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Fabrication of Impedimetric Transducers Using a Compact and Low-Cost Prototype for Photolithography

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Abstract. Impedimetric gold transducers were fabricated on glass substrates using a simple photolithography method without requiring a photolithography machine. An acetate sheet containing printed electrode designs and edge markings for alignment during pattern transfer was used as photomask. A compact pattern phototransfer system named Expotransfer, was designed for this process. Gold deposition was performed by electron beam evaporation. The electrodes obtained have a diameter of 2 mm with a minimum line thickness of of 250 µm and the separation between patterns of equal magnitude. Electrochemical impedance spectroscopy (EIS) tests showed a predominantly capacitive behavior in the frequency range of 100 kHz to 1 kHz, which follows a parallel plate model. Repeatability between the manufactured electrodes was also achieved.

Keywords. Gold transducers, photolithography without photolithography machine, electrochemical impedance spectroscopy.

1 Introduction

In recent years, the need to address specific challenges in health research and development has driven innovation in the detection of biomolecules for clinical diagnosis and monitoring, leading to the development of impedimetric transducers with defined patterns and sizes [1,2].

These customized electrodes allow for the adjustment of characteristics such as material, shape, size and active surface area, which improves the interaction with the molecules of interest and maximizes the selectivity and responsiveness of the sensor.

However, the applicability of sensors and biosensors depends not only on their performance in terms of application, but also on the ability to manufacture them on a large scale within acceptable time and cost constraints, which is a critical aspect in the development of these devices [3]. In recent years, photolithography has become the standard fabrication technique for such devices due to its precision, high resolution, and feasibility for mass production [4, 5, 6]. However, the equipment and infrastructure required for photolithography demand significant investment, specialized personnel for operation, and regular technical maintenance.

To address these challenges, we developed a low-cost, compact photolithographic prototype to fabricate gold transducers, which can be subsequently integrated with biological recognition systems such as molecularly imprinted polymers.

2 Materials and Methods

2.1 Reagents and Materials

The white 3D printing resin, DLP Craftsman, was purchased from ANYCUBIC®. Hydrogen peroxide was purchased from WÖHLER® and sulfuric acid 95-97% from J.T.Baker® (Germany). Analytical grade acetone was purchased from MACRON Fine Chemicals (USA). Negative photoresist AZ®nLOF

2020 and developer AZ®300 MIF were purchased from EMD Performance Materials Corp (USA). Phosphate buffer saline (PBS) at pH 7.4 was purchased from Sigma-Aldrich (United Kingdom).

The 2.5 x 7.5 cm glass slides, model 2947, were purchased from CORNING®. Rectangular N35 neodymium magnets measuring 20 x 10 x 2 mm were used and purchased from Magnetika SAIFFE. All solutions were prepared using ultrapure water with a resistivity of 18.2 MΩ•cm obtained from the Merck Millipore® brand Simplicity® purification system.

2.2 Instrumentation

A Branson 3800-CPXH5 ultrasonic cleaning equipment and an IKA®C-MAG HS4 heating grill were used. A UV Led lamp with a wavelength of 365 nm commonly commercialized for nail gel curing was purchased. The ANYCUBIC Mono 2 printer was used for 3D printing and a Specialty

Coating Systems SCS 6800 series centrifugal coating system was used for photoresist deposition. Evaporation of metals was carried out with Intercovamex® D18 deposit system. EIS measurements were performed with a *B*io-Logic® potentiostat model VSP-300 and EC-Lab software version 10.19. Profilometry measurements were performed with a Veeco Dektak' 6M profilometer.

2.3 Fabrication Process of the Planar Electrodes

The general manufacturing process is shown in the schematic in Fig. 1.

First, the glass substrates were cleaned using piranha solution (3:1 hydrogen peroxide and sulfuric acid), rinsed with ultrapure water, and dried with nitrogen. Negative photoresist was applied to the glass using the spin coating technique at 2500 rpm to obtain a uniform film of approximately 2.3 µm, as described in the datasheet [7], and then soft baked at 110 °C for 1 min on a hot plate. Subsequently, the coated substrate was placed on the Expotransfer base, the photomask was aligned on it and the cover was added, securing it with magnets.

