

The light-addressable potentiometric sensor for multi-ion sensing and imaging

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Accepted 1 May 2005

Abstract

The light-addressable potentiometric sensor (LAPS) is a semiconductor-based chemical sensor with an electrolyte–insulator–semiconductor structure. The LAPS can have many measuring points integrated on the sensing surface, which are individually accessed by a light beam. By modifying the measuring points with different materials, a single sensor plate can be used as a multi-analyte sensor. In this paper, instrumentation and application of LAPS to multi-ion sensing and imaging are described. As a new application of LAPS, potentiometric imaging of a microfluidic channel is proposed.

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Keywords: Chemical sensor; Light-addressable potentiometric sensor; Chemical imaging sensor; Semi conductor; Microfluidic device

1. Introduction

The light-addressable potentiometric sensor (LAPS) [1–3] is a semiconductor-based chemical sensor with an electrolyte–insulator–semiconductor (EIS) structure. It belongs to the family of the EIS sensors, in which the variation of the potential on the insulator surface changes the carrier distribution in the semiconductor. The ion-sensitive field-effect transistor (ISFET) [4] and the EIS capacitive sensor are two examples of this kind [5–7]. In the cases of the ISFET and the EIS capacitive sensor, the entire surface of the insulating layer in contact with the solution works as the sensing surface, whereas the sensing area on the LAPS surface is defined by illumination. Thanks to this

“light-addressability,” LAPS can be used as a basis for multi-analyte sensing [8–12] and chemical imaging [13–17]. In the multi-analyte sensing application, two or more membranes with sensitivities to different chemical species are immobilized at different positions on the sensing surface and each of them functions as an independent sensor when they are individually illuminated. In the chemical imaging application, a focused laser beam scans the sensor plate and the sensor signal is recorded as a function of position to construct a chemical image or a map of the spatial distribution of a specific ion or molecule to be measured.

In this paper, the principle and characteristics of the LAPS, instrumentation, multi-ion sensing and imaging are described. Our recent results on the potentiometric imaging of microfluidic channels are also presented.

2. Principle

The principle of the LAPS is most easily understood by comparing it with other field-effect sensors, i.e., the ISFET

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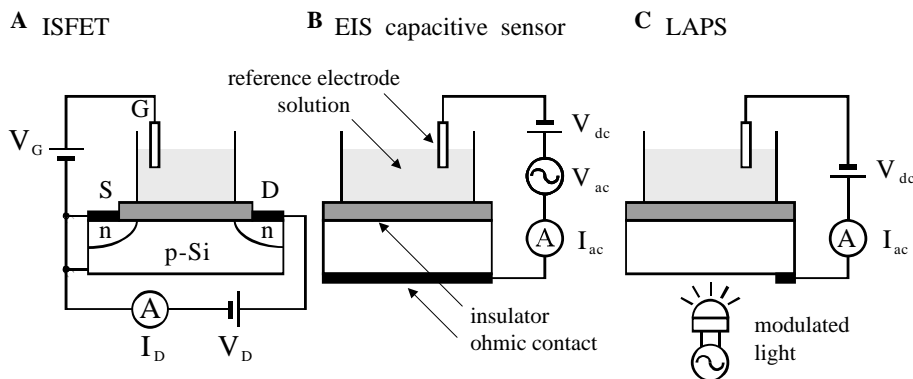


Fig. 1. Comparison of field-effect structures. (A) ISFET, (B) EIS capacitive sensor, and (C) LAPS.

and the EIS capacitive sensor [5–7]. Fig. 1 compares the structures of these three sensors. All three sensors have the same EIS structure, and the insulator surface in contact with the solution serves as the sensing surface. The ISFET has a structure which is similar to that of the field-effect transistor (FET) with the source, drain, and gate electrodes. The metal electrode on the gate insulator of the FET is replaced by the electrolytic solution in the case of ISFET. The structures of the EIS capacitive sensor and the LAPS are similar to that of the metal–insulator–semiconductor (MIS) diode, which has a metal electrode on the insulator surface and an ohmic contact on the back surface of the semiconductor substrate.

When the sensor is in contact with the solution to be measured, a double layer is formed on the insulator surface and the potential at the surface varies with the pH or the concentration of the target species (ions or molecules) in the solution. In response to the change of the potential at the sensing surface, the carrier distribution in the semiconductor is modified by the electric field effect. In the case of the ISFET, the field effect changes the width of the channel under the gate insulator and therefore the conductance between the source and drain electrodes. In the cases of the EIS capacitive sensor and the LAPS, the field effect changes the width and the capacitance of the depletion layer at the insulator–semiconductor interface induced by a negative dc bias voltage. In the case of the EIS capacitive sensor, a small amplitude of ac voltage is superposed onto the dc voltage for measuring the capacitance of the EIS system. In the case of the LAPS, instead of applying the ac voltage, the semiconductor substrate is illuminated with a modulated light and the amplitude of the ac photocurrent is measured.

Fig. 2A shows a typical current–voltage characteristics of a LAPS with p-type Si for different pH values. Here the bias voltage is defined as the voltage applied to the semiconductor with respect to the reference electrode in the solution (electrochemical notation). The sensor signal increases as the semiconductor is more deeply depleted. In Fig. 2B, the inflection points of the curves in Fig. 2A are plotted versus the pH value, giving a nearly-Nernstian value of the pH sensitivity.

These three types of EIS sensors have their respective advantages and disadvantages. In the case of the ISFET,

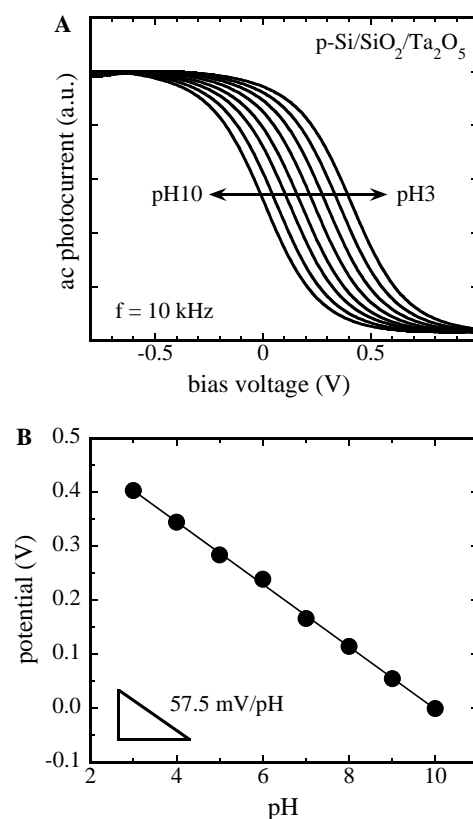


Fig. 2. (A) Current–voltage characteristics of LAPS for different pH values and (B) calibration plot.

the source–drain current through the channel is isolated from the solution, and therefore, it is not affected by the impedance of the solution to be measured. On the other hand, the sensor signal of the EIS capacitive sensor and the LAPS is the ac current that flows through the solution. Calibration is required if the impedance of the solution changes very much. Another advantage of the ISFET is that it has a possibility of integration with the peripheral circuits on chip. On the other hand, the simple structure is an advantage of the EIS capacitive sensor and the LAPS. In addition, the “light-addressability” of the LAPS gives it the possibility of multi-analyte sensing and chemical imaging applications.

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