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ROTATIONAL BROWNIAN MOTION OF MAGNETICALLY CLAMPED SILICON NANONEEDLE: TOWARDS NANO-MOTORS FUELED BY BROWNIAN MOTION

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Abstract: This paper presents the rotation of a silicon nanoneedle fueled by Brownian motion which may lead to a new class of thermo-mechanical nano-motors. A nanoneedle with a magnetic bead at one end is immobilized at the end by a permanent magnet in the water and its rotational Brownian motion is observed. DRIE of a silicon substrate with magnetic nanobeads as the etching mask results in 3.5 μm long needles with aspect ratios close to 10. They are ultrasonicated and centrifuged to obtain needle suspension. The suspension is introduced onto the magnet and sealed by a cover glass. A magnetic field clamps the needle at the magnetic bead end to constrain 3D random motion into the observation plane. Similar to biomolecular motors, Brownian motion is exploited to rotate the needle at the free end.

Keywords: Brownian motion, magnetic beads, nanosphere lithography, nano-motor, rotation.

1. INTRODUCTION

Brownian motion is the random movement of microscopic particles due to thermal fluctuations. It is one of the dominating phenomena in nano-environment [1] and therefore an attractive motive force for driving nano-objects. This work, inspired by molecular motors that exploit Brownian motion to obtain net-movement or rotation [2], aims to develop a rotary Brownian motor, which harvests random thermal fluctuations to fuel the rotation of nanoscopic particles. Our main objective is to exploit this phenomenon to manipulate micro- and nanostructures. Exploiting Brownian motion requires micro-nano particles. To clearly observe rotation, slender particles such as nanoneedles are preferred to spherical beads.

We previously showed that a silicon nanoneedle encapsulated properly in a disk-shaped PDMS chamber (Fig. 1) experiences rotational Brownian motion [3] shown in Fig. 2. The chamber is used to limit the degree of freedom of the Brownian motion only to rotation and to suppress the motion in vertical and translational directions.

In this paper, we present an alternative way to restrict the rotational Brownian motion of a nanoneedle. We attached a magnetic bead to one end of the needle and applied magnetic field into the observation plane. The magnetic field trapped the needle at the end with the magnetic bead. The needle rotated randomly around the trapped end because of the Brownian motion of the other end. To obtain a net-rotation out of the random rotation, however, requires a rectification process not to violate the thermodynamics. If we accomplish this in the future, we can build nano-motors with superior performances in micro-nano scales.

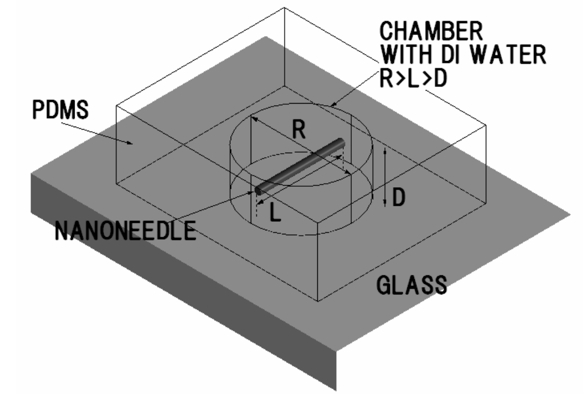

Figure 1. Encapsulation of silicon nanoneedle. (Chamber diameter > Nanoneedle length > Depth of the microchamber.)

2. FABRICATION

In order to fabricate a nanoneedle with a magnetic bead at one end of the needle, we used nanosphere lithography (Fig. 3). Magnetic nanobeads (Bangs Labs., Inc.) were used as mask to fabricate silicon nanoneedles [3, 5]. Nanobead suspension was spun on the wafer (Fig 3.1) followed by Deep RIE of Si. (Beads have an average diameter of 830 nm. They contain 66 % magnetite. The original concentration was diluted by DIW with a ratio of 200:1). At the last cycle of anisotropic DRIE, we applied isotropic etching of Si to facilitate breaking the needles at a specific length. (Close image of magnetic bead after the DRIE of Si can be seen in Fig. 3.2.2). After ultrasonication and centrifuging, needle suspension was prepared (Fig. 3.3).

