MICROMACHINED LINEAR BROWNIAN MOTOR: NET-UNIDIRECTIONAL TRANSPORT OF NANOBEADS BY TAMED BROWNIAN MOTION WITH ELECTROSTATIC RECTIFICATION

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ABSTRACT

This paper reports for the first time on net-unidirectional transport of nanobeads by Brownian motion using a periodic 3-phase electrostatic rectification. The transportation of beads is performed in 1 µm deep, 2 or 3 µm wide PDMS microchannels, which constrain three dimensional random motion of nanobeads into 1D fluctuation, so-called tamed Brownian motion. 3 µm wide and 2µm separated ITO electrodes are fabricated by lift-off process on a 24x36 mm^2 coverglass, and a previously fabricated PDMS sheet with microchannels and processed for inlets is aligned and sealed with the electrodes. Diluted fluorescent nanobead, 500 nm in diameter, solution is introduced and equilibrium of the flow is awaited. Electrostatic rectification observations are performed by an inverted microscope. Rectified net-unidirectional transport of nanobeads is achieved at 200 mVpp and 400 mVpp at 1 MHz. 2 different beads are transported along the channel over 20 and 10 µm, respectively, in about 100 seconds, while other bead just wandered around in the same microchannel.

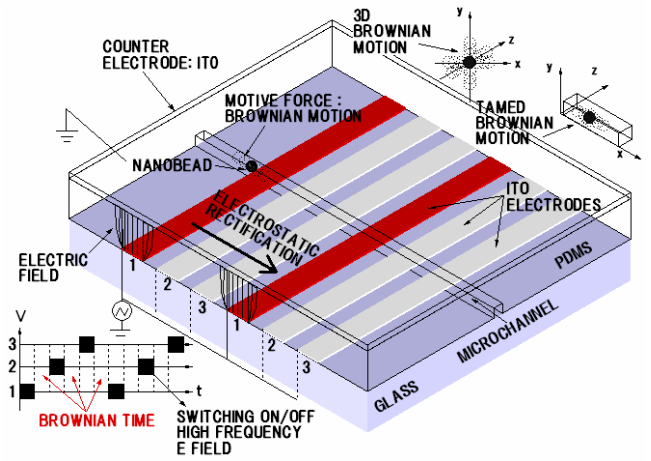

Figure 1. Micromachined linear Brownian motor. 3D Brownian motion is tamed in microchannel and turned into 1D motion. 3-phase electrostatic field rectifies this random motion. (E-field is shown on the left side only. PDMS and glass are not to scale. Electrodes are 3 µm wide and separations are 2 µm.)

1. INTRODUCTION

Brownian motion, the random motion due to thermal fluctuations in liquids, is one of the dominating phenomena in nano-environment and therefore an attractive motive force for driving the actuation of nano-objects [1, 2]. Its inverse relationship with size facilitates the transport of nano-particles in nano-domain. This work, inspired by biomolecular motors that exploit Brownian motion to obtain net movement [3], aims to develop a device called a linear Brownian motor, which harvests random thermal fluctuations to fuel the linear transport of nanoscopic particles with the help of micromachined electrodes providing 3-phase rectification in PDMS microchannels. Devices producing net-unidirectional motion from Brownian motion are known as Brownian Ratchets or Motors [1, 4].

Our device employs a microchannel to tame, i.e. to limit the 3D random motion of nanobeads into 1D motion and 3-phase electrodes to rectify the motion (Fig. 1). The electrodes are 3 µm in width and equally spaced such that they have a 2 µm separation from each other. During the rectification, the electrostatic trapping force is kept small enough to prevent attraction of the bead directly from the adjacent inactive electrodes, but sufficient to counteract the Brownian force on the active electrode. Therefore, a bead travels from one electrode to the next by Brownian motion only. With the rectification in one direction, the probability that the bead moves in that direction becomes higher than the opposite one.

