Characterization of an Integrated Fluorescence-Detection Hybrid Device With Photodiode and Organic Light-Emitting Diode

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***Abstract*—A new integrated fluorescence-detection hybrid device with a photodiode and an organic light-emitting diode (OLED), and its characteristics are presented. To detect the fluorescent signal using OLED as a light source, a finger-type photodiode with low parasitic resistance was designed, which utilizes the side depletion region in the p^+n junction. In addition, OLED was designed to have the peak intensity at an excitation wavelength from rhodamine 6G. The integrated fluorescence-detection hybrid device fabricated had a background signal of 153 nA and a limit of detection of 1 μM, and was applied in the competitive assay.**

***Index Terms*—Biosensors, fluorescence, microfluidic, organic light-emitting diode (OLED), photodiode, p-type intrinsic n-type (p-i-n) diode.**

I. Introduction

RECENTLY, many research groups have focused their work on highly integrated microfluidic systems. Although miniaturization, system integration, and parallelization afford many performance advantages such as speed, analytical efficiency, and throughput, new problems are also encountered. A significant challenge arises directly from the existence of small volumes within microfluidic systems. High-sensitivity detection is therefore a prerequisite for performing analysis in microfluidic systems [1]. The most common chip-based detection method is laser-induced fluorescence (LIF). However, a laser system is difficult to miniaturize and integrate on microfluidic systems. The photomultiplier tube (PMT) is used as a photodetector in commercially bulky analytic systems and integrated fluidic channels [2], [3]. Some research groups reported that the p-type intrinsic n-type (p-i-n) diode is used as a photodetector on silicon or glass substrates with laser system as an optical light source [4], [5]. However, the integration of the photodetector with the light source in fluidic systems is not yet established without additional optical methods. There remain many obstacles to be overcome to obtain a reasonable sensitivity in an integrated fluorescence-detection hybrid device with a photodetector and a light source [6], [7].

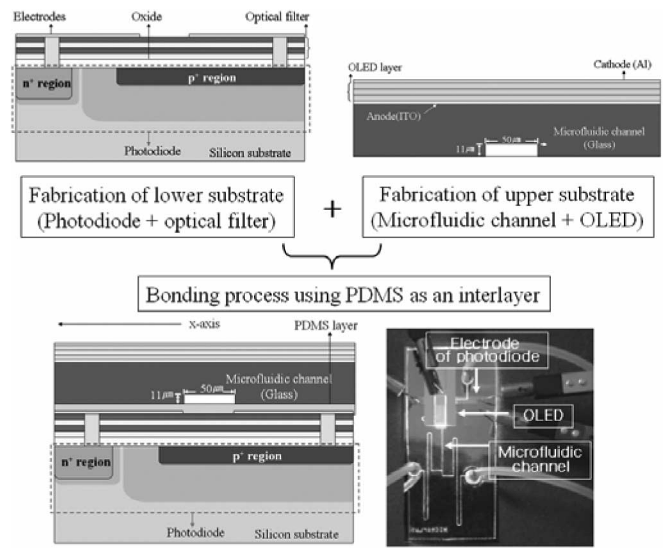

Fig. 1. Photograph, structure, parts, and cross-sectional view of an integrated fluorescence-detection hybrid device.

In this letter, we present an integrated fluorescence-detection hybrid device with a light source and a photodiode. The LIF system is not suitable for an integrated fluorescence-detection hybrid device, owing to the difficulty of integration. The organic light-emitting diode (OLED) replaces the laser light source and can be integrated on a chip.

II. Device Design and Fabrication

The new integrated fluorescence-detection hybrid device consists of two parts, as shown in Fig. 1: First, a microfluidic channel was constructed within the glass using microelectromechanical systems (MEMS) process technology, and OLED as a light source was deposited on a glass-based microfluidic channel [8], [9]. Second, a photodetector was fabricated on a silicon substrate, and then, the photodetector was covered with an interference optical filter to allow the transmission of

