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MODELING THE PARAMETERS OF LIGHT-ADDRESSABLE POTENTIOMETRIC SENSORS

Based on Lab-on-chip principle, different sensorial membranes consisting of Light-addressable potentiometric structure output photocurrent is modeled in MatLab medium.

Keywords: Lab-on-chip, light-addressable potentiometric sensor, ferroelectric.

Due to the tremendous increase in the demand for analytical and biomedical information, as well as because the quality control has become a worldwide topic, the number of analytes that have to be detected and the number of analyses conducted is increasing dramatically (worldwide more than 10^9 analyses are now performed every day-with a double-digit growth rate [1]). This means that new tools are necessary for high throughput analysis and cost reduction. The microarrays and lab-on-a-chip systems are going to fulfill these new requirements, including the miniaturization of biological assays as well as the parallelization of analysis.

In recent years, the biological and biomedical applications of micro- and nanotechnology (commonly referred to as Biomedical or Biological Micro-Electro-Mechanical Systems [BioMEMS]) have become increasingly prevalent and have found widespread use in a wide variety of applications such as diagnostics, therapeutics, and tissue engineering. The devices and integrated systems using BioMEMS are also known as lab-on-a-chip (LOC) and micro-total analysis systems (μ-TAS or ATAS). In general, lab-on-a-chip can be defined as ‘‘devices or systems constructed using techniques inspired from micro/nano-scale fabrication, that are used for processing, delivery, manipulation, analysis, or construction of biological and chemical entities’’[2]. A LOC system can perform critical functions of sample preparation, mixing, reaction, transport, collection, and separation of samples and reagents on a single substrate in an automated fashion. The advantages of the LOC system include smaller amounts of samples and reagents required, fast analysis, and high sensitivity. The advantages of LOC devices are: 1) their small size; 2) lower cost; 3) small consumption of biological analytes; 4) increased portability; and 5) ability to be integrated with other types of micro-analysis systems. LOC systems, especially disposable ones, are often controlled by off- chip control units, embedded in a dedicated instrument. These control units receive the information sent both by on-chip and off-chip sensors to determine the direction of the flow, activate biological procedures and stop the experiment in case of an exception. A variety of sensors is used such as thermal, pneumatic, mechanical, electrical and optical.

One of the simple representatives of the LOC is the LAPS (light-addressable potentiometric sensor) [3- 5]. The LAPS is a semiconductor-based potential sensitive device that usually consists of the metal-insulator-semiconductor (MIS, for example, $Si/SiO_2/Si_3N_4(Al_2O_3Ta_2O_5)$ or electrolyte-insulator-semiconductor (EIS) structure. As for constructing a cell-based biosensor, electrolyte is needed for cells to live, thus the LAPS with the EIS structure is always adopted. The LAPS with the MIS structure is schematically shown in Fig.1. The easier fabrication process of the LAPS is fully compatible with the standard microelectronics facilities. The encapsulation of LAPS is much less critical since no metal contact is formed on the surface. In the common case, the LAPS system may consist of different membranes, such as: pH; humidity, hydrogen peroxide vapor, oxygen, CO_2, heavy metal ions (Fe^{3+}, Hg^{2+}, Pb^{2+}, Cd^{2+}, Cu^{2+} and Zn^{2+}), as well as sensitive membranes of different cell physiology parameters (including human blood, glucose and lactate enzyme, chemical-biological and DNA, antibodies recognition element, extracellular acidification rate, various metabolites in extracellular microenvironment and action potential etc, Fig.1). Moreover, with different sensing materials, this device can be used to detect several components of the sample parallelly. These "distinguish" functions provide the LAPS with some promising applications in biomedical fields, such as cell biology, pharmacology, toxicology makes the LAPS array system a good platform for clinical diagnostics and point-of-care testing as well as in drug analysis. Based on multifunctional properties of perovskite oxides, particularly $Ba_xSr_{1-x}TiO_3$ [6-8], in this work we suggest to use $Ba_xSr_{1-x}TiO_3$ nanofilms as sensitive membranes for different analytes.

