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Optically controlled electrophoresis with a photoconductive substrate

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ABSTRACT

A photoconductive substrate is used to perform electrophoresis. Light-induced micro-particle flow manipulation is demonstrated without using a fabricated flow channel. The path along which the particles were moved was formed by an illuminated light pattern on the substrate. Because the substrate conductivity and electric field distribution can be modified by light illumination, the forces acting on the particles can be controlled. This technique has potential applications as a high functionality analytical device.

1. Introduction

Various micro total analysis systems (μTAS) have been developed for medical, biological, and chemical applications. The advantages are small volumes, small sizes, high portability, and low energy consumption. The μTAS components include flow channels, pumps, valves, mixers, separators, filters, reactors, and sensors precisely fabricated on a chip via photolithography and micro-electromechanical systems (MEMS) fabrication techniques. In 1979, a gas chromatographic analyzer was fabricated on silicon [1]. Pumps [2–7], valves [8–10], mixers [11], separators [12], filters [13], reactors [14], and sensors [15–20] were fabricated in miniaturized analytical instruments. These processes require time-consuming and complex fabrication of flow channels. Furthermore, the systems are expected to change the flow channels quickly for various demands and applications.

Electro-kinetic processes such as electrophoresis and dielectrophoresis are used to manipulate particles and cells because they are highly controllable, low-cost, and less damaging to samples. Electrophoresis [21,22] is widely used to separate electrically charged particles [21], DNA [23], RNA [24], proteins [25], and cells [26] and have been integrated into μTAS [27–30]. Because an electric field exerts a force on charged materials, they move along the potential gradient at a speed determined by the amount of charge. Dielectrophoresis [31–33] can also manipulate micro-particles and biological materials. The materials do not need to be charged if they are polarizable in a non-uniform electric field. Hence, manipulation techniques related to dielectrophoresis have been developed for small objects [34–36].

The objective here is to develop a cost-effective and flexible μTAS that can freely form virtual flow channels induced by laser irradiation. With a photoconductive [37] substrate, micro-particles can be manipulated without a flow channel. Specifically, electrophoretic particle collection and extraction by laser-induced patterns are demonstrated. The patterns change the potential gradient of the electric field on the photoconductive substrate. Optical control can dynamically reconfigure virtual channels, separators, filters, and mixers for high-functionality analytical devices.

2. Principle of electrophoresis using a photoconductive substrate

Fig. 1(a) schematically depicts the principle of increasing the conductance of a photoconductive material with light illumination. Like a semiconductor, a potential gradient arises at an applied voltage. Light excites electrons in the valence band to the conduction band, generating mobile electrons and holes and increasing the conductance. Here, crystalline $Bi_{12}SiO_{20}$ (BSO) [38] is used as a photoconductive substrate, where Fig. 1(b) is a schematic of optically controllable electrophoresis. When a droplet containing micro-particles is placed on the photoconductive substrate, an external voltage is applied to the both ends to create a potential gradient in which the particles move from the negative electrode to the positive electrode by electrophoresis. Electrophoresis is the motion of dispersed particles relative to a fluid in a spatially uniform electric field. Charged particles experience electrostatic forces in the external electric field. When a line-shaped beam illuminates the photoconductive substrate, the potential gradient in the illuminated area is flattened because of increased conductance, and the electric field in that area is reduced. Thus, when the particles move to irradiated area, they stop because there is little or no force exerted on them. Hence, the force (magnitude and direction) acting on the particles depends on the potential gradient.

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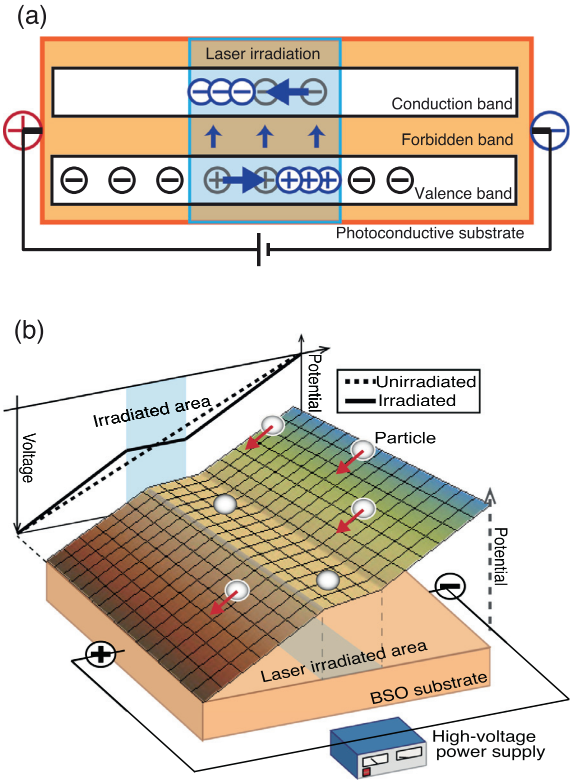

Fig. 1. (**a**) A principle of increasing the conductance of a photoconductive material with light irradiation. (**b**) A schematic diagram of the optically controllable electrophoresis.

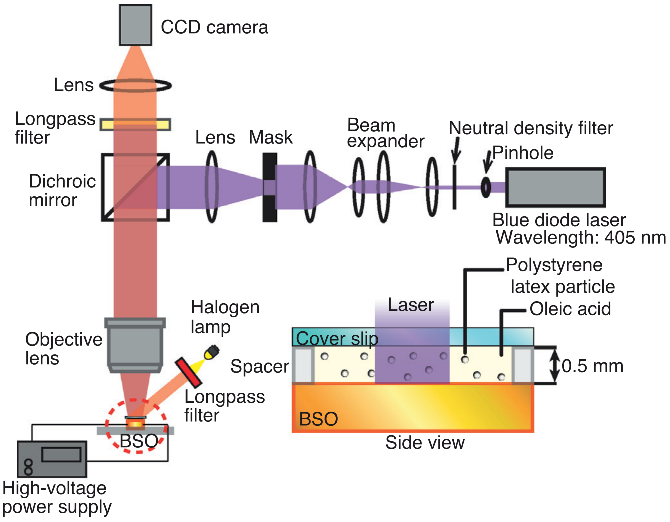

Fig. 2. The experimental schematic diagram of the optical setup for electrophoresis with a photoconductive substrate. The laser power was 0.5 mW and the wavelength was 405 nm. A BSO substrate was used. The pattern was reductively projected on a BSO crystal surface using a lens and an objective lens to change the potential gradient of the BSO surface. The movement of particles on the surface of the BSO crystal was imaged with red illumination. The red illumination does not affect the potential gradient of the BSO. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Experiment results of optically controllable electrophoresis

3.1. Experiment setup

Fig. 2 illustrates the experimental optical arrangement for electrophoresis on a photoconductive substrate. A 405-nm, 0.5-mW blue laser diode was used for changing the electric potential on the BSO photoconductive substrate. The laser irradiation pattern was determined by a mask. The BSO crystal efficiently absorbs the laser light, producing high photoconductivity [38]. The laser beam was initially passed through a beam expander to cover the whole mask. The pattern was then reduced by a lens and an objective lens as it was projected on a BSO crystal surface. An imaging system for observing movement of the polystyrene microspheres was also constructed. The imaging system used red light because it is not absorbed by the BSO crystal [38] and does not affect the electric potential. The scattered and reflected light was collected by the objective lens and focused on a CCD camera with a projection lens. A long pass filter blocked the blue laser light. Polystyrene microspheres were suspended in an oleic acid solution that was dropped on the BSO substrate. A spacer was used to maintains a space between the substrate and a cover slip.

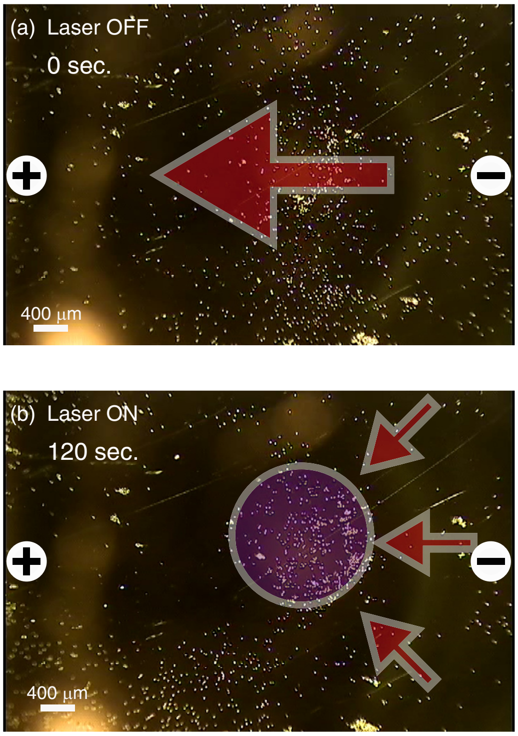

Fig. 3. Experimental result of a collecting manipulation (see Visualization 1). The BSO substrate was illuminated with a uniform circular laser beam. The diameter of the polystyrene microspheres was 20-μm. The laser power was 5 mW. The voltage of 3 kV was applied between the end of the BSO substrate. The particles went to the illumination area and stopped.

3.2. Collecting manipulation

Fig. 3 demonstrates optically controllable electrophoresis. Polystyrene microspheres (20 μm) were collected in a circular area of the BSO substrate that was uniformly illuminated with a 5-mW laser. A voltage of 3 kV was applied between the ends of the substrate. Fig. 3(a) shows the substrate before laser illumination. The microspheres moved in a straight line from negative electrode to positive electrode, as the potential uniformly decreases from right to left. Fig. 3(b) shows the substrate 120 s after laser illumination in the center. When the illumination was started, the direction of the microspheres was changed and their velocity decreased as they approached the illumination area. The potential thus was changed to a bowl shape by the laser illumination, which essentially trapped the microspheres. When laser light was blocked, the microspheres moved from the negative electrode to the positive electrode again. The irradiated laser pattern can be controlled by changing the mask, and the microspheres can be controlled freely.