2. PRINCIPLE

The working principle of the Brownian motor is given in Fig. 2. A bead is initially trapped on an electrode (a-b). By switching off the voltage, the bead starts Brownian motion and the probability density function becomes wider (c). Then, the electrodes of the next phase are energized. When the bead happens to come to the active electrode, it is trapped on that electrode. The density function will be like the one shown in (d). By continuing this procedure, the probability of the transportation to the right will be higher than to the left. Since the applied voltage is lower than the

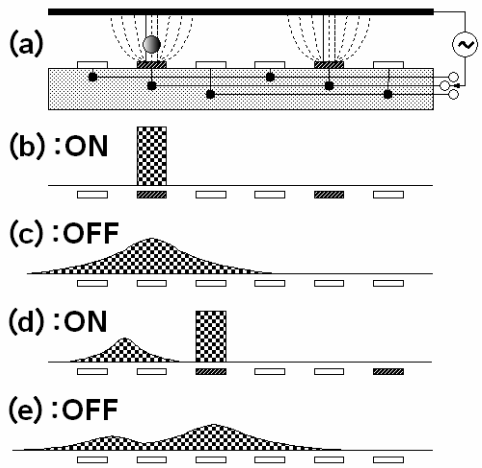

Figure 2. Principle of Brownian motor. 3-phase electrostatic rectification of Brownian motion provides net-motion. (a-b) Trapping of the bead. (c) Probability distribution. (d) Next phase and trapping. (e) Next probability distribution.

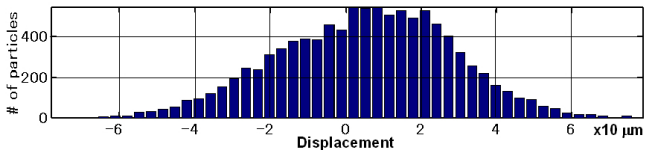

Figure 3. MATLAB simulation results. Shift of the distribution to the right is clear. The distribution is shown after 4 minutes where Brownian time; diffusion time, intervals are 2 seconds. 10.000 particles are injected at "0" position. Particles with inverse motion are a natural phenomenon of the Brownian motor (Diameter of the particle is 500 nm.)

one needed for a pure electrostatic transportation, the energy from Brownian motion is cleverly utilized.

MATLAB™ simulations show the possibility of the net-unidirectional motion supporting our concept of the motor (Fig. 3). 10.000 spherical particles with a diameter of 500 nm, which corresponds to the probability distribution, are simulated at room temperature. In the simulation, electrodes are assumed infinitely narrow and designed be to centered perfectly at -2, 0, 2,…, 26, 28, 30 µm. Brownian time or diffusion time and excitation time are set to 2 seconds. The simulation time is fixed to 4 minutes which means 60 on/off cycles. The particles are injected at "0" position. The mean of the distribution moves in the excitation direction, i.e. to the right, with each cycle. But some particles drift to the left, which shows the random nature of the Brownian motor.

3. FABRICATION

Our experimental device consists of a cover glass with lifted-off ITO electrodes aligned by a PDMS sheet. Electrodes in the design are 3 µm in width and separated by 2 µm. For the electrode fabrication, we selected the photoresist, S1818, due to its relatively high thickness, ~2 µm by spin-coated at 3000 rpm for 30 seconds, for enhancing the lift-off process. It is possible to fabricate the electrodes with a negative photoresist such as ZPN1150-90. S1818 was patterned and postbaked to withstand the following BHF processing step. The glass was etched isotropically by BHF for 30 seconds and 100 nm ITO was sputtered. The sample was lifted-off in acetone, and rinsed successively by ethanol and DI water.

PDMS microchannels were prepared from a Si mold whose surface was preprocessed by CHF_3 in a RIE system (Samco, RIE-10NR) to enhance the peeling off of PDMS. Mixture was prepared from silicone elastomer:curing agent:magic solution (FZ-77) (500:50:1, Dow Corning). PDMS is hydrophobic; hence we included magic solution to make it hydrophilic to carry the bead solution spontaneously. After mixing, it was degassed, and poured onto Si mold, and spin coated (300 rpm-60 sec, 3000 rpm-2 sec [To get rid off excess amounts]). Following this, the sample was cured at 110 °C on a hot plate. The thickness around the channels was measured as 93±2 µm. PDMS was peeled off, inlet and outlet were opened and the alignment of the channels with the electrodes were performed by a mask aligner (Union Aligner). The channels are 1 µm deep (bead diameter: 500 nm) and 2 or 3 µm wide (Fig. 4).

