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Review Article

Optoelectrofluidic Manipulation of Nanoparticles and Biomolecules

Hyundoo Hwang and Je-Kyun Park

Department of Bio and Brain Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

Correspondence should be addressed to Je-Kyun Park, jekyun@kaist.ac.kr

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This paper presents optoelectrofluidic technologies for manipulation of nanoparticles and biomolecules. Optoelectrofluidics provides an elegant scheme for the programmable manipulation of particles or fluids in microenvironments based on optically induced electrokinetics. Recent progress on the optoelectrofluidic manipulation of nanoobjects, which include nanospheres, nanowires, nanotubes, and biomolecules, is introduced. Some potential applications of the optoelectrofluidic nanoparticle manipulation, such as nanoparticles separation, nanostructures manufacturing, molecular physics, and clinical diagnostics, and their future directions are also discussed.

1. Introduction

A number of advances in micro- and nanomanipulation techniques have been made due to the increase of needs for high performance manipulation—trapping, transportation, separation, concentration, and assembly—of micro-/nanoobjects in a variety of applications. In particular, manipulating nanoobjects such as nanospheres, nanowires, and biomolecules has provided tremendous opportunities in various application fields, including from device manufacturing to chemical analysis. For addressing such nanoparticle applications, numerous techniques based on various forces such as mechanical [1–4], optical [5–9], electrical [10–13], and magnetic [14, 15] forces have been introduced. In this paper, we present the fundamentals of optoelectrofluidics and the major experiments performed to date for manipulating nanoparticles and molecules using the optoelectrofluidic platforms. Recent progress and some potential applications of optoelectrofluidic technology for nanoparticle manipulation, as well as its future direction are discussed.

2. Conventional Techniques for Nanoparticle Manipulation: Optical and Electrical Methods

Optical manipulation techniques have attracted much attention for a long time since the appearance of optical tweezers in 1970 [5] and been one of the most frequently used methods because one can directly trap and transport individual particles on demand based on the optical field of a tightly focused laser beam. However, it is well known that a lower bound on the size to which light can be focused is limited by the diffraction limit, which is given by $d = 1.2\lambda/\text{N.A.}$, where λ and N.A. are the wavelength of the light and the numerical aperture of the lens, respectively [16]. Despite such limitations, conventional optical tweezers have been used to trap not only viruses [17] and biological cells [18] but also metallic nanoparticles [6], nanowires [7], and carbon nanotubes (CNTs) [8]. When the target object is much smaller than the diffraction limit as the case of nanoparticles, the trap stability is dependent on the polarizability of the particles because they can be treated as

point dipoles in an inhomogeneous electromagnetic field of the optical trap [6]. In the Rayleigh regime, however, the trapping force is proportional to the volume of the particle, thereby an extremely high power laser source is required for trapping nanoparticles. For dielectric nanoparticles such as latex, the situation is more challenging than for metallic nanoparticles because the laser power needed for trapping latex nanoparticles is significantly higher than that for metallic particles of similar size. For biomolecules, most of the researchers have tried to manipulate and characterize the physical properties of the molecules by attaching them onto microbeads and manipulating the beads [9]. In this paper, however, only the direct manipulation of molecules, which are not immobilized onto any supporting substrates as a carrier, would be considered. To our knowledge, there are no studies, in which direct trapping and transporting of biomolecules using a conventional optical tweezers system have been demonstrated.

To deal with the limitation of conventional optical tweezers, several types of advanced optical manipulation techniques using near field photonics have been reported [19]. Silicon waveguides have been applied to directly manipulate nanoparticles and λDNA molecules [20]. By using the subwavelength slot waveguides, the intensity of the optical field and the sharpness of the gradient could be increased, resulting in the increase of the optical force. Recently, an alternative method based on an optical resonator, which amplifies the local optical fields, has also been demonstrated [21]. They could generate extremely strong optical field gradients in three dimensions while simultaneously enhancing the trap stiffness due to the optical field amplification within the resonator. Methods based on localized surface plasmon resonance (LSPR) have also been applied to trap nanosized particles. For example, excitation of LSPR between two gold nanodots with a focused laser beam could generate strong optical forces to trap [22]. Plasmonic dipole antenna has also been applied to enhance the optical field and to trap 10 nm gold nanoparticles with stronger forces [23]. Although these methods offered a new way to reduce the incident laser power to trap nanoparticles with higher stability compared to the conventional optical tweezers, transportation of trapped nanoparticles at a specific region of interest is not possible because they always require the patterned metal structures in a predefined design to enhance the optical fields and to trap the particles. In addition, these methods still require relatively complicated optical setup for flexible manipulation of the optical pattern and fine alignment of the optical path, which affect the performance of nanoparticle manipulation.

Electrical methods, especially using electrokinetic mechanisms such as electrophoresis, dielectrophoresis (DEP), and AC electroosmosis (ACEO), have been widely used for the manipulation of nanoparticles as well. For example, under a nonuniform electric field formed by patterned microelectrodes, nanospheres, nanowires, and nanotubes as well as biomolecules move towards or repel from the edge of the electrodes, around which an electric field is the strongest, by DEP forces, which depend on the dielectric properties of target matters and surrounding medium. Some drag forces due to the flow effects such as ACEO and electrothermal (ET) flow also affect the movement of nanoparticles. In 1997, Green and Morgan [10] first demonstrated the DEP-based manipulation of 93 nm latex beads using microelectrode arrays. Precise alignment and placement of semiconducting nanowires onto electrode patterns have been recently demonstrated on the basis of positive DEP, which means the movement of particles towards the strongest electric field area [11]. Separation of metallic single-walled CNTs from semiconducting ones has also been demonstrated based on their different dielectric properties, which cause different DEP behaviors [12]. In addition, gold nanoparticles were concentrated and assembled onto the electrodes by several AC electrokinetic mechanisms such as positive DEP, ACEO, and ET flows [13]. Although these electrical techniques offer simple and versatile setup for nanoparticle manipulation compared to the optical methods, it has been only possible to manipulate them under a fixed electric field distribution formed by predesigned electrode patterns.

