Sensors and Actuators B 198 (2014) 225–232

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

A high-speed, flexible-scanning chemical imaging system using a light-addressable potentiometric sensor integrated with an analog micromirror

Anirban Das [a], Tsung-Cheng Chen [a], Chia-Ming Yang [a,b,c,d,*], Chao-Sung Lai [a,c,d,*]

[a] Department of Electronic Engineering, Chang Gung University, Taoyuan 333, Taiwan
[b] Institute of Electro-Optical Engineering, Chang Gung University, 259 Wen-Hwa 1st Road, Taoyuan 333, Taiwan
[c] Healthy Aging Research Center, Chang Gung University, 259 Wen-Hwa 1st Road, Taoyuan 333, Taiwan
[d] Center for Biomedical Engineering, Chang Gung University, 259 Wen-Hwa 1st Road, Taoyuan 333, Taiwan

ARTICLE INFO

Article history:
Received 28 November 2013
Received in revised form 16 February 2014
Accepted 9 March 2014
Available online 21 March 2014

Keywords:
Light-addressable potentiometric sensor (LAPS)
Analog micromirror
Chemical imaging sensor
pH distribution

ABSTRACT

A semiconductor-based chemical imaging sensor is a type of field-effect, label-free sensing system that can visualize a two-dimensional distribution of concentrations for specific chemical species on a sensor surface. This report presents the development of a high-speed, flexible chemical imaging sensor system using an analog micromirror as a light-addressing setup to scan the light-addressable potentiometric sensor (LAPS) surface from the underside. In the proposed system, a two-axis electrostatic comb-driven micromirror is used to control a modulated laser beam with rapid and tunable scanning capabilities. The position, *X*- and *Y*-axis step, direction of movement and speed of the moving laser spot can be arbitrarily defined using the programmed control on the angular rotation of the micromirror. A high-speed spatiotemporal recording of the change in pH at a rate of approximately 16 fps (frames per second) using backside illumination has been achieved by the current setup. In addition, a high-resolution chemical image with 200k pixels of a test pattern in a sensor area of $14.5 \times 10.5\,mm^2$ was achieved within 40 s. The frequency-dependent photovoltage, photovoltage-reference bias voltage characteristics, and pH sensitivity are also demonstrated and discussed systematically for optimization.

1. Introduction

A light-addressable potentiometric sensor (LAPS) is an important field-effect semiconductor-based, label-free chemical imaging sensor system used for visualizing the two-dimensional (2-D) distribution of chemical species in electrochemical and biological systems. This system was first developed by Hafeman et al. by combining a scanned light pulse technique (SLPT) with a capacitive electrolyte-insulator-semiconductor (EIS) sensor platform [1–4]. In the case of the LAPS, the ion concentration on the sensing surface that influences the width of the space-charge region in the semiconductor can be detected locally by monitoring the amplitude of the photocurrent generated at the point of illumination. Additional detailed information on the working principle and the characteristics of the LAPS can be found in other sources [5,6].

In the LAPS sensing unit, a focused and modulated light source is used to stimulate the semiconductor surface locally, and a 2-D electrochemical image is obtained by moving the light beam along the sensor surface. The surface potentials generated by the electrolyte in the entire scanned sensor surface can therefore be converted into a color map by defining the pixel position and gradient color as the light spot position and corresponding amplitude of the recorded photosignal, respectively [7]. LAPS-based electrochemical image sensors have extensive applications in various fields of biology and chemistry. For example, the electrochemical image created using this technique can visualize the activity of biological systems for Escherichia coli [8] and enzymes [9], the generation and distribution of H^+ and OH^- ions in electrolytic solutions [10–12] and multi-ion imaging [13].

In the LAPS chemical imaging system, addressability and density of the measurement sites along with measurement speed depend significantly on the flexibility of the light source. In recent years, several approaches toward the flexibility of the light source unit in the LAPS have been developed. The prime limitation of the

* Corresponding authors at: Chang Gung University, Department of Electronic Engineering, 259 Wen-Hwa 1st Road, Kwei-Shan, Tao-Yuan 333, Taiwan. Tel.: +886 3 2118800x5786/5960; fax: +886 3 2118507.
E-mail addresses: cmyang@mail.cgu.edu.tw (C.-M. Yang), cslai@mail.cgu.edu.tw (C.-S. Lai).

