Enhancement of the Spatial Resolution of the Chemical Imaging Sensor by a Hybrid Fiber-Optic Illumination

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Abstract

The chemical imaging sensor, which is based on the principle of the light-addressable potentiometric sensor (LAPS), is a powerful tool to visualize the spatial distribution of chemical species on the sensor surface. The spatial resolution of this sensor depends on the diffusion of photocarriers excited by a modulated light. In this study, a novel hybrid fiber-optic illumination was developed to enhance the spatial resolution. It consists of a modulated light probe to generate a photocurrent signal and a ring of constant light, which suppresses the lateral diffusion of minority carriers excited by the modulated light. It is demonstrated that the spatial resolution was improved from 92 μm to 68 μm.

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1. Introduction

The chemical imaging sensor [1] is a chemical sensor based on the field-effect in semiconductor. This sensor and its applications have been developed in the past 20 years as a powerful tool to visualize ion distributions. It utilizes the principle of light-addressable potentiometric sensor [2], the sensing area can be flexibly addressed by an illumination of light beam. By combining the LAPS measurement with a focused light beam, which is mounted on a scanning stage,
visualization of ion distribution / pH distribution can be realized. As schematically shown in Fig. 1, the modulated light beam scans the sensor plate and the amplitude of the photocurrent is recorded in a spatially resolved manner. The photocurrent map can then be converted into an ion concentration map or a chemical image. Due to its advantages of label-free measurement and flexible imaging capability, the chemical imaging sensor is expected to be a powerful tool in the field of analytical chemistry and biology. For example, pH profile in a microfluidic channel caused by an enzymatic reaction was successfully observed [3].

![Fig. 1: Chemical imaging sensor based on the light-addressable potentiometric sensor.](image1)

However, the spatial resolution of the conventional system is insufficient to fulfill the requirements of certain applications (e.g., single cell studies). The spatial resolution depends on both the illuminated area and the diffusion of photocarriers in the semiconductor layer. Even when the illumination is focused to a small area, the spatial resolution is limited by the thickness of the semiconductor layer and the diffusion length of minority carriers. Using a thinner sensor plate is an effective approach to improve the spatial resolution, which is then limited by the diffusion length of minority carriers. A thin sensor plate, however, has the problem that it is fragile and difficult to handle.

In our recent paper [4], we proposed a novel photo-excitation method, in which the modulated light is surrounded by constant lights. The increased carrier concentration by the constant light enhances recombination of carriers, which suppresses lateral diffusion of photocarriers generated by the modulated light at the center and improves the spatial resolution. A simulation study [4, 5] predicted improvement of the spatial resolution from 82.32 μm to 50.93 μm when the distance between modulated and constant lights was 230 μm.

In this study, we developed a hybrid fiber-optic illumination, which delivers both modulated and constant lights as shown in Fig. 2. The effect of constant illumination on the spatial resolution was experimentally investigated to verify the predictions of the simulation study.

![Fig. 2. Schematic view of the hybrid illumination consisting of a modulated light and surrounding constant lights. Recombination is enhanced in the regions indicated by arrows.](image2)
2. Experimental

As shown in Fig. 3, the measurement system consists of the sensor substrate, a control software and the optics of the hybrid illumination. The sensor substrate was n-Si with a thickness of 200 μm, on which insulating layers of SiO₂ and Si₃N₄ were deposited. On the sensor surface, a stripe pattern was fabricated by photo-resist to study the spatial resolution. The control software was developed by ourselves.

In this study, the hybrid illumination is realized by a bundle of optical fibers, one of which at the center delivers a modulated light to generate the photocurrent signal and the others project a ring of constant light surrounding the modulated light. The inset in Fig. 3 shows a schematic of the hybrid fiber-optic illumination and a photograph of its light-emitting end. The diameter of each fiber is 250 μm and the gap between those for modulated and constant lights is 310 μm. The constant light generates a ring of increased carrier concentrations in the semiconductor layer, in which the recombination is enhanced.

Fig. 3: Implementation of the hybrid illumination using a bundled-fiber optics. (The diameter of the bundled-fiber is about 2.5 mm.)

3. Result and discussion

The spatial resolution was examined by scanning the stripe pattern from the back-side of the sensor substrate. Fig. 4 presents the decay of the photocurrent at edges of a stripe pattern (w=500 μm). The photocurrent obtained by the hybrid illumination was decreased about 50 % in comparison to that of the conventional illumination (Data not shown). It suggests that a part of the photocarriers was consumed by recombination with the photocarriers from the constant illumination.

The spatial resolution was defined as the lateral distance between two positions, where the photocurrent becomes 60% and 40% of the maximum. Compared to the conventional illumination, a steeper decay of the photocurrent is clearly observed with the hybrid illumination.

Fig. 4: The decays of the photocurrent at the edges of the photoresist pattern. A steeper decay is obtained with the hybrid illumination. The spatial resolution was improved from 92 μm to 68 μm (averaged values at both edges).
Figures 5a and 5b show the chemical images obtained with the conventional illumination and the hybrid illumination, respectively. The stripe pattern was resolved only with the hybrid illumination. After optimization of experimental conditions, the spatial resolution was improved from 92 μm to 68 μm.

4. Summary

To improve the spatial resolution of the chemical imaging sensor, a novel geometry of illumination which consists of a modulated light beam and surrounding constant lights was proposed. It was implemented with bundled-fiber optics, and the enhancement of the spatial resolution was demonstrated. The optimization of the illumination will be discussed in our presentation at Eurosensors 2014.

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