3. Optoelectrofluidics

To combine their own advantages of optical and electrical manipulation technologies, an alternative manipulation technique, so-called optoelectrofluidics, has been suggested. Optoelectrofluidics refers to the motions of particles or fluids under an electric field, which is induced or perturbed by an optical source [24]. There are two typical approaches for optoelectrofluidic manipulation [25]: (i) direct change of liquid properties by light and (ii) change of surface conductivity by light. Although both methods have been applied for optoelectrofluidic manipulation of nanoparticles including biomolecules, more widely used method is the latter one, which is based on the photoconductivity of a surface, because there is no significant change in the natural properties of sample fluid and more flexible application is available based on several electrokinetic mechanisms such as DEP and ACEO by forming a nonuniform electric field in the fluid.

In the case of the former one, local temperature increase of fluid under an electric field by illuminating a strong light source has been usually used to induce electrohydrodynamic vortices due to local change of electrical conductivity and permittivity of the fluid depending on its temperature (Figure 1(a)). Mizuno et al. [26] have first demonstrated the ET vortices induced by a strong infrared (IR) laser source and applied to transport DNA molecules in 1995. Although they have also simultaneously applied an optical field and an electrical field to manipulate particles and molecules [27–29], those works are not included in this paper since two fields independently worked for different purposes in those studies: an optical force for trapping, positioning, or cutting; and an electrostatic force for rotating or extracting.

In the case of the latter one, a light source is used to make only the partially illuminated area of the surface become more conductive than other area and to form a nonuniform electric field in the liquid sample, resulting in several electrokinetic phenomena (Figure 1(b)). Hayward et al. [30] have first demonstrated the electrokinetic patterning of microbeads under a nonuniform electric field formed

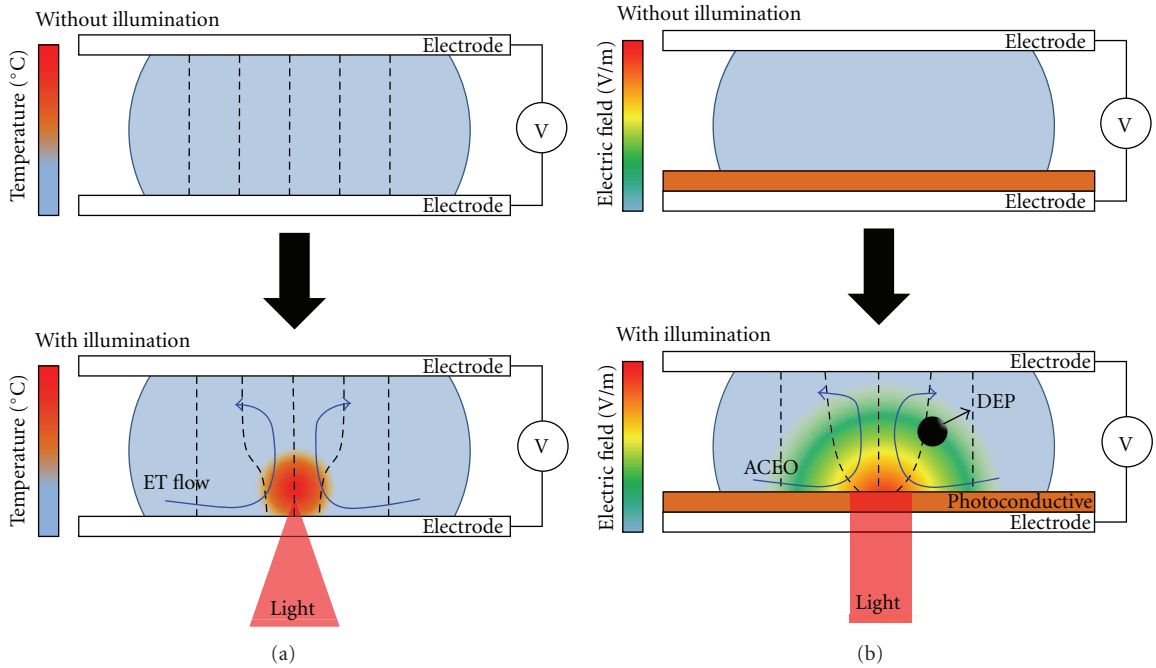


Figure 1: Schematic illustration of two typical approaches for optoelectrofluidic particle manipulation: (a) using light for changing sample properties and (b) using light for changing conductivity of the surface.

by an ultraviolet (UV) light pattern projected onto an indium tin oxide surface in 2000. Since the appearance of a technology so-called optoelectronic tweezers (OET) [31] in 2005, photoconductive materials such as hydrogenated amorphous silicon (a-Si : H) have started to be used so that a weak conventional white light source is applicable for inducing electric fields and operating the optoelectrofluidic devices [31–34]. In addition, several types of display devices, such as a digital micromirror device [31], a beam projector [33], and a liquid crystal display [32, 35], have been utilized to generate a dynamic image pattern for programmable manipulation of the electric field distribution.

The OET-based optoelectrofluidic platforms provide many advantages over the conventional methodologies based on optical and electrical mechanisms. Compared to optical manipulation technologies, the OET-based optoelectrofluidic technologies require much less optical power and offer much larger manipulation area. In addition, compared to conventional electrical methods, in which fixed electrode patterns are applied, reconfigurable virtual electrodes formed by an optical manner allow parallel manipulation of massive amount of particles at a specific region of interest in a wide area. Due to those advantages, the optoelectrofluidic platforms have been widely applied to manipulate several kinds of cells, including blood cells [35], motile bacteria [36], and oocytes [37], as well as nonbiological microparticles including polymeric microbeads [38].

Since the optoelectrofluidic devices are originally based on the electrokinetic phenomena under an electric field, which is induced or controlled by an optical source, the operating mechanisms for the manipulation are also the same with the conventional electrokinetic devices except for those electrokinetic driving forces are controlled in an optical way. Therefore, typical electrokinetic mechanisms, including electrophoresis, DEP, ACEO, and ET flows, have been usually applied to manipulate particles or fluids in the optoelectrofluidic devices. There are some helpful literatures, in which those physical phenomena in the optoelectrofluidic device are presented in detail [25, 39, 40]. In this paper, therefore, we focus on dealing with typical experimental studies for nanoparticle manipulation in optoelectrofluidic devices and the physical mechanisms utilized in those studies.

