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# Recent developments of chemical imaging sensor systems based on the principle of the light-addressable potentiometric sensor

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ABSTRACT

The light-addressable potentiometric sensor (LAPS) is an electrochemical sensor with a field-effect structure to detect the variation of the Nernst potential at its sensor surface, the measured area on which is defined by illumination. Thanks to this light-addressability, the LAPS can be applied to chemical imaging sensor systems, which can visualize the two-dimensional distribution of a particular target ion on the sensor surface. Chemical imaging sensor systems are expected to be useful for analysis of reaction and diffusion in various electrochemical and biological samples. Recent developments of LAPS-based chemical imaging sensor systems, in terms of the spatial resolution, measurement speed, image quality, miniaturization and integration with microfluidic devices, are summarized and discussed.



## 1. Introduction

The ion-sensitive field-effect transistor (ISFET) [1,2] and the light-addressable potentiometric sensor (LAPS) [3–5] share much in common as for the sensing mechanism, but they also differ very much in the way the signal is read out [6–9]. As shown in Fig. 1, they both have a field-effect structure that consists of the stacking of the electrolyte–insulator–semiconductor, in which the insulator surface acts as the sensing surface. In the case of the ISFET, a variation of the Nernst potential at the electrolyte–insulator interface changes the thickness and the conductance of the inversion channel at the insulator–semiconductor interface by the field effect. The drain current therefore contains the information of the activity of the target ions binding to the sensing surface. In the case of the LAPS, a variation of the Nernst potential changes the thickness and the capacitance of the depletion layer $C_d$ at the insulator–semiconductor interface. When the semiconductor layer is illuminated with a modulated light, electron–hole pairs are generated and separated by the electric field of the depletion layer, which is represented by the ac current source $I_{photo}$ in the simplified circuit model in Fig. 2(a). The photocurrent signal $I$ measured in the external circuit is a function of $C_d$, which responds to the total of the bias voltage and the Nernst potential. Fig. 2(b) shows the shift of the $I$–$V$ curve due to the variation of the Nernst potential, which is a function of the concentration of the target ion in the solution.

The light-addressability is the most important feature of the LAPS, as explicitly stated in its name. The measured area on the sensing surface is defined by illumination, or more precisely, by photocarriers generated by illumination. By illuminating various positions on the sensing surface, as many sensing areas can be defined on the sensing surface of a single sensor plate. This unique feature immediately allows three different types of applications. Firstly, by partitioning a plurality of measurement areas on the sensing surface and using each of them as an independent sensor, a LAPS can serve as a multi-well sensor array that can handle a plurality of samples of the same kind [10,11]. Secondly, by modifying each of the measurement areas with different sensing materials, a LAPS can serve as a multi-analyte sensor that can detect and measure a plurality of chemical species [9,12–17]. Thirdly, a LAPS can serve as a chemical imaging sensor that can visualize the two-dimensional distribution of a specific chemical species within the solution in contact with the sensing surface [17–19].

Based on these features, the LAPS and the chemical imaging sensor are expected to be useful for analysis of electrochemical systems and biological specimens. The former includes visualization and dynamic analysis of electrolysis, electrochemical deposition and corrosion processes. The latter includes detection of microorganisms, measurement of metabolic activities of living cells, visualization of tissue preparations and measurement of neural activities.

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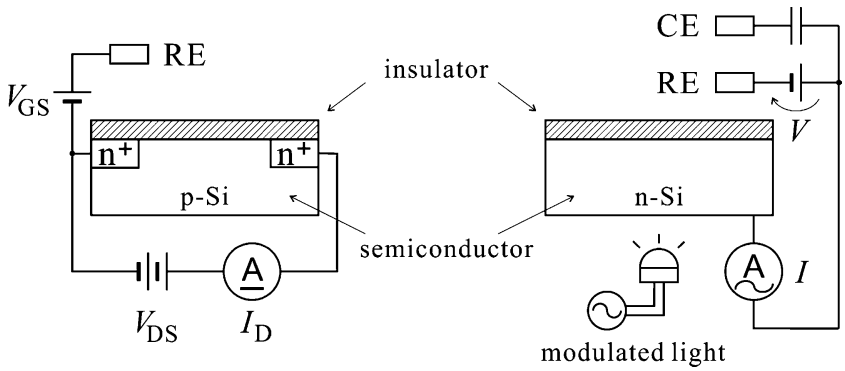


**Fig. 1.** Comparison of the structures of (a) ISFET and (b) LAPS.

In this paper, recent developments of the LAPS-based chemical imaging sensor systems are summarized in terms of the spatial resolution, measurement speed, image quality, miniaturization and application to microfluidic devices.