The principle of the operation of the LAPS is the following. An external DC bias voltage is applied to scan the MIS structure to form a depletion layer at the interface of the insulator (SiO_2) and the semiconductor (Si), sequentially. When a modulated light pointer illuminates the bulk silicon, the light induced charge carriers are separated by the internal electric field and thus photocurrent can be detected by the peripheral circuit. The amplitude of the photocurrent depends on the local surface potential. By detecting the photocurrent of the LAPS, the localized surface potential can be obtained.

The amplitude of this light-induced photocurrent is sensitive to the surface potential and thus the LAPS is able to detect the potential variation caused by an electrochemical event. Therefore, in principle, any event that results in the change of surface potential can be detected by the LAPS, including the change of ion concentration, pH, redox effect, etc. In fact, the LAPS is an integrated sensor itself, whose integration level is defined by the spatial resolution and the illuminating system. Thus, a miniaturization with a high integration level can be achieved. The light pointer used for the LAPS detection can be focused by a microscope and an optical lens, which suggests the LAPS is possible for cell analysis on any non-predetermined testing site. A focused laser (usually 10 μm in diameter) is usually used to illuminate the front side of the chip to address the membrane to be monitored. Excitable cells can generate any potential. This potential is coupled to the bias voltage applied to the membrane, which correspondingly changes the amplitude of the photocurrent. Thus, by monitoring the photocurrent at a constant bias voltage, different signals from membranes can be detected. Illuminating different sensing areas with modulated lights of different frequencies generates a photocurrent signal, from which the corresponding information of each testing site can be obtained by FFT (Fast Fourier Transform) methods.

The aim of this work is to design four different $Ba_xSr_{1-x}TiO_3$ membranes based on the LAPS structure, and to model its output photocurrent dependences on semiconductor substrate, surface potential change and light illumination parameters.

It is assumed that the photocurrent of each membrane depends of its surface potential changes and each membrane is illuminated by moduling on intensity optical signals with different modulation frequencies.

Based on semiconductor device physics theory [9,10], the analytical expression for the photocurrent of membranes is obtained:

$$|i_m| = \frac{2\pi \cdot 10^{-3} f \cdot \tau \cdot \delta\psi_{SLO}}{\sqrt{1+\theta^2}} \left\{ |C_{SCL}| + \frac{1.3 \cdot 10^{-8}\sqrt{1+\theta^2}}{\sqrt{2\delta\psi_{SLO}}} \right\} \frac{\theta_{OX}}{\sqrt{1+(\theta_{OX}+\theta_{SCL})^2}}$$

where $\theta_{OX} = \dfrac{211 \cdot 10^2 f \cdot Rs}{t_{OX}}$,

$$\theta_{SCL} = 6.28 \cdot 10^9 f \cdot R_{SC}|C_{SCL}|,$$

$$\theta = 6.28 \cdot 10^{-3} f \cdot \tau,$$

$$\delta\psi_{SL} = 0.018 \cdot 10^{-6}\sqrt{\frac{\psi_{SO}}{Na}}\Phi_0 \tau \left[1 - e^{-1.14\alpha\sqrt{\psi_{SO}}}\right]\left[1 + \frac{1}{\sqrt{1+\theta^2}}\right],$$