4. EXPERIMENTS AND DISCUSSIONS

Experiments are observed by an inverted microscope (Olympus IX71). The aligned sample is fixed onto a pinch board whose center is holed for the objective of the microscope. The sample is fixed onto the stage of the microscope and electrical connections are provided. An IC circuit which consists of an 8-bit analog/digital multiplexer

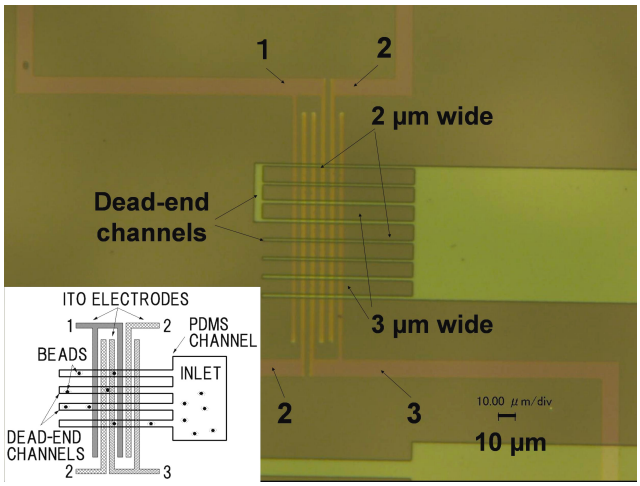

Figure 4. Keyence digital microscope image (VHX-500). The 3-phase electrodes are aligned with the dead-end PDMS microchannels. Depth is 1 µm. (Left-bottom is the schematic.)

fed by 1 MHz excitation source, a counter connected to the selection input of the multiplexer to switch the electrodes phase excitation and an AND gate to reset the counter for cycling. The phases 1, 2 and 3 are taken from 0^{th}, 2^{nd}, 4^{th} outputs respectively, and 1^{st}, 3^{rd}, 5^{th} outputs are kept for Brownian time for the particles to experience the random motion. LEDs are used at the outputs of the multiplexer to synchronize the system with the recording apparatus (Sony DVD recorder, RDR-HX10).

Diluted fluorescent nanobead solution (Fluoresbrite plain microspheres, 2.5% solid latex, 0.5 µm, YG, Polysciences Inc., 1:800-Original:DIW) with water was injected into inlet, after it had reached to the microchannels. The second injection was done from the outlet, and then it was left until stabilization had achieved. The counter ITO electrode consisting of the coverglass whose both sides are sputter-coated by ITO with a resistance around a few kilo-ohms was placed on the PDMS sheet. 1D random motion of the beads is confirmed by the optical microscope.

The system is operated and recorded with a speed of 30 frames/second. The recorded video is converted into DVD and then into mpeg format. For the tracking analysis software, Cosmos, we converted the mpeg format into avi format by Acrobat Premiere which is the only format recognized by the analyzing software. Optical pictures are captured from the mpeg images using Acrobat Premiere. Figure 5 shows the rectified transportation of nanobead A (Fig. 7) where nanobead B wanders around. The excitation of the electrodes are performed from the closed end to the open end to eliminate any suspicion related to the micro/nano flows that could be caused by inlets or water level differences between inlet and outlet. The depth of the channels is 1 µm, double of the diameter of the beads. The widths are 2 and 3 µm, due to photolithography limits, which provides 1D random motion to some extent.

A nanobead with a diameter of 500 nm in DIW at room temperature has a diffusion constant of 0.987 $\mu m^2/s$ and a root-mean-square displacement of 2.8 µm in 4 seconds. This shows that 4 seconds are sufficient time for the nanobeads to experience Brownian motion and to diffuse from one electrode to another in this Brownian time interval of the linear Brownian motor (Fig. 6).

