(^{17-19}\)

Figures 4b and 4d display cross-sectional FE-SEM images of CuO and \( \alpha \)-Fe\(_2\)O\(_3\) films, respectively. The thickness values obtained were approximately 802 nm and 376 nm for CuO and \( \alpha \)-Fe\(_2\)O\(_3\), respectively. Furthermore, the EDX analysis shown in Figures 4b and 4d confirms the presence of copper and iron metal, respectively, without diffusion of atoms. The results obtained confirm the formation of two-dimensional nanometric material willing as a thin film.

The morphologies of the films with spherical and worm-shaped obtained for CuO and \( \alpha \)-Fe\(_2\)O\(_3\) films, respectively, were in agreement with results obtained by dip-coating in previous works.\(^{20,21}\) Furthermore, coating attained for CuO and \( \alpha \)-Fe\(_2\)O\(_3\) using the dip-coater fabricated in our research could be compared with other physical accuracy techniques of fabrication.\(^{22-24}\)

HAZARDS

The circuits of the dip-coater use a low voltage (12 V, 0.5 A), thus no electrical shock risk exists. Notwithstanding, electrical safety measures have been taken as using electrical tape to insulate all wires and electrical pieces. Besides, because the wooden pine frame and other equipment components are burnable, they should be handled with care and kept away from heat, hot surfaces, sparks, open flames, and other ignition sources. The dip-coater should be seated on a firm, not sloped surface. We recommend fixing the beaker, that contains the precursor solution, to the device to avoid spills. Finally, it would be appropriate to wear personal protective equipment for handling it.

CONCLUSIONS

A low-cost dip-coater Arduino-based was fabricated from a step motor recycled of a printer and other no expensive components. The total fabrication cost of this equipment was less than 100 USD. The speed of the dip-coater was set in the range of 0.1 – 6.0 mm s\(^{-1}\) left out vibrations and controlled by the motor driver. The user can get started straight away once entering the parameters desires, either just one cycle coating or multiple coating cycles. Measurement results obtained in this research work are repeatable and consistent with the results achieved by previous works. The dip-coater was tested in the fabrication of CuO and \( \alpha \)-Fe\(_2\)O\(_3\) thin films, demonstrating a high quality of these films in terms of crystallinity and homogeneity, as well as in obtaining their thicknesses in the nanometric range. It could be mentioned that this equipment can be constructed by students, the operation is familiar and simple for untrained personnel. The goals achieved were the simple and economic fabrication of dip-coaters, likewise an improvement in the construction behavior of simple devices based on computer programming.

SUPPLEMENTARY MATERIAL

Materials list, wiring circuit, assembling of electrical and mechanical parts, and Arduino code are described at the supplementary material and free of charge at http://quimicanova.sbq.org.br.

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REFERENCES


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