Then, the system was irradiated with a UV LED lamp for 45 seconds, followed by a post-exposure

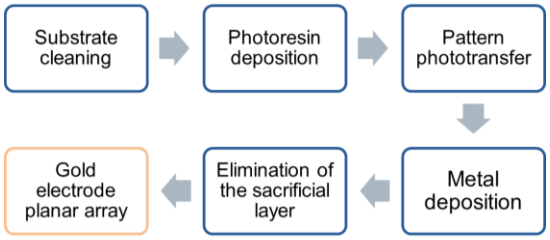

Fig. 1. General scheme of the fabrication process of the planar electrodes

bake at 110 °C for 60 seconds. The substrate was then immersed in developer (AZ®300) for 10 seconds, immediately washed with ultrapure water and dried with nitrogen.

Gold deposition was performed by electron beam evaporation using the Intercovamex® D18 system. In this step, a 20 nm titanium layer was first deposited to promote adhesion with the substrate, followed by a 200 nm gold layer.

Subsequently, excess metal and photoresist residues were removed using an ultrasonic bath in acetone for 15 minutes. Finally, the planar arrays of gold electrodes obtained were washed with ultrapure water and dried with nitrogen.

2.4 Profilometry Measurements

The thickness of the photoresist deposited by spin coating on the glass substrate was evaluated using a profilometer and compared with the values provided in the product datasheet [7]. Once the electrodes were fabricated, they were also subjected to profilometry tests and compared with the values given by the metal deposition system.

2.5 Electrochemical Impedance Spectroscopy Measurements

Electrochemical impedance spectroscopy (EIS) measurements were performed on three randomly selected gold electrodes. A sinusoidal signal with an amplitude of 20 mV was applied over a frequency range from 100 kHz to 1 Khz.

Measurements were conducted in air, ultrapure water and phosphate-buffered saline (PBS) in that order. For the ultrapure water and PBS measurements with, a 2.5 µL drop of solution was

applied to the electrodes, and the measurements were started 30 seconds after application. After each measurement, the drop was removed, and the electrodes were washed twice with ultrapure water.

All measurements were carried out in triplicate. The results are presented as Bode diagrams in section 4.3.

3 Expotransfer and Photomask Design

3.1 Design and Fabrication of the Expotransfer Prototype

The Expotransfer was designed to perform the phototransfer of patterns, offering an alternative to more sophisticated equipment when resolution less than 100 um is not required. The prototype consists of four main components: base, cover, UV LED lamp and photomask.

- A commercial UV LED lamp with a wavelength of 365 nm and a power of 27 W was used.
- The base and cover were designed in AutoCAD 2025 (student version) and include spaces for magnets to provide a firm hold and easy disassembly, as well as areas for inserting tweezers to facilitate substrate manipulation.
- The design also incorporates grooves along the edges of the base to allow for an optional lid. The final design was 3D printed using an ANYCUBIC Mono 2 printer and AnyCubic Photon Workshop software version 3.1.4., with white Craftsman DLP resin.

3.2 Photomask Design

The geometry and arrangement of the electrodes were designed using the CleWin4 tool, version 4.3.7.0. The design includes two planar electrodes, a circular working electrode and a counter electrode that surrounds it almost entirely. Additionally, connection pads are linked to the electrodes by connection lines.

The size of the electrodes was defined based on two factors: the capabilities of the printing

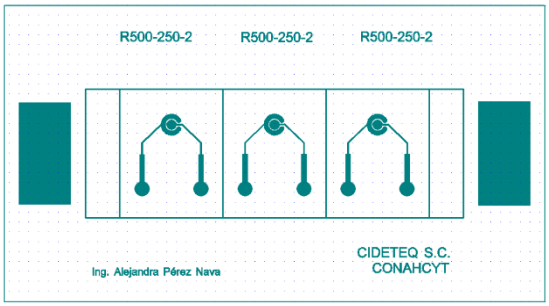

Fig. 2. Photomask adapted to the size and design on the Expotransfer

equipment and the performance of the pattern phototransfer technique using the Expotransfer.