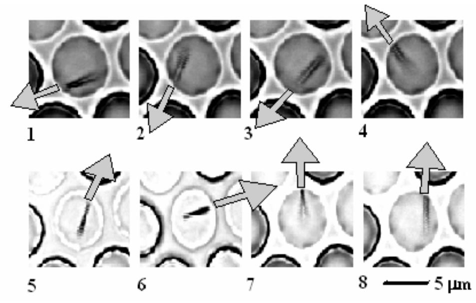

Figure 2. Rotational Brownian motion of an encapsulated 3.5 µm long-Si nanoneedle in PDMS chamber. (R>L>D, 6 µm > 3.5 µm > 2.2 µm. Captures are taken in different time intervals.)

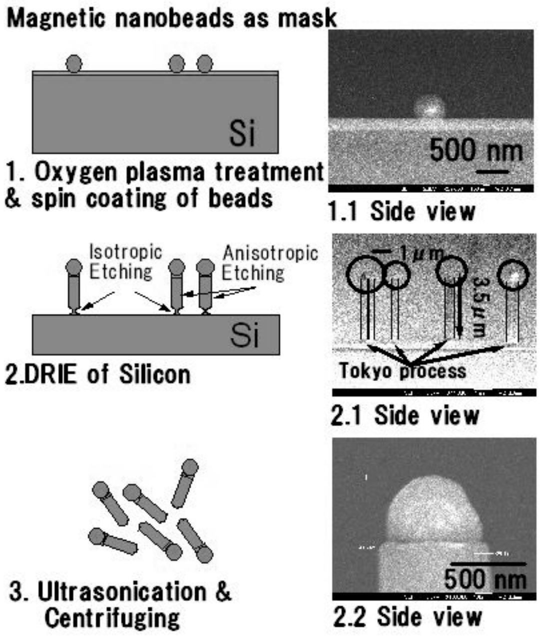

Figure 3. Fabrication of Si nanoneedles functionalized by magnetic nanobeads: (1) Enhancing hydrophilicity of the surface (2) DRIE of Si (3) Ultrasonication and centrifuging.

The diameter of the cross-section of needles varied between 300 and 800 nm. The variation was most probably caused by being broken into small pieces of beads during ultrasonication before spin-coating (The ultrasonication is applied to avoid the aggregation of beads.). Needle length was close to 3.5 µm with an aspect ratio near to 10. But, the strength of Brownian motion is inversely proportional to the sizes. As the size gets larger, imaging is easier but the motion becomes ineffective. Considering the trade-off, we selected needle length of a few micrometers in order to exploit Brownian motion and to observe by optical microscope.

3. EXPERIMENTS

When we obtained the rotational Brownian motion of a nanoneedle in a disk-shaped PDMS chamber, we encapsulated the needle between a PDMS sheet with microchambers containing DI water and a glass substrate; this allows the observation by an inverted microscope (Olympus IX71). In one of those experiments, we observed the rotational Brownian motion of a nanoneedle attached to the glass substrate at one end by chance (Fig. 4). It resembles a rotary molecular motor, e.g. F_1ATPase [4], but it differs in that the direction of the rotation is random here, which shows the effect of Brownian motion. An important point was that it rotated around a fixed axis.

These results inspired us to propose an alternative system to rotate a nanoneedle with the help of a magnetic bead attached at one end. A magnetic bead attached to a nanoneedle can be clamped by a magnetic field that traps the

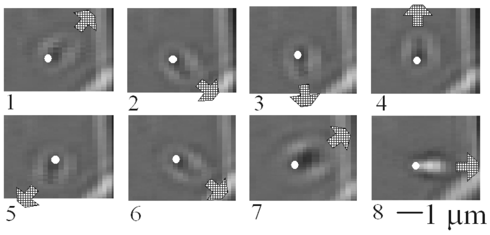

Figure 4. Optical captures of rotational Brownian motion of a nanoneedle trapped at one end. Time intervals are 4 seconds. Arrows are the reference for the direction.

magnetic bead end. Brownian motion actuates the nanoneedle at the free end. In this situation, Brownian motion must be strong enough to overcome the friction