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Polysilicon interdigitated electrodes as impedimetric sensors

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Abstract

The suitability of polysilicon as a material for the fabrication of interdigitated electrodes and their application to the development of sensors is studied in this work. The main interest in using this material lies in the possibility of obtaining integrated sensors with commercial CMOS technologies and simple post-processing steps. Electrodes with 3 μm finger width and 3, 10, and 20 μm spacing were fabricated and characterised. Conductivity measurements in the range from 4 to 50 μS/cm yielded a linear response with cell constants of 0.0416 cm^{-1}, 0.155 cm^{-1} and 0.33 cm^{-1}, respectively. Permittivity measurements in the range from $\varepsilon_r = 80.1$ to $\varepsilon_r = 1.89$ yielded a linear response and similar cell constants. The possibility to functionalise both the electrode fingers and the space in between them using a single silanisation process is an interesting advantage of polysilicon electrodes. An urease-based biosensor was obtained with this procedure and characterisation results are reported.

Keywords: Interdigitated electrodes; Polysilicon; Impedimetric sensor; Conductometric sensor; Biosensor

1. Introduction

Planar microelectrodes for impedimetric measurements offer many possibilities for the construction of physical, chemical and "bio-" sensors. Their robust and simple structure, their long term stability and reliability, and easy fabrication have attracted much attention from the sensor research community. Applications that have been proposed for these microelectrodes include measurement of the concentration of calcium [1], potassium [2], *p*(CO2) [3], pH [4], ethanol/methanol in gasoline [5], heavy metals [6], nitrate [7], urea [8,9], glucose [10], total prostate-specific antigen (PSA) [11], bacteria [12], red blood cells (hematocrit) [13], and detection of specific sequences of DNA [14]. In some applications, the measurement of a physical magnitude such as dielectric constant or conductivity of the media provides direct information of the analyte concentration [5,13]. In other applications, the deposition of a membrane or functional monolayer on top of the electrodes as a recognition element is necessary to obtain sensitivity and selectivity to particular species [1–4,6–14].

Different arrangements of electrodes (i.e. different number of electrodes and geometries) may be used for impedimetric measurements. Among them, interdigitated electrodes have significant advantages for certain applications: (1) their low cell constant (resistance to resistivity ratio) permit the measurement of very low conductivity solutions, (2) measurement of dielectric properties is possible thanks to a high inter-electrode capacitance (higher than stray capacitance even for conductive substrates), (3) the short penetration depth of electric fields make them less dependent on the measurement cell geometry and allow the use of thin membranes for tailoring selectivity.

In this paper, the suitability of polysilicon as a material for the fabrication of interdigitated electrodes and their application to the development of sensors is studied. Particularly, the feasibility of measuring solution conductivity and permittivity with polysilicon electrodes is demonstrated. The main interest in using this material lies in the possibility of fabricating the electrodes with commercial CMOS technologies and simple post-processing steps, and therefore being able to integrate them as sensors in a

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more complex system-on-chip. Another interesting advantage is that this material can be easily modified following a one-step silanisation reaction. In this way, robust immobilisation of either biomolecules or membranes can be carried out on to both the electrode fingers and the area in between them with the aim of developing a sensor device. As an example, a fully functionalised biosensor for the detection of urea is also presented.

The basic structure of the interdigitated electrodes is depicted in Fig. 1. The polysilicon traces forming the interdigitated geometry are separated from the silicon substrate by a thick silicon dioxide layer. Fig. 2 shows the equivalent circuit of the interdigitated electrodes in aqueous solution. The elements that are repeated for each electrode have been grouped in a single equivalent component. This equivalent circuit is similar to the one previously proposed in [15]. The resistance and capacitance of the solution are represented by R_{sol} and C_{sol}. From these components, the resistivity ρ (or the conductivity σ) and the permittivity ε of the solution can be estimated, respectively. The ratio between measured components and actual physical parameters of the solution, the so-called cell constant, is defined as:

$$k \equiv R_{sol}/\rho = \varepsilon/C_{sol} \tag{1}$$

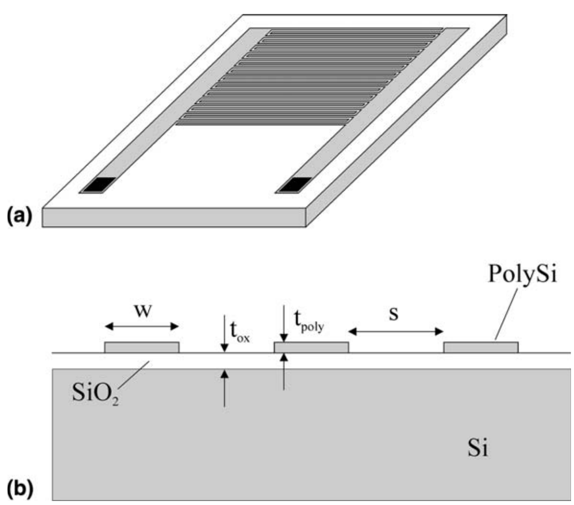

Fig. 1. Schematic representation of the interdigitated electrodes layout (a) and their cross-section (b). Geometrical parameters are indicated.

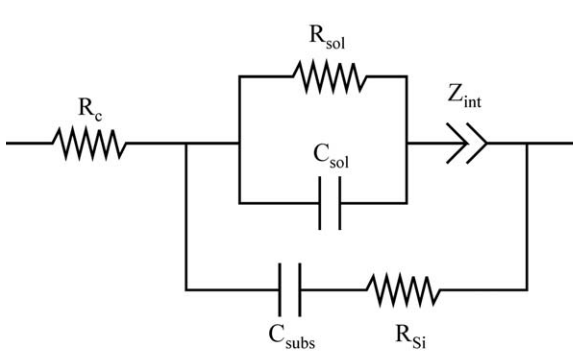

Fig. 2. Equivalent circuit of the interdigitated electrodes immersed in a solution.

The cell constant value is set by the electrode geometrical parameters. There are approximate analytical expressions to calculate the theoretical cell constant corresponding to a particular electrode geometry (defined by w and s parameters in Fig. 1b) [16]. However, for the present technology, where the thickness of the polysilicon fingers (t_{poly}) is not negligible compared to their width and spacing, the cell constant is more precisely calculated by finite element analysis (FEA) simulations. In the present work, the low frequency electromagnetic field simulation software Maxwell2D (Ansoft Inc.) has been used for this aim.

The resistance of the polysilicon traces is represented by R_c in the equivalent circuit. Polysilicon is more resistive, even if doped to degeneration, than noble metals typically used for the fabrication of interdigitated electrodes. However, thicker polysilicon layers can be deposited and patterned with standard processes, which partially compensates for the higher resistivity. The capacitance of the electrodes to the substrate is represented by C_{subs}, and its value depends on the thickness of the silicon dioxide layer isolating the electrodes from the silicon substrate. R_c and C_{subs} limit the minimum resistivity and permittivity that can be measured and should be minimised in the design. The resistance in series with C_{subs}, R_{Si}, represents the resistance of the silicon substrate.

The impedance of the interface between the polysilicon and the solution is represented in the equivalent circuit by Z_{int}. For a typical metal electrode in the presence of an electroactive compound, the interface impedance is represented by a Randless circuit. This circuit is composed of the double layer capacitance in parallel with the impedance of the charge transfer processes, the so-called faradic impedance. In the case of polysilicon electrodes, the impedance of the native oxide layer has to be added in series. This layer spontaneously grows on top of the polysilicon structures in contact with air. The presence of the native silicon oxide passivates the electrode surface, thereby obstructing the charge transfer processes between the polysilicon and electroactive compounds present in the interface. As a consequence, these electrodes seem to be unsuitable for electrochemical impedance measurements and the possibility to use them for that purpose has not been further studied. In the equivalent circuit presented here the whole interface impedance has been modeled by a constant phase element:

$$Z_{int} = \frac{1}{C_{CPE}(j\omega)^{\alpha_{CPE}}} \tag{2}$$

With the aim of studying the appropriateness of the proposed equivalent circuit, three different interdigitated electrode designs have been tested in this work. Every design has the same sensor area but different spacing between fingers, and therefore different number of fingers. The finger width and length is 3 μm and 1600 μm, respectively. The spacing between fingers is 3, 10 and 20 μm, with a total of 218, 101 and 57 fingers for each layout. The solution resistance, R_{sol}, should increase with decreasing number of fingers, and therefore the cell constant should also increase.