Multiple tests were carried out, varying the size and separation of the parts that make up the design. Once the design was finalized, the electrodes were arranged so that the mask could accommodate the largest number of electrodesbased on the substrate size (7.5 x 2.5 glass slides), as shown in Figure 2.

4 Results and Discussion

4.1 Design and Fabrication of the Expotransfer Prototype

The Expotransfer functioned as a substrate positioning and fixation system during pattern phototransfer. The prototype (Figure 3) has a compact design (8.0 x 13.0 x 2.0 cm) and enabled the definition of patterns with a minimum line thickness of 250 µm and an equal separation, using 45 seconds of exposure and 10 seconds of development. Under these conditions, the electrode patterns retained their geometric properties, as shown in the micrographs in Figure 4. The critical area of the design is highlighted in Figure 4a where the patterns were properly transferred. Moreover, reveals shorter than 10 seconds did not completely remove photoresist in specific areas, while longer times caused resin loss in critical areas.

The fabricated electrodes obtained, shown in the Figure 4b, have a diameter of 2 mm, with connecting lines that maintain in minimum thickness of 250 µm.

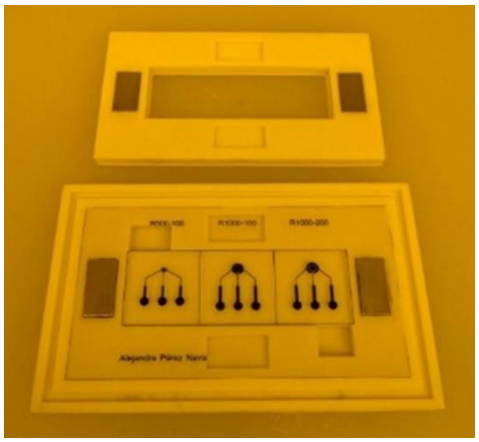

Fig. 3. Expotransfer prototype

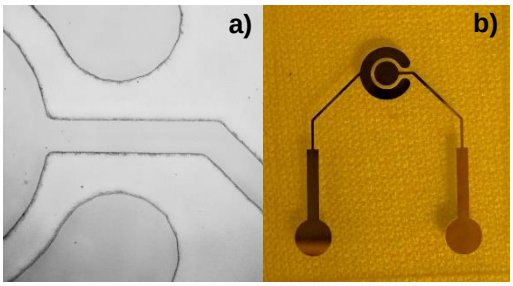

Fig. 4. Micrographs of patterns obtained. a) critical region after development. b) gold electrodes

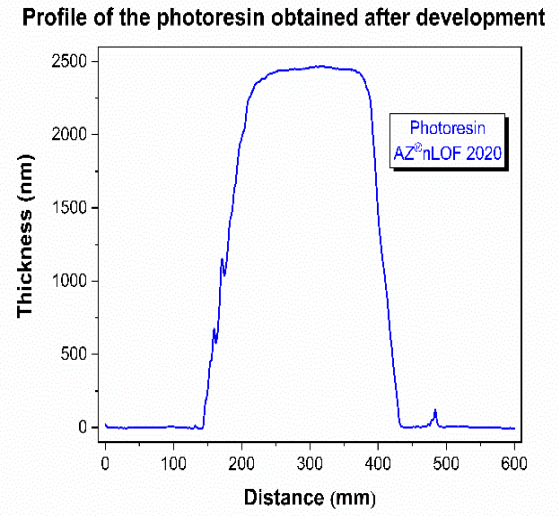

Fig. 5. Profile of the photoresin obtained after development

4.2 Profilometry

The graph of the Figure 5 shows that the deposited photoresist was slightly under 2500 nm thick, consistent with the datasheet values for the selected parameters. The thickness of the metallic layer, as reported by the Intercovamex D18 system, was 221 nm, matching the profilometry measurements for the gold electrodes, as shown in Figure 6.