## 2. Comparison with ISFET/CCD-based chemical imaging

As a semiconductor device that was developed in analogy to a metal-oxide–semiconductor field-effect transistor (MOSFET), a large-scale integration of the ISFET was a natural course of its development. An integrated ISFET array functions as another type of a chemical imaging sensor [20–24]. A read-out mechanism similar to that of a charge coupled device (CCD) image sensor has been also proposed [25–27]. In this type of chemical imaging sensors, every pixel is realized by an independent sensor device structure, whereas a pixel in a LAPS-based chemical imaging sensor is defined by an illumination.

The ISFET/CCD-based chemical imaging sensor has following advantages. Firstly, a large-scale and high-density array of sensors can be prepared with the help of the mature complementary MOS (CMOS) technology except for the sensing layer on top, which must be both sensitive to the target ions and resistant to chemicals. Secondly, the peripheral circuits such as amplifiers, analogue-to-digital (AD) converters, memories and the communication interface can be integrated on chip, which allows a fast read-out of the signal. High frame rates of 100 frames per second (fps) and 333 fps have been reported for $64 \times 64$ and $16 \times 16$ ISFET arrays, respectively [23,24]. The disadvantages of the ISFET/CCD-based chemical imaging sensor are as follows. The number and positions of pixels are fixed at the time of fabrication. This may be a problem in certain biological applications where the location of the sample is unpredictable until it is cultured or captured on the sensing surface. The microfabrication process raises the fabrication costs and limits the size of the active area.

In contrast, LAPS-based chemical imaging sensor systems have following advantages. Firstly, the LAPS sensor plate requires only an insulating layer and an ohmic contact formed on the front surface and the back surface, respectively, of the semiconductor substrate. It requires no device structures to be microfabricated and no wirings that need to be protected from the chemicals [28]. This is a great advantage in terms of the fabrication costs and the long-term stability. Also, the unnecessity of the microfabrication or photolithographic processes allows the whole wafer size to be employed as a single sensor plate, with which even large samples over a diameter of 10 inches can be measured. Secondly, pixels are not predefined and fixed by the sensor device structure. They can be freely defined by illumination after the sensor plate is fabricated, which allows a stepless zoom-in/zoom-out at the time of use. There is no limitation on the number of pixels, which is practically limited by the measurement time. The disadvantages of the LAPS-based chemical imaging sensor are as follows. It requires additional elements such as a light source, a focusing optics and a scanning mechanism, which may hinder miniaturization of the system. The read-out is usually slow, especially in the case where a single light beam is used to scan the sensor plate in a pixel-by-pixel manner.

The LAPS-based chemical imaging sensor and the ISFET/CCD-based chemical imaging sensor therefore have respective fields of suitable applications in which the requirements are met better.

## 3. Improvement of the spatial resolution

The spatial resolution is one of the most important properties of chemical imaging sensor systems [29–32]. The size of the measurement spot on the sensing surface is determined by the arrival of the minority carriers at the depletion layer, which depends on the size of the illuminated area and the lateral diffusion of minority carriers [33,34]. When the former is reduced by an appropriate optics, the latter remains the main factor.

Fig. 3 shows the geometry of diffusion in the case of back-side illumination. If the wavelength of the illumination is short and the penetration depth is small, the diffusion starts from the point of illumination on the back surface. The number of minority carriers arriving at the depletion layer with a lateral displacement of $x$ is

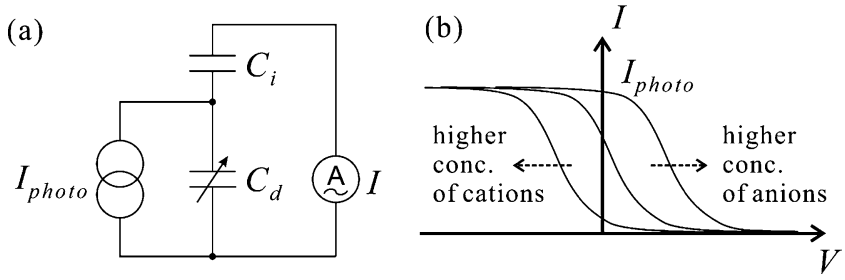


**Fig. 2.** (a) Simplified circuit model of the LAPS. (b) Shift of the current–voltage curve in response to the variation of the ion concentration.