$$\psi_{so} = \left(\frac{a + \sqrt{a^2 + 4V_g}}{2}\right)^2,$$

$$d_{eff} = 1.14 \cdot 10^{-4} \cdot \sqrt{\frac{\psi_{SO}}{Na}},$$

$$C_{SCO} = 9.1 \cdot 10^{-9}\sqrt{\frac{Na}{\psi_{SO}}},$$

$$a = 0.37 \cdot tox \cdot 10^{-2} \cdot \sqrt{Na} \,,$$

$$\psi_{SL} = \psi_{SO} - \delta\psi_{SL},$$

$$\gamma = 1 - \frac{\delta\psi_{SO}}{\psi_{SO}},$$

$$|C_{SCL}| = \frac{C_{SCO}}{\sqrt{\gamma - (1-\gamma)/\sqrt{1+\vartheta^2}}}.$$

The numerical modeling has been done for the following parameters of the sensor: pSi substrate doping concentration, $N_a \to (1 \div 100) \cdot 10^{15} cm^{-3}$, f_i (light modulation frequency $1 \div 100 kHz$); life time of photogenerated charge carriers $\tau_0 \to 10^{-4} \div 10^{-6}\ s$, light flux surface concentration Φ_0 - $\Phi_0 \to 10^9 \div 10^{15}$ $photon/cm^2$, thickness of SiO_2 oxide $t_{ox} \to (30 \div 200) nm$, gate bias voltage $V_g = 0.....5V$, the depletion layer shunt resistivity R_{sc} ~ 5 MOhm, the oxide shunt resistivity R_s~ 10 Mohm, $\varepsilon_{si} \sim 11.8$, $\varepsilon_o = 8.85 \cdot 10^{-14}\ F/cm$, absorption coefficient of Si substrate $\alpha \to (0.1....10)x10^4 cm^{-1}$. The results of modeling on MatLab program package is presented in Fig.2. For comparison with the experiments, in Fig. 3 are presented the experimental results of one membrane LAPS, based on $Ba_{0.25}Sr_{0.75}TiO_3$ nanofilm [11].