4.3 Electrochemical Impedance Spectroscopy

The Bode diagrams (Figure 7) for the different samples show a strictly capacitive behavior in the frequency range from 100 kHz to 1 kHz, indicating that the fabricated electrodes function as capacitors, with the samples placed on them acting as the dielectric material connecting the electrodes. and the samples placed on them act as the dielectric material connecting both electrodes.

The diagrams reveal a slight difference in the impedance magnitudes for air compared to the other two samples, which have very similar values do to their comparable relative permittivities. As capacitance is directly related to permittivity (Eq.1) and permittivity is inversely proportional to impedance (Eq.2), higher permittivity results in lower impedance. This agrees with the experimental results, where air (the lowest permittivity) exhibited the highest impedance:

$$C = E_0 E_r \left(\frac{A}{d}\right), \quad (1)$$

$$Z = \frac{1}{2\pi f C}. \quad (2)$$

5 Conclusion

The compact prototype developed in this study enabled the accurate positioning and fixation of substrates during the phototransfer process, eliminating the need for a photolithography machine for fabricating lines of 250 µm or larger. Electrochemical impedance spectroscopy tests demonstrated similar behaviour between PBS and ultrapure water, likely due to the similarity in their relative permittivities. Additionally, a predominantly capacitive behaviour was observed in the

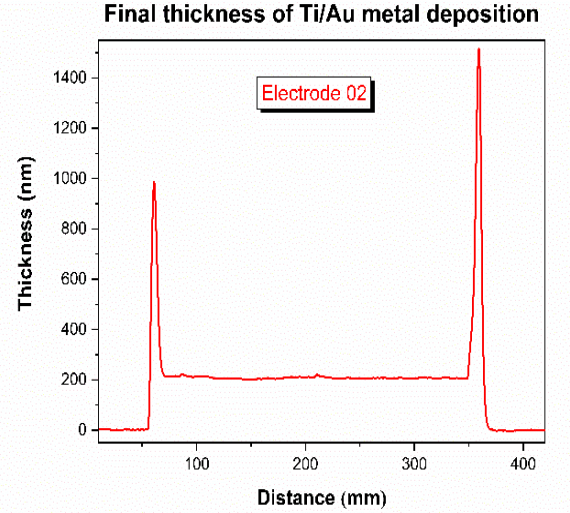

Fig. 6. Thickness of Ti/Au metal deposition

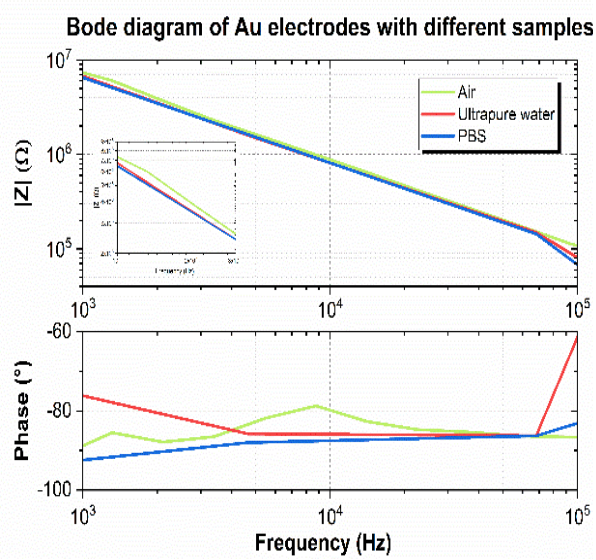

Fig. 7. Bode diagram of Au electrodes with different samples

frequency range of 100 kHz to 1 kHz, supporting a model of parallel plates separated by a dielectric.

This study establishes a viable, effective, and low-cost prototype for fabricating gold electrodes, providing a strong foundation for various sensor and biosensor applications using impedimetric transducers.

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