4. Optoelectrofluidic Manipulation of Nanoparticles

Some research groups have tried to manipulate several types of nanoscale objects from spherical nanoparticles to biological molecules using the optoelectrofluidic platforms. In this section, we will introduce typical experiments, in which various nanoobjects including nanospheres, nanowires, nanotubes, and biomolecules have been manipulated using several types of optoelectrofluidic platforms, with the physical mechanisms applied therein.

4.1. Nanospheres. There were a few studies, in which nanospheres were manipulated using an optoelectrofluidic platform. Due to the extremely small volume of nanospheres, relatively small electrode gap and high voltage are required for manipulating them only with the DEP force [41], $F_{\mathrm{DEP}} \propto r^3 \nabla |E|^2$, where r is the particle radius and E is the electric field, as overcoming the Brownian motion

related to the random force, $F_{\text{thermal}} \sim k_B T/2r$, where k_B is the Boltzmann constant and T is the temperature [42]. Therefore, spherical nanoparticles have been usually manipulated using the hydrodynamic drag forces, $F_{\text{drag}} = 6\pi r\eta(u - v)$, where η is the fluid viscosity, u is the flow velocity, and v is the particle velocity, by the optically induced electrohydrodynamic effects—ACEO and ET flows [43–45].

The optically induced ACEO is a fluidic motion generated by the ionic motion within the electric double-layer (EDL) along the tangential electric field, E_t, which is formed by partial illumination of the photoconductive layer [38]. The ACEO slip velocity, u_{slip}, which is the velocity at the top of the EDL, along the surface of the photoconductive layer is proportional to the charges contained in the EDL; the tangential electric field strength; and the Debye length, $\lambda_D \propto (c_0 Z^2)^{-1/2}$, where Z is the valance of the ions and c_0 is the concentration [46]. Chiou et al. [43] have demonstrated the concentration of 50 nm and 200 nm polystyrene nanoparticles and quantum dots using this ACEO in an OET device. When a light pattern was projected onto the photoconductive layer, the ACEO vortices were generated around the pattern and concentrated the nanospheres towards the pattern within several tens of seconds. They could determine the concentration of nanospheres through increase of the fluorescence intensity in the illuminated area as shown in Figure 2(a).

The optically induced ET effect, which is due to the thermal gradient in a fluid, has also been applied to concentrate and to pattern nanospheres. The thermal gradient, which can be generated by local illumination of a strong light source [26] or by Joule heating [39], induces a gradient in the fluid permittivity and conductivity, resulting in a fluidic motion under an electric field [47]. Williams et al. [44] have applied the ET vortices, which were created by IR-induced local heating of a fluid under an electric field, to concentrate and pattern 49 nm and 100 nm polystyrene nanoparticles. They also characterized those concentration phenomena against the applied AC frequency and voltage (Figure 2(b)). On the other hand, Jamshidi et al. [45] have concentrated and patterned metal nanoparticles using the ET vortices, which were induced by Joule heating in an OET device as shown in Figure 2(c). The Joule heating-based ET effect requires much weaker light source than that for sample heating-based ET effect and is dominant in the OET-based optoelectrofluidic platforms, in which virtual electrodes are formed by partial illumination of the photoconductive layer, because the heat is originally generated by an electrical source, not by an optical source.

4.2. Nanowires and Nanotubes. Nonspherical nanoparticles such as nanowires and nanotubes have also been manipulated on the basis of the optoelectrofluidic methods. In the case of nanowires or nanotubes, DEP force acting on them can be defined as $F_{\text{DEP}} \propto r^2 l\ \text{Re}[K]\nabla|E|^2$, where l is the length of nanowires or nanotubes and $\text{Re}[K]$ is the real part of the Clausius-Mossotti factor [41]. Thus, the DEP force acting on the nanowires or nanotubes can become much larger than that on spherical nanoparticles, which have the same r with the nanowires or nanotubes, depending on their length.

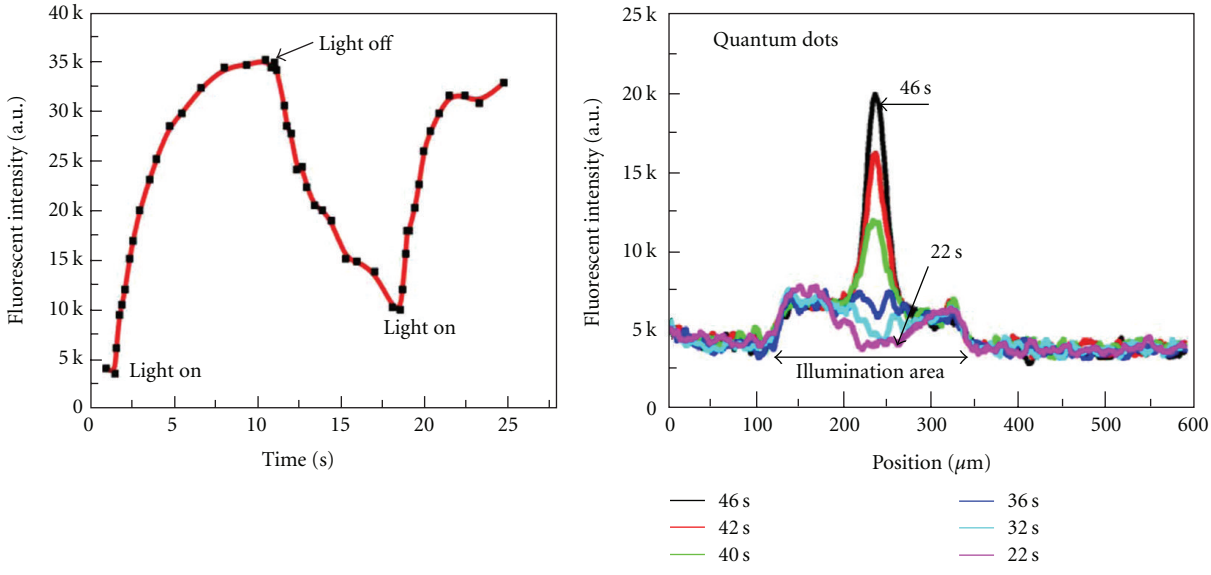
Jamshidi et al. [48] have utilized these characteristics of DEP for trapping and transporting silver nanowires (100 nm diameter and 5 μm length) with positive DEP force induced by a laser source in an OET device. The metal nanowires were much more polarizable than the surrounding media, thus the $\text{Re}[K]$ was larger than 1, resulting in the positive DEP, in which the particles move towards a light pattern where the electric field strength is larger than other area. They could also separate silver nanowires from silicon nanowires based on their different DEP mobility depending on the $\text{Re}[K]$ (Figure 3(a)). Based on the same principles, Pauzauskie et al. [49] have successfully addressed multiwalled CNTs with high translation velocity over 200 μm/s. They could also modulate the density of CNTs based on their repulsive interactions (Figure 3(b)). The repulsion among those concentrated CNTs might be due to the electrostatic interaction force which depends on the distances among the particles, the polarizability of the particles, the electric field, and the particle size [50]. Therefore, the density of nanoparticles within a specific area would also be controllable based on the intensity and the shape of an image pattern, which correlates with the strength and the direction of an electric field, respectively.