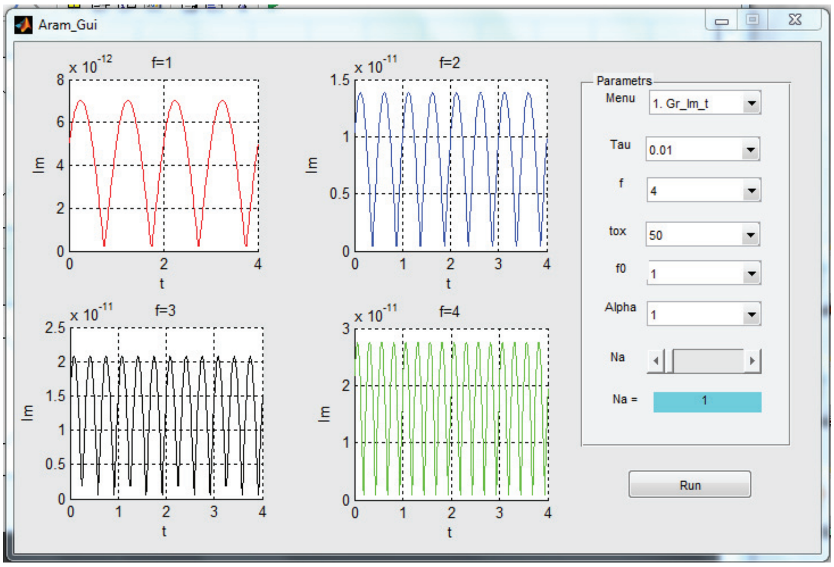

Fig. 1. The results of modeling on MatLab program package

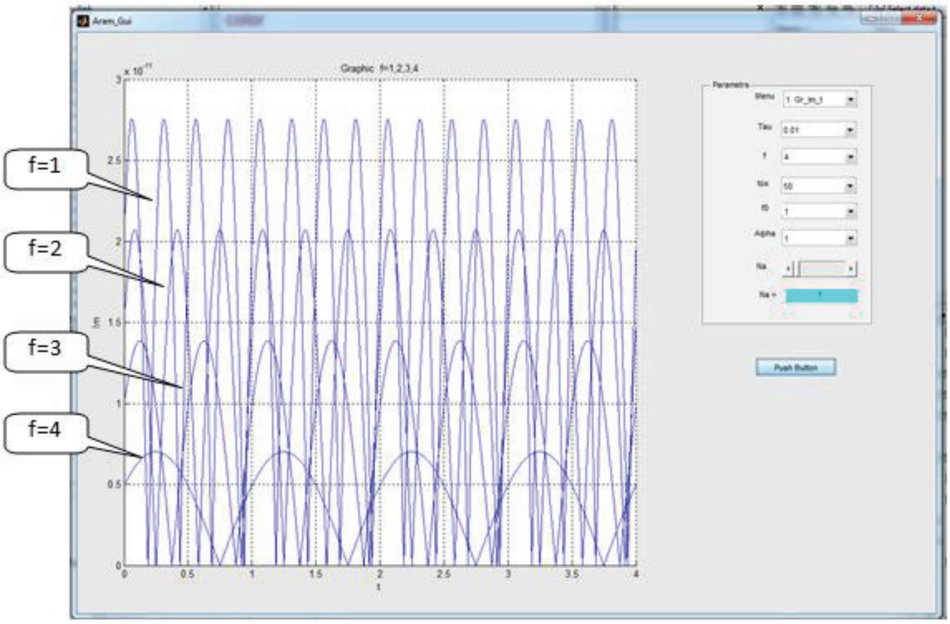

Fig. 2. The results of one membrane LAPS, based on $Ba_{0.25}Sr_{0.75}TiO_3$ nanofilm

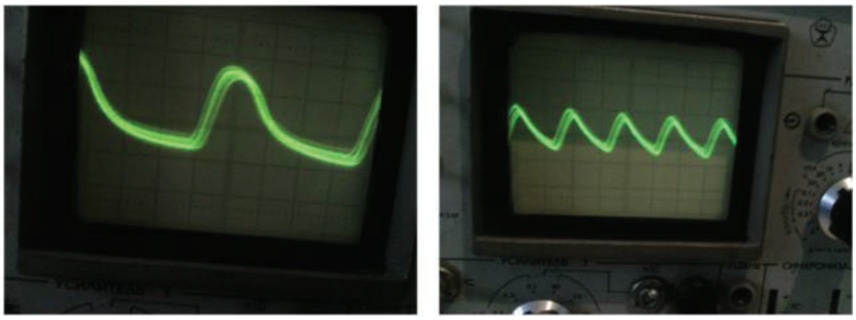

Fig. 3. Experimental dependences of $i_m(t)$ for different modulation frequencies; a-2kHz, b-5kHz

Conclusions. As it follows from Fig. 2, illuminating different sensing membranes with modulated lights of different frequencies generates a photocurrent signal, from which the corresponding information of each testing site can be obtained.

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ԼՈՒՍԱՀԱՍՑԵՈՒՆԱԿ ՊՈՏԵՆՑԻՈՄԵՏՐԱԿԱՆ ՏՎԻՉՆԵՐԻ ՊԱՐԱՄԵՏՐԵՐԻ ՄՈԴԵԼԱՎՈՐՈՒՄԸ

«Լաբորատորիա՝ չիպի վրա» սկզբունքով MatLab միջավայրում մոդելավորվել է տարբեր զգայնությամբ մեմբրաններից բաղկացած լուսահասցեունակ պոտենցիոմետրական կառուցվածքով ելքային ֆոտոհոսանքը:

Առանցքային բառեր. «Լաբորատորիա՝ չիպի վրա», լուսահասցեունակ պոտենցիոմետրական տվիչ, ֆերոէլեկտրիկ:

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МОДЕЛИРОВАНИЕ ПАРАМЕТРОВ СВЕТОАДРЕСОВАННЫХ ПОТЕНЦИОМЕТРИЧЕСКИХ ДАТЧИКОВ

Основываясь на принципе “Лаборатория-на-чипе” в среде MatLab, смоделирован выходной фототок светоадресованной потенциометрической структуры, состоящий из различных сенсорных мембран.

Ключевые слова: лаборатория-на-чипе, светоадресованный потенциометрический датчик, ферроэлектрик.