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Trapping, sorting and transferring of micro-particles and live cells using electric current-induced thermal tweezers

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ABSTRACT

We demonstrate the manipulation of micro-sized particles in water using Joule heating induced temperature gradient. Using simple sputter deposition and photolithography, we have fabricated disparate gold micro-structures on silica glass. Electric current crowding at narrow channels results in temperature gradients that can be readily controlled by varying the electric power input. This also, in turn, leads to a tunable balance between forces due to convective flow and thermophoresis in the surrounding aqueous medium. The net force can actually be used for trapping target objects. We have used the device to perform sorting, trapping and transferring of polystyrene sphere (PS) and live cells. The reported method offers a new approach for photon-free particle manipulation, while also holds promise for direct integration with lab-on-chip devices.

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1. Introduction

Manipulation of cells and particles in microfluidic systems is attracting considerable research interest due to the rapid growth of microfluidic techniques [1]. Several major approaches have been reported, which are based on the use of hydrodynamic fields [2,3], magnetic elements [4,5], ultrasonic standing waves [6,7] and dielectrophoretic forces [8,9]. As a contact-free approach, optical tweezers are also capable of trapping microscopic particles using a highly focused laser beam. The so-called optical tweezer traps a target by exerting gradient and scattering forces through the transfer of momentum as photons undergo refraction. This manipulation tool is now widely used in the field of biology [10], physical chemistry [11] and lab-on-a-chip [12].

Recent development based on plasmonic structures, including nano-disc [13], bowtie nano-antenna arrays (BNAs) [14], random nano-island [15] and gold nanopyramidal-dimer arrays [16], has increased the scope of applications for optical tweezers because of much-improved trapping performance. These metallic nanostructures exploit surface plasmon resonance (SPR) to condense the incident light into a hot spot. By increasing the depth of trapping potential, plasmonic structures can break the diffraction limit and trap nano-objects in the near field. Moreover, opto-thermal effects, which use focused light as a heating source, have also received increasing attention. One typical method is to manipulate optothermally generated bubbles on a strong laser-absorption metal to realize microfluidic control [17], stretching of single DNA [18] and microscale assembly [19]. Dynamic temperature gradient caused by opto-thermal effects in the fluid is also an interesting topic because it may result in particle motion along this gradient, a phenomenon named as thermophoresis. It is now widely accepted that particle-solvent interaction plays a crucial role in determining thermophoretic mobility. Meanwhile, the effect of molecular weight [20,21], particle size [22,23,24], temperature [22,24,25], pH value [26], non-ionic contribution [27], colloidal attraction [28] and other parameters are being explored. Taking the advantage of different particle/solvent interactions, thermophoresis may offer possibilities for diverse applications, such as particle separation [29,30], trapping [31], migration [32], DNA detection [33] and even single nano-objects manipulation [34,35].

Apart from laser heating, the resistive heater is also a good choice to generate temperature gradient. Since no photons are needed, it is possible to perform particle manipulation directly on an opaque substrate such as silicon wafer. This also enables full incorporation with microelectronic devices. In our previous work, we fabricated a micro-scale electric thermal heater (METH) at the center of a gold thin film using femtosecond laser writing [36]. When a voltage is applied across the structure, the temperature within the micro-scale metal strip rises, which then leads to the formation of a photon-free trap. Here, we report the use of a photolithography approach to fabricate an array of METHS for conducting 2-dimensional manipulation of target objects. By

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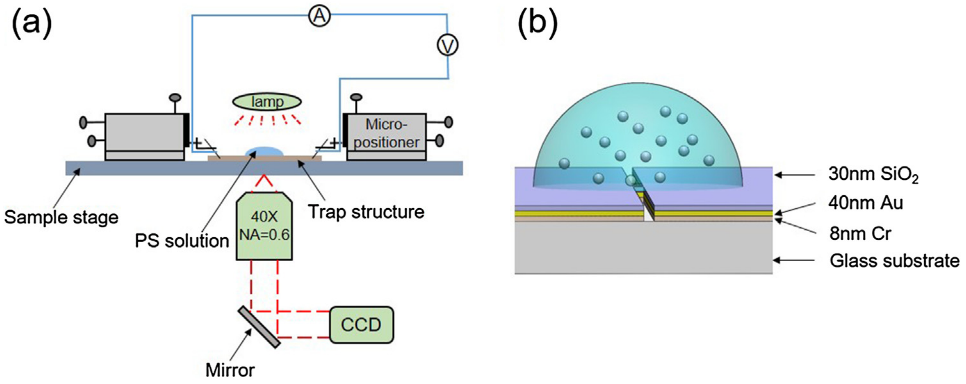

Fig. 1. Schematic of the experimental setup and the METH structure.

sequentially controlling the current through various METH devices, we have achieved a range of manipulation events on the target particles including trapping, separation, and transfer. Also, it is feasible to manipulate live cells such as *E. coli* using our structures. These simple micro heaters have led to new opportunities for the lab-on-chip device platform.

2. Material and methods

2.1. Device fabrication

To fabricate the METH arrays, microscope slides (Thermo Scientific, No. 10144633B) were cut to 25 × 25 mm^2 in size for the substrate. After ultrasonic cleaning with acetone, isopropanol, and DI water, the substrate was placed in a plasma cleaner (Oxford Inc.) to ensure that the surface was free from contaminants. This was followed by a standard photolithography process to print device patterns on the photoresist coated substrate. As depicted in 0b, the device structure was a tri-layer stack containing Cr, Au, and SiO_2. A sputter coating system (Anatech USA) was used for preparing the layers. The bottom adhesion layer was 8-nm thick Cr, while the active heating layer was 40-nm Au and the electrical isolation layer was 30-nm SiO_2. The metal and dielectric layers were deposited using DC mode and RF sputtering respectively. After completion of the material deposition, the sample was taken out of the chamber and immersed in acetone for around 5 min to remove organic contaminants. Then the sample was rinsed and blow dried, and followed by 3 min on a hotplate to remove moisture.

2.2. Experiment setup

Fig. 1a shows a schematic of our experimental setup. Two needle tips manipulated by micro-positioners (ESCITEC Ins.) serve as electrical contacts for launching the required current for driving the METH devices. As depicted in Fig. 1b, we fabricated a narrow constriction within the layer stack to induce local heating through Ohmic effect. The temperature field surrounding the resistive heater then led to the formation of thermophoretic forces for trapping particles or live cells. All optical images were captured with a CCD camera (QImaging) and a × 40 objective lens with NA = 0.6.

2.3. Manipulation of colloidal particles

2.3.1. Formation of multiple trapping sites

To test the trapping capability of our resistive thermal heaters, we fabricated a series of structures including narrow slit, annular ring, and long wire bridge. They were all shown to be capable of trapping 1.5-μm polystyrene spheres (PS), as shown in Fig. 2. In the case of a narrow slit (Fig. 2a), as we gradually increased the current to 8 mA, particles from the surrounding region were drawn towards the center because of convection flow induced by the hot zone. When they arrived at the slit, thermophoretic forces associated with the temperature gradient resulted in the accumulation of particles at the center. Around ten minutes later, the aggregated particles formed a steady round-shaped cluster of 20 μm in diameter. Upon switching off the electrical power, the trapped particles dispersed back to the surrounding solution within a few minutes. For long heating elements, the cluster of trapped particles conformed to the narrow shape of the device. This result suggests the possibility of forming a long chain of particles along a narrow heating element.

2.3.2. Single particle trapping

As shown in Fig. 3, we used a short heater element to first generate convection to bring a single PS particle of 3 μm in diameter to the device. The final trapping force to keep the single particle in place was generated from thermophoretic effect. The current used in the experiment was 10 mA. With the use of an image process software [37], the trajectory of the single particle is also shown in Fig. 3. At the start, the device took approximately 0.2 s for the center temperature to increase to a sufficient level. Particles randomly moving in the vicinity started to “feel” the convective flow and began to move in. The average velocity was 0.64 μm/s for 3-μm PS particles. It should be mentioned that our experiments also confirmed that the device possesses the capacity to trap single particles with diameters ranging from 1.5 to 20 μm under appropriate drive current level. Due to the low concentration, it usually takes several minutes to attract the single particle to the capture area. To increase the trapping efficiency, first, a higher current 16 mA is needed to generate a stronger horizontal convective flow to drag the particle to the center. Then a lower current 10 mA is needed for the particle immobilization at the target spot, which means the current should be more precisely controlled, compared with the massive trapping.

2.3.3. Particle sorting

Our experiments also revealed an interesting phenomenon in which particles of different sizes require different drive current levels for optimal trapping to take place. In other words, for a given drive current, only particles of a certain size will be trapped, while other sizes will be pushed away by convective flow surrounding the structure. This suggests the possibility of achieving particle sorting according to size. The mechanism is related to the influence of particle size on the thermophoretic force, convective drag force, and the sedimentation effect if it is comparable with the former two forces. From Stokes law, we know the drag force is linear to particle radius while for thermophoretic force, both linear and non-linear rela-

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