The displacement with time is given in Fig. 7. Electrode pairs of one phase are switched on and off for 4 seconds successively and they are overmapped onto the displacement characteristic to simplify the visualization of the motion of the beads on or near to the electrodes. The rectification is towards the open end to eliminate any suspicion of bias due to fluid flow. The nanobeads, *A* and *C*, move to the rectification direction with occasional reverse motions showing the random nature of Brownian motor. The applied voltage between the electrodes and the counter electrode is 200 and 400 mV_{pp} at 1 MHz (Fig. 1). We applied voltage at high frequency because; liquid flow by AC electro-osmosis disturbed the experiment at low frequency [5]. Furthermore, the motion of the beads due to fluid flow was clear at high voltages such as 10Vpp at the high frequency. We decreased the voltages between 1 Vpp to 0.2 Vpp. Tracking analyses around 1Vpp has shown abrupt displacements of the beads which reinforce the existence of the electrostatic attraction and/or fluid flow due to AC electro-osmosis.

At voltages lower than 1Vpp, the electrostatic field is effective in the vicinity of the electrodes which show dielectrophoretic effects due to fringing fields. While the motion of bead *A* is rectified, *B* wanders around. This is a further evidence for the absence of micro-nano flows. Furthermore, this supports that the motion of *A* is not a linear motion due to electrostatic forces and it is an electrostatically rectified Brownian motion in unidirection. From the graph we can say that, nanobead A and C are transported over 20 µm and 10 µm, respectively, approximately in 100 seconds.

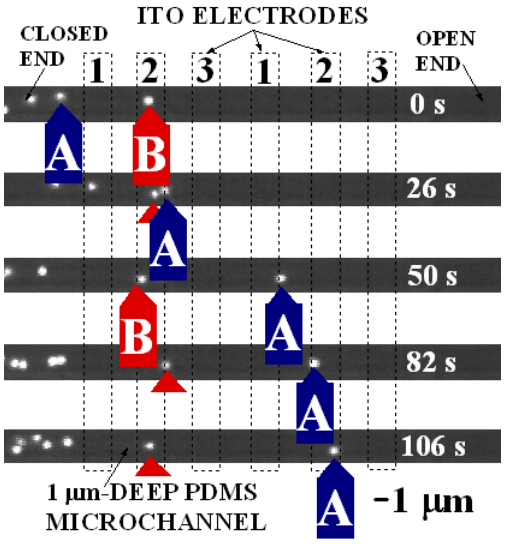

Figure 5. Optical captures of net-unidirectional motion of nanobead A (Fig. 7) in a 1 µm deep channel. Rectification is to the right. Diameter is 500 nm.

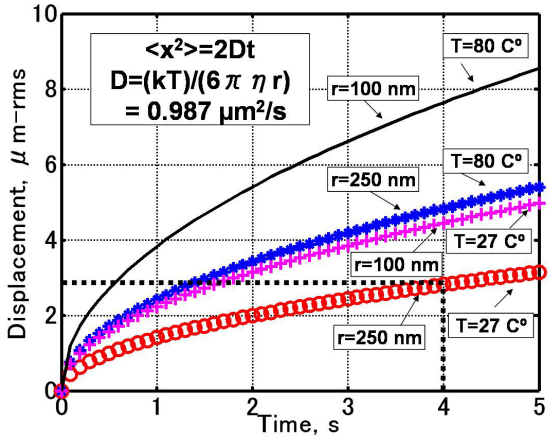

Figure 6. Theoretical 1D displacement due to Brownian motion. r and k stand for the radius of the bead and the Boltzman constant, respectively.

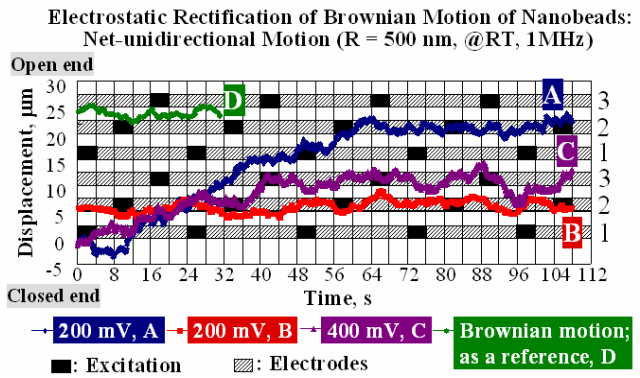

Figure 7. Rectified Brownian motion of nanobeads and net-unidirectional motion to the open end. Inverse motion is possible in Brownian motor due to random nature of the motion. (200-400 mVpp-1 MHz, square wave, R stands for the diameter of the beads).