4.3. Molecules. Several types of optoelectrofluidic platforms and various mechanisms have been applied to manipulate biological molecules such as DNA and proteins [43, 51–54]. Here we will review them according to the underlying mechanisms for manipulation.

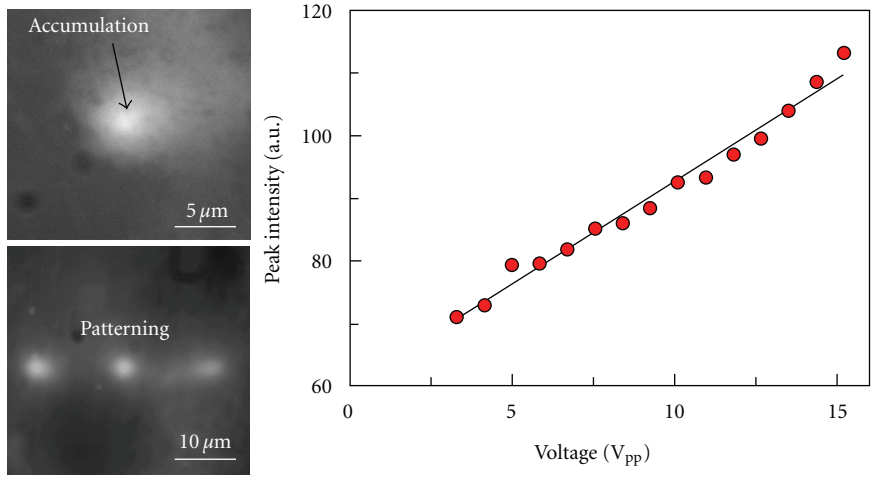
Most biomolecules are charged under a specific pH of the solution, thus the electrophoretic force acting on a charged objects in an electric field, which is defined by $F_{\text{EP}} = qE$, where q is the net charge of the particle, is very useful to manipulate them. The optoelectrofluidic devices, in which TiO_2 and Ge photoanodes were used as the photoconductive layer, have been applied for transport and separation of charged proteins such as bovine serum albumin (BSA) and cytochrome c under an optically modulated DC electric field within agarose gel (Figure 4(a)) [51]. They also applied this technique to separate DNA fragments based on their size—10 bp and 3000 bp [52]. It took relatively long time over several tens of minutes because they applied a gel system, which is much more viscous than a liquid system, resulting in much stronger drag force.

The optically induced DEP and ET flows in an OET device have also been applied to manipulate DNA molecules. Hoeb et al. [53] have tried to manipulate DNA with DEP induced by projecting a diode laser onto the a-Si : H layer. They could also observe some convection-like motions of DNA molecules due to the local heating of the sample fluids by a strong laser source. The moving characteristics of DNA molecules after correcting the motion by thermal flows were agreed well with the calculated DEP characteristics of DNA as shown in Figure 4(b).

DNA has been manipulated with the optically induced ACEO as well. Chiou et al. [43] could successfully concentrate λ-phage DNA with the light-induced ACEO vortices



(a)



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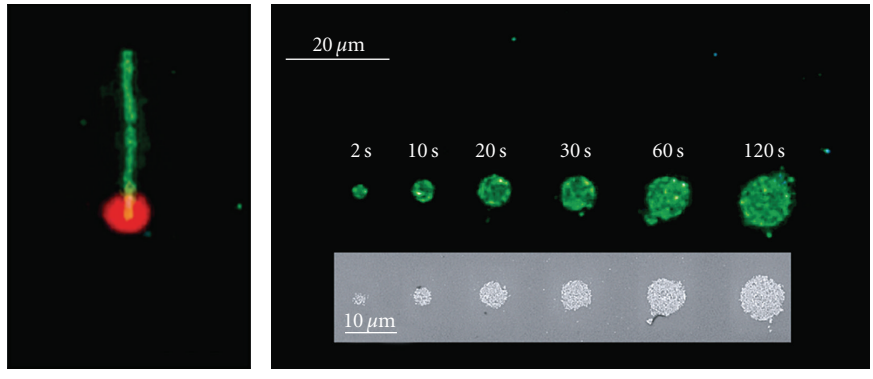

(c)

Figure 2: Optoelectrofluidic concentration and patterning of nanospheres. (a) Fluorescent polymeric nanoparticles and quantum dots using optically induced ACEO flows (adapted with permission from Chiou et al. [43] Copyright 2008 IEEE). (b) Voltage-dependent concentration of fluorescent polymeric nanoparticles using a laser-induced electrothermal (ET) effect (Williams et al. [44]—reproduced by permission of The Royal Society of Chemistry). (c) Dynamic concentration and patterning of metal nanoparticles using a Joule heating-induced ET effect and DEP-mediated immobilization (adapted with permission from Jamshidi et al. [45], Copyright 2009 American Chemical Society).

as like polymeric nanoparticles and quantum dots. Hwang and Park [54] have manipulated proteins such as BSA, polysaccharides such as dextran, and fluorescent dyes such as fluorecein and bisbenzimide using the same phenomena. They investigated the frequency-dependent concentration effect of those molecules depending on several electrokinetic mechanisms including DEP and electrostatic interactions as well as ACEO (Figure 4(c)). Moreover, they could control their local concentration in both temporal and spatial manner by controlling the applied AC signal and the light pattern.

Not only the OET devices, but also the optically induced ET effect in microelectrode system have also been applied for manipulating molecules. Mizuno et al. [26] have first demonstrated transport of DNA molecules by the ET flows induced by a laser spot focused in the middle of an AC electric field. Nakano et al. [55] have applied the laser-induced ET flows in a microelectrode system to trap and stretch long DNA molecules based on high-shear rate as shown in Figure 4(d).

5. Applications

Much research has been actively conducted on the optoelectrofluidic manipulation of nanoparticles over worldwide as mentioned above, but most of them have focused only on demonstrating the concentration and patterning of nanoparticles or molecules. Only a few practical applications, in which the optoelectrofluidic platforms provide their own advantages over other conventional tools for the same purposes, have been developed to date. Here we introduce some studies, in which potential applications of the optoelectrofluidic technologies for nanoparticle manipulation are shown, and discuss about the future directions of this technology for its more practical uses.

5.1. Separation of Nanoparticles. Purification of nanoparticles remains as one of significant challenging issues in the preparation of well-defined materials. For separating or purifying nanoobjects using the optoelectrofluidic phenomena, the separation criteria might be almost the same with that for conventional electrokinetic separation technologies—size, dielectric constant, or charge of the target particle. For example, size-based separation of synthesized metal nanoparticles [56, 57] or purification of single-walled CNTs from catalytic impurities [58, 59] would be possible based on the differences in their size or dielectric properties using the optoelectrofluidic mechanisms such as optically induced DEP. In practice, silver nanowires could be separated from semiconducting silicon nanowires based on their DEP characteristics in an optoelectrofluidic device (Figure 3(a)) [48]. This study is the first demonstration of optoelectrofluidic separation of nanowires. However, it might be more meaningful if one could apply this elegant scheme not only for simple demonstration to show what kind of particles they can move, but also for more practical uses. For example, separation of metallic single-walled CNTs from semiconducting CNTs would be more practical in the perspective of purification of CNTs prepared by a chemical vapor deposition method—it has been demonstrated using DEP in metal microelectrodes [12].

In addition, in the perspective of separation performances such as purity, recovery, resolution, and throughput, it is still questionable whether the optoelectrofluidic techniques are more practically useful or have better performances compared to conventional separation technologies. Even if continuous processing for injection of mixtures and recollection of the separated samples is available based on integrated microchannel structures [60], the reasons, why we should use the optically induced virtual electrodes, which requires the photoconductive layer in addition to an electrode, instead of just-patterned microelectrodes, might still remain as an unanswered question. On the same line with this, for practical uses of the optoelectrofluidic technologies for nanoparticle separation, fully integrated processing from sample preparation or separation to applications—assembly or detection—in a tiny volume of sample droplet without any fluidic components would be required.

5.2. Manufacturing of Nanostructures. For the application of optoelectrofluidic platforms in nanoscience except biology and chemistry, manufacturing or synthesis of nanostructures might be one of the most potential applications, in which they can be applied to practical uses, because most of the research in this field have focused on the concentration, alignment, assembly, or patterning of various nanoobjects. For example, dynamic manipulation of individual nanowires (Figure 3(a)) [48] and patterning of metal nanoparticles (Figure 2(c)) [45] based on optoelectrofluidics showed the potential of this technology on nanofabrication well.

Jamshidi et al. [45] have shown that a metal nanostructure patterned by the optoelectrofluidic concentration is applicable as a photonic nanostructure like surface-enhanced Raman scattering (SERS) substrate. However, compared to conventional techniques for manufacturing photonic structures, such as chemical self-assembly [61], electron beam lithography [62], focused ion beam milling [63], the optoelectrofluidic patterning of nanoparticles has still a lot of room for improvements in the view-points of reproducibility and tenability. In addition, such approaches to fabricate SERS-active substrates, in which metal nanoparticles were concentrated and patterned into a predefined area, could be achieved not only by the optoelectrofluidic methods but also by conventional electrokinetic methods based on prepatterned microelectrodes [64, 65]. To overcome those conventional technologies and to develop more practical tools based on the optoelectrofluidics, the own intrinsic advantages of the optoelectrofluidic platforms, in which dynamic control of virtual electrodes is available using a light pattern, could be applied. For example, the nanostructures, which are actively controllable using a light pattern, could be generated in a specific area of interest by projecting a light pattern into the desired area. Such an on-demand formation of nanostructures would be useful for constructing an active SERS platform for detecting chemicals with enhanced Raman scattering signals in a specific area of interest whenever we want. Recently, such an optoelectrofluidic-active