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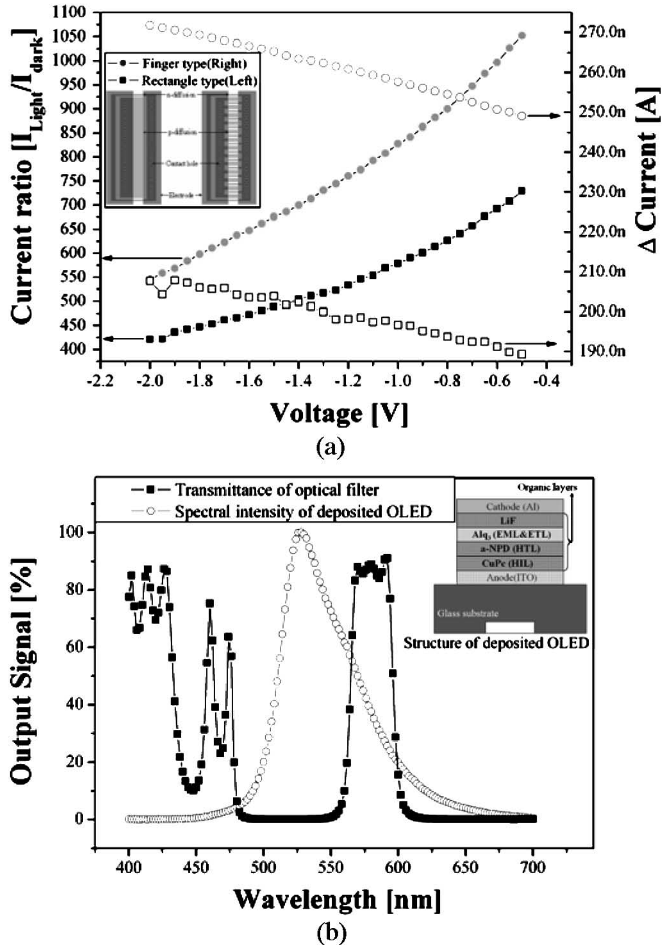


Fig. 2. Characteristics of the photodiode, optical filter, and OLED. (a) Comparison results of the finger-type photodiode with the rectangle-type photodiode in terms of electrical characteristics under the same light condition. (b) Spectral intensity of a deposited OLED and the transmittance of an optical filter on a photodiode.

a fluorescent emission and to block the background noise from excitation light.

The normal width of microfluidic channel was about 50 μm. The p-i-n diode was designed to get high sensitivity in the visible spectrum. It was reported that most of the visible spectra was absorbed to a depth of about 1 μm from the silicon surface [10]–[12]. Therefore, we designed the process to form a junction depth of 150 nm in the p^+ region and the finger-type photodiode to reduce the loss of the generated carriers using the side depletion region between the n^+ region and the p^+ region. The fabrication process was simulated using TSupreme. From the simulation results, the depth at the peak of the concentration of the p^+ region is calculated to be 80 nm thick.

The interference optical filter (2.3 μm in thickness) composed of 16 pairs of SiO_2/TiO_2 layer was deposited on the photodiode. The OLED was designed to obtain the peak spectral intensity at 530 nm, and the OLED fabricated was passivated with 1-μm SiO_2 and had a lifetime of 72 h. Finally, the fabricated OLED was bonded to a photodiode substrate using the interlayer of polydimethlysiloxiane (PDMS) to form a completely integrated fluorescence-detection hybrid device [13].

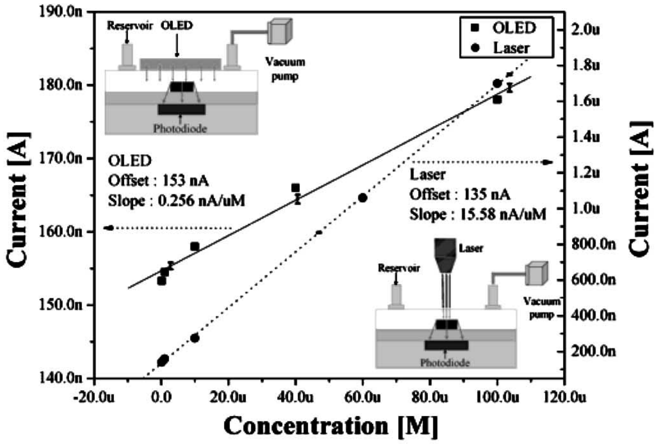
III. Results and Discussion

Fig. 2(a) shows the comparison results of the finger-type photodiode with the rectangle-type photodiode in terms of electrical characteristics under the same light condition. The figure displays the current ratio $I_{\text{light}}/I_{\text{dark}}$ and the current difference. The current difference $I_{\text{light}} - I_{\text{dark}}$ in the finger-type device was about 60% larger than that in the rectangle-type device. Since the internal electric field in the side depletion region was directed to the p^+ region, owing to the doping gradients near the junction region, most of the generated electrons in the side depletion region were pushed into the n^- region by the internal electric field [3], [14]. These electrons were collected within the n^+ region by the external electric field, which has the same direction as the internal field in this case, and contributed to the photocurrents. Although the p^+ regions were shallow, the light flux decayed exponentially with depth, and so most of the light was absorbed at the surface. However, the light absorbed in the neutral p^+ regions did not produce a photocurrent. In addition, when the electrons were generated below the p^+ region, some of them were diffused into the substrate, owing to the direction of electric field, which contributed to the loss of the generated currents. Therefore, it was better to replace the neutral p^+ regions by depletion regions as much as possible, so that more of the carriers absorbed at the surface were collected as photocurrents.

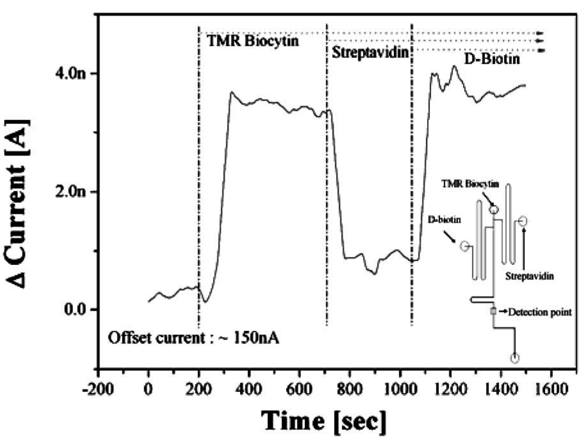
Fig. 2(b) shows the spectral intensity of the deposited OLED with a peak intensity at 530 nm and a full-width at half-maximum (FWHM) of 50 nm. In addition, the figure displays a transmittance as a function of wavelength in the deposited interference optical filter on the photodiode. It is shown that only 0.1% of the light was transmitted at 528 nm and more than 80% at 580 nm.

Fig. 3(a) shows the measurement configuration and output characteristics of a new integrated microfluidic hybrid device. In the measurements, rhodamine 6G (emission wavelength of 580 nm) was used as a fluorescent dye. We compared the properties of OLED with those of laser as light sources in an integrated fluorescence-detection hybrid device. The laser had an excitation wavelength of 530 nm and power of 2 mW. The hybrid device comprising laser as a light source had a linear response, a background signal of 135 nA, and a slope of 15.58 nA/μM according to the concentration. The hybrid device comprising OLED as a light source had a higher background signal of 153 nA and a lower slope of 0.256 nA/μM than that in a laser source because of OLED properties such as broad-spectrum distribution and low-power intensity. The slope of the fluorescent signal in an OLED is two orders in magnitude lower than that in a laser, owing to the low intensity at 530 nm, which limits the detection range of the fluorescent signal. The limit of detection (LOD) in an integrated fluorescence-detection hybrid device with an OLED light source was estimated to be 1 μM in this experiment.

Finally, an integrated fluorescence-detection hybrid device was applied in the competitive assay with tetramethylrhodamine (TMR)-biocytin (10 μM), streptavidin (10 μM), and D-biotin (15 μM) in the microfluidic channel, as shown in Fig. 3(b). First, we filled the microfluidic channel with a buffer



(a)



(b)

Fig. 3. Output characteristics of an integrated fluorescence-detection hybrid device. (a) Output currents as a function of concentration in OLED and laser as light sources, and the measurement configuration. In a laser light source, the detection device did not have a deposited OLED. (b) Output signal of the competitive assay and schematic of the microfluidic channel fabricated. The plot shows an offset current subtracted from the output signal.

solution. TMR-biocytin, streptavidin, and D-biotin were prepared for the each reservoir. Second, the TMR-biocytin flowed in the channel, and the fluorescence was monitored in the detection point. Then, streptavidin was replaced with a buffer in another reservoir, and the fluorescent signal was quenched until D-biotin flowed in the other reservoir because TMR-biocytin was enclosed by streptavidin. When D-biotin flowed in the channel, the fluorescent signal was recovered, owing to the D-biotin bound to the streptavidin taken off from the TMR-biocytin [15], [16].

IV. Conclusion

We have demonstrated an integrated fluorescence-detection hybrid device with a photodiode and an OLED. The integrated fluorescence-detection hybrid device fabricated had a background signal of 153 nA and a LOD of 1 μM, and was applied to the competitive assay. Presently, such LOD is not enough to get high-intensity signals in the assay without amplification, but there is room for improvement of LOD through the optimization of OLED characteristics such as FWHM and light intensity. In addition, our integrated fluorescence-detection hybrid device plays an important role in the realization of portable fluorescence-detection systems.

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