http://dx.doi.org/10.1016/j.snb.2014.03.028
0925-4005/

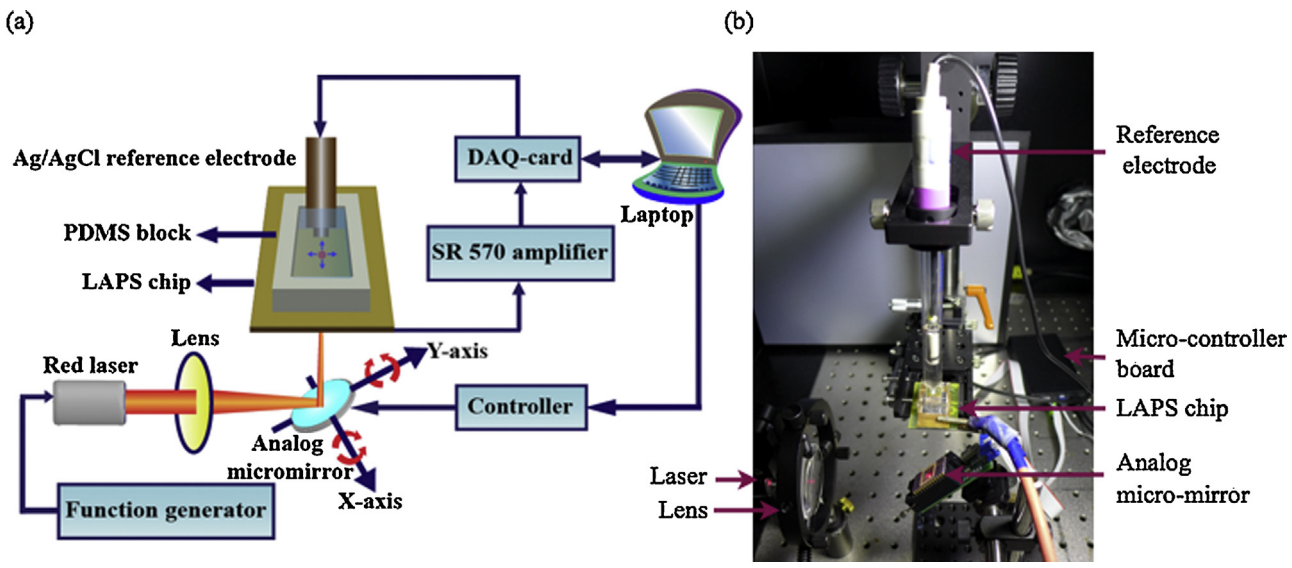

Fig. 1. (a) Schematic illustration of the proposed ultra-high speed chemical imaging sensor system. A two-axis electrostatic comb-driven analog micromirror was used to deflect the modulated laser beam to perform a 2-D raster-like scan on the sensor. (b) System setup.

conventional setup is the use of mechanical scanners, such as an *XY*-axis stage for 2-D scanning of sensors [14,15]. The disadvantages for this type of imaging system is large size and slow scanning speed; therefore, it is applicable only for static or slowly changing specimen activities. A high-speed chemical imaging system is still required to study the spatiotemporal activity of chemical reactions. Recently, a vertical-cavity surface-emitting laser (VCSEL) diodes array replaced the mechanical scanner and was used to increase the speed of the setup [16]. Although this setup significantly improves the measurement speed, a linear stage is still needed to move the laser diode array in one direction, and the complexity in the setup for addressing numerous individual light sources with different modulation frequencies still needs to be resolved. In another approach, an organic light emitting diode (OLED) display panel was used as a light source and placed directly under the sensor chip [17]. However, this setup can only be operated at 135 Hz and results in approximately 1 s for each pixel scan, which can be used for slow scanning. Using a customized driver circuit, chemical imaging at 1.74 kHz was also demonstrated using the same setup [18]. Nevertheless, the speed needs to be increased, and the small scale (max to 60 rows) of total addressable light sources limits the resolution of the image. A simple and straightforward approach of using a commercial video projector as a light-addressing tool was also attempted [19,20]. However, the modulation frequency of the light spot in this setup depends on the refresh rate of the projector; therefore, the measurement speed is extremely slow. Furthermore, a chemical imaging system based on a digital micromirror device (DMD) was developed, in which the modulation frequency of the light pattern was generated by vibrating micromirrors that reflect static light [21]. Although this setup can produce an image of high pixel density, it can only be operated at modulation frequencies up to 720 Hz. Considering the band pass characteristic LAPS's structure and speed of the measurement, a more direct control of the micromirror and light source is now desired [22,23]. In 2013, a high-speed chemical imaging system with a frame rate approximately 70 fps (frames per second) was developed by combining a frequency division multiplex (FDM) and a LED matrix with 7×5 LEDs as a front side light source [24]. However, the LED array in that setup was fixed in position. Furthermore, the front side illumination may not be desirable for certain applications because the light beam may be blocked during the transition through the measuring object. Any possibility in variation of the light transmittance of the object may result in certain noises or degradations on the LAPS signal. The backside illumination is free from such issues, which is also more convenient for setup and application.

In this study, a high-speed, flexible chemical imaging system was developed using an analog micromirror as a light-addressing platform for scanning the LAPS surface from the backside. A single laser beam reflected from the micromirror is used to scan the LAPS surface pixel-by-pixel, based on the microlectromechanical system (MEMS) projection principle [25]. High-speed chemical imaging of a spatiotemporal change of pH distribution in solution at approximately 16 fps can be obtained by the current setup. In addition, a high-resolution chemical image with 200k pixels of a photoresist pattern in uniform solution on the sensor surface was generated within 40 s.

2. Materials and methods

2.1. Setup of analog micromirror based LAPS imaging system

A detailed schematic and the photograph of the proposed chemical imaging system are provided in Fig. 1(a) and (b), respectively. A gimbal-less two-axis scanning micromirror device (Mirrorcle Technologies Inc., USA) was located just under the sensor. The tilt angle of this mirror is analog rather than digital on-off mode, which can be used for arbitrary-direction optical beam steering. A steady-state analog angle of rotation of the micromirror can be obtained by applying a corresponding voltage. A universal serial bus (USB) MEMS controller card (Mirrorcle Technologies, Inc., USA) was used to control the micromirror. A silicon LABS F120 microcontroller is used in this card. This controller serves 12-bit analog outputs for *X*- and *Y*-axis control with sampling rates up to 65 kHz. A simple 'user interface' (UI) executable software allows users to drive the MEMS controller card easily. A linear raster scan with uniform velocity and defined steps could be performed using a programmed control on the *X*- and *Y*-axis of the analog micromirror. Users can define the number of lines, pixel per line and duration per line for scanning. Furthermore, users can adjust the angle of scanning line. A raster scan can be operated in two different modes, including a point-to-point and uniform velocity scan. In this study, a light spot with diameter of 300 μm was used. The scanning window could be modified by the position and tilt angle of the micromirror and