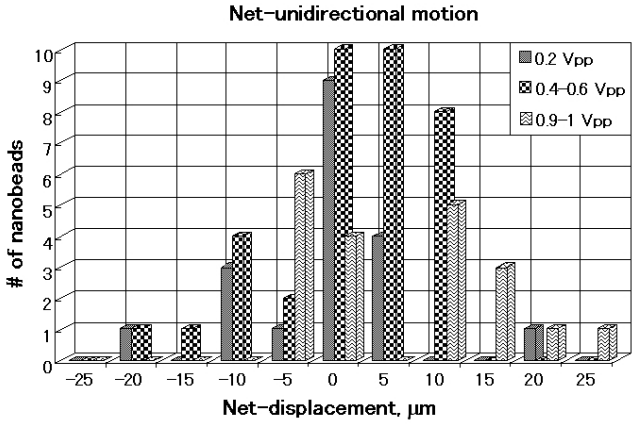

Figure 8. Net-unidirectional motion of beads in 100 seconds at different excitation voltages. Displacements are rounded to the nearest integer multiples of 5. (Net-displacement is the distance from final position to initial position)

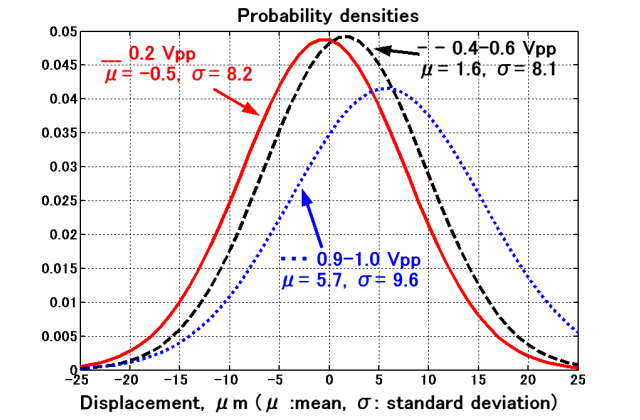

Figure 9. Shift of the probability densities with the excitation voltage in 100 seconds. As voltage increases, distribution shifts to the rectification direction, i.e. to the right.

We have been working on larger number of particles to investigate the net-displacements of the nanobeads at different voltage levels. Videos are divided into 100 seconds, and the distance from final position to the initial position of the beads (net-displacements) are determined (Fig 8). The mean value and standard deviation were calculated for each distribution. Figure 9 represents normal distributions for the set of those associated with each voltage level. The probability densities shift to the rectification direction with increasing voltage. The rectification around 0.2 Vpp seems weak, even though we achieved the rectification (Nanobead A, Fig. 7). It is good around 0.5 Vpp where we can call as Brownian motor region. The right-hand side shift is clearly seen around 1Vpp. We might say that it is partly caused by electrostatic actuation. Those data show the existence of an operation region for the Brownian motor as expected. The system can be characterized by investigating the effects of temperature, viscosity, the size of the bead, the separation between the electrodes which is necessary for the beads to diffuse and the diffusion time or Brownian time. We have been working on the distribution characteristics of the net-transport of the beads by changing Brownian time and the separation of the electrodes, which are easy to manipulate.

5. CONCLUSIONS

We have achieved the exploitation of Brownian motion of nanobeads, similar to biomolecular motors, to fuel the transportation. This may lead to a new field for the nano-manipulation in the engineering world. To reinforce such exploitation, we are currently collecting statistical data on the motion of larger numbers of particles at specific voltage, which will be compared with our models. Furthermore, our studies have been continuing to implement the rotary counterpart of this linear model.

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