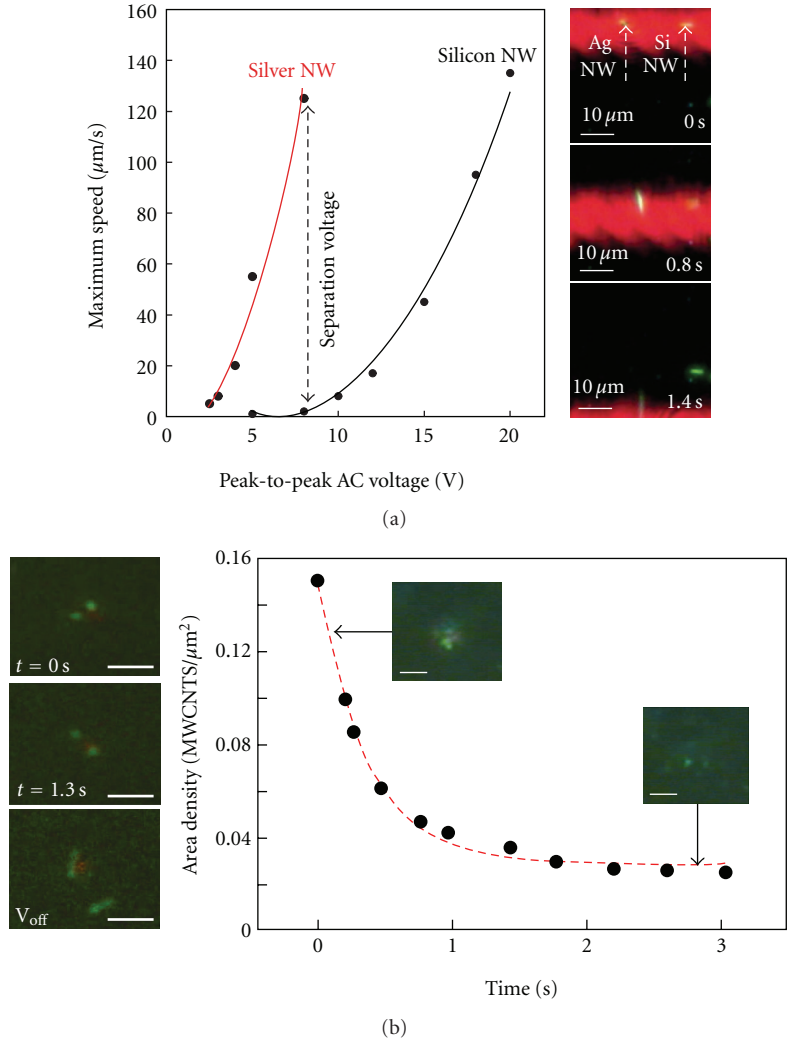

FIGURE 3: Optoelectrofluidic trapping and manipulation of nanowires and nanotubes. (a) Separation of metal nanowires from semiconducting nanowires based on their different dielectric characteristics (adapted by permission from Jamshidi et al. [48], Copyright Macmillan Publishers Ltd. 2008). (b) Trapping of carbon nanotubes using optically induced dielectrophoresis and their electrostatic repulsion (adapted with permission from Pauzauskie et al. [49], Copyright 2009, American Institute of Physics).

SERS platform has been reported [66]. In that study, active generation of SERS substrate by optoelectrofluidic concentration of gold nanoparticles into a specific area of interest and *in situ* measurement of SERS signals from small molecules around the area has been demonstrated as shown in Figure 5(a).

5.3. Molecular Physics. Hwang and Park [67] have developed a new system based on an optoelectrofluidic manipulation platform for measuring the mobility of molecules in a liquid solution (Figure 5(b)). They utilized the phenomena that the molecules were immediately depleted from the illuminated area in the application of extremely low AC frequency around 100 Hz. After turning off the voltage, the depleted molecules were diffused into the area, resulting in the recovery of the fluorescence signal. By measuring the recovery rate, the diffusion coefficient of molecules could be measured. Compared to the conventional techniques such as fluorescence recovery after photobleaching [68] or fluorescence correlation spectroscopy [69], this method does not require high-power lasers, high-speed camera, photobleaching of the sample, fluidic components, and complicated optical components. In addition, this technology provides wider operation range because the molecular depletion area can be controlled by adjusting the light pattern size. However, the optoelectrofluidic technique is not applicable for *in vivo* measurements and always requires an electrical source, which is not necessary for the conventional optical technologies.

Elongation of DNA molecules by the optically induced ET vortices has also been demonstrated by Nakano et al. [55] in 2006. They trapped λ- and T4-phage DNA molecules within the ET vortices induced by a laser spot focused into an AC electric field and observed their coil-stretching transitions by strong shear flows (Figure 4(d)). They could

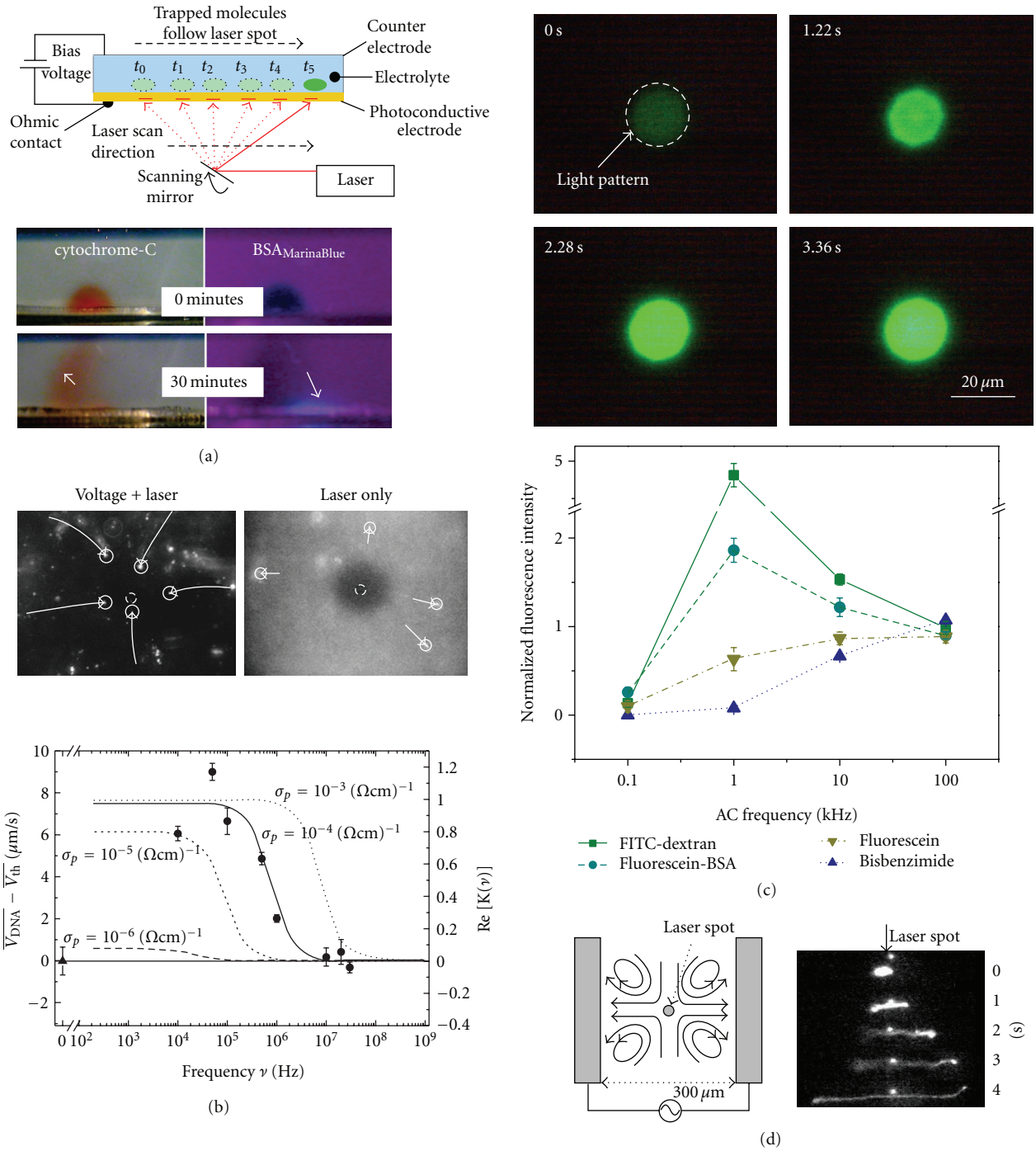

Figure 4: Optoelectrofluidic manipulation of biomolecules. (a) Electrophoretic separation of proteins based on optically modulated DC electric field (adapted by permission from Hafeman et al. [51], Copyright 2006 National Academy of Sciences, USA). (b) Concentration of DNA molecules using optically induced dielectrophoresis (DEP) and quantification of their DEP mobility (adapted from Hoeb et al. [53], Copyright 2007, with permission from Elsevier). (c) Dynamic control of local concentration of proteins, polysaccharides, and fluorescent dyes using optically induced ACEO vortices and their characteristics depending on the applied AC voltage and frequency (adapted with permission from Hwang and Park [54], Copyright 2009 American Chemical Society). (d) Trapping and stretching of long DNA molecule using ET flows induced by a laser source focused into an AC electric field (adapted with permission from Nakano et al. [55], Copyright 2006, American Institute of Physics).

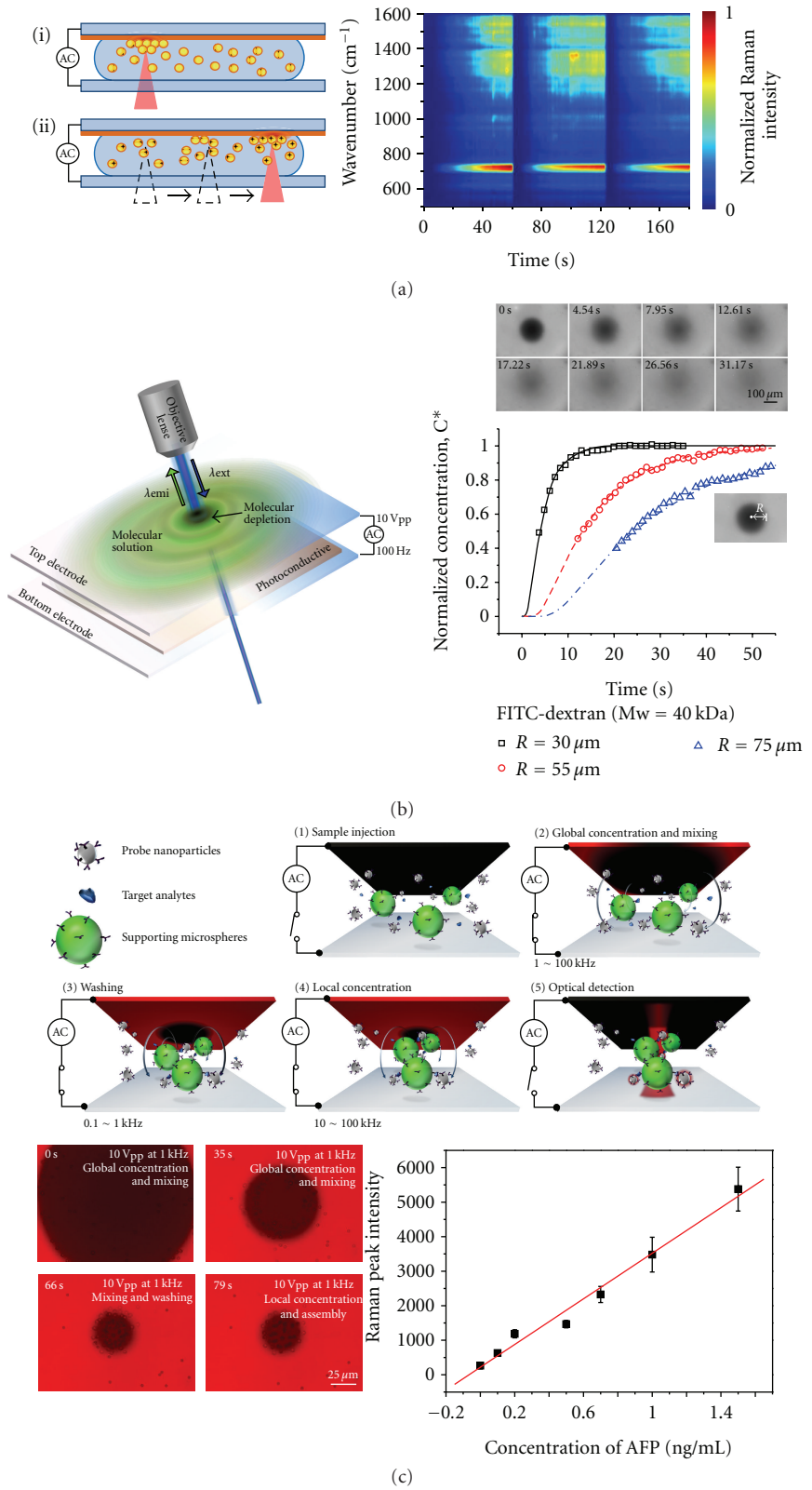

Figure 5: Optoelectrofluidic tools for biological and chemical applications. (a) Active surface-enhanced Raman scattering (SERS) substrate for *in situ* detection of molecules in a specific area at a specific time of interest (Hwang et al. [66]—reproduced by permission of The Royal Society of Chemistry). (b) Measurement of molecular diffusion coefficient by analyzing recovery rate after optoelectrofluidic molecular depletion from the illuminated area at a low AC frequency condition (adapted with permission from Hwang and Park [67], Copyright 2009 American Chemical Society). (c) Sandwich immunoassays driven by a dynamic image pattern and optoelectrofluidic mechanisms for detection of human tumor marker using SERS probe nanoparticles (adapted with permission from Hwang et al. [76], Copyright 2010 American Chemical Society).

also adjust the flow velocity by controlling the laser power. The higher laser power was applied, the faster ET flows occurred, resulting in longer extended length of DNA.

In spite of these studies, the area of molecular physics, which can be studied with the direct manipulation of molecules, is restricted. Thus, many people applied some supporting substrates such as polymeric microbeads capturing the target molecules to make it easier or possible to accurately manipulate molecules and measure their physical properties using the manipulation tools. Although we did not review those cases, various manipulation tools such as optical tweezers [70, 71], magnetic tweezers [72], and atomic force microscopy [73] have been applied for those purposes [74]. Molecular manipulation through the indirect manipulation of a supporting microbead, on which DNA molecules were attached, has also been demonstrated in an optoelectrofluidic device. They could stretch DNA molecules by moving the supporting microbeads based on the optically induced DEP [75]. This method showed the potential of optoelectrofluidic technologies as a single molecule force spectroscopy, but quantification of the force acting on those molecules might be much more difficult than other technologies, in which only one kind of forces works on deforming the molecules, differently from the optoelectrofluidic devices wherein various AC electrokinetic mechanisms such as DEP, ACEO, ET flows, and electrostatic forces simultaneously exist. In addition, the limitation of the optoelectrofluidic platforms that the driving forces are dependent on the electrical properties of the sample fluid also interferes with the flexible application of those platforms to the studies using chemical and biological samples, of which properties are also sensitive to the buffer conditions.

5.4. Immunoassays. The first optoelectrofluidic tool for clinical diagnostics has been recently developed by Hwang et al. [76]. They demonstrated sandwich immunoassays for detection of human tumor marker using an optoelectrofluidic platform (Figure 5(c)). They could simultaneously control the motions of the probe nanoparticles and the supporting microbeads as well as the target molecules based on their frequency-dependent optoelectrofluidic behaviors. All the steps for sandwich immunoassay, including mixing, washing, and detection, were automatically conducted in an OET-based optoelectrofluidic device with various electrokinetic mechanisms such as DEP and ACEO, which were controlled by a dynamic light pattern generated from an LCD and by the applied AC signals. Simple and quantitative SERS-based immunoassay of human tumor marker, alpha-fetoprotein, with lower detection limit of about 0.1 ng/mL has been possible in a ~500 nL total sample droplet within 5 min. Compared to the conventional microfluidic devices for immunoassays [77, 78], this optoelectrofluidic platform does not require any fluidic components and spends less dead volumes and disposables. They also showed the simultaneous control of multiple assays using a programmed LCD image. However, as like the molecular studies based on the optoelectrofluidic devices, the conductivity of physiological samples significantly affects the manipulation performance of the optoelectrofluidic devices. For the direct analysis of salty solutions such as blood plasma, therefore, an optoelectrofluidic device with much higher photoconductivity is necessary. However, the devices developed to date such as a phototransistor-based OET device [79] are so complicated and require high costs and long time for the fabrication. Therefore, more research for developing the optoelectrofluidic devices which can be operated even under physiological conditions should be promoted. More studies on the interactions of proteins or nanoparticles under an electric field as well as the development of stable nanoprobes should be accomplished to increase the sensitivity of the optoelectrofluidic immunoassays.

6. Conclusions

In this paper, we reviewed recent progress in optoelectrofluidics for nanoparticle manipulation and discussed future challenges for development of practical applications. Some typical experiments for manipulation of nanoparticles—nanospheres, nanowires, nanotubes, and biomolecules—using various optoelectrofluidic mechanisms such as electrophoresis, DEP, ACEO, and ET flows induced in an optical manner were introduced. In addition, potential applications of the optoelectrofluidic nanoparticle manipulation such as separation of nanoparticles, manufacturing of nanostructures, molecular physics, and immunoassays were suggested and their future directions for overcoming the current challenging issues were discussed.

There were a lot of advances in this optoelectrofluidic field especially during a few past years. Several types of optoelectrofluidic devices from the optically induced ET systems, which were constructed with simple plate electrodes and a strong laser source, to the OET devices based on a photoconductive layer and a display device have been developed and applied for manipulation of various target particles from polymeric microbeads and nanoparticles to cells and biomolecules. Various physical mechanisms have also been investigated including electrostatic particle-particle interactions and surface-particle interactions as well as electrokinetic mechanisms such as electrophoresis, DEP, ACEO, and ET flows. This optoelectrofluidics, which is the combination of optics, electrokinetics, and fluidics, might be one of the most powerful tools for noncontact manipulation of nano- and microparticles and would provide valuable capabilities for creating novel applications and extraordinary advances in nanoscience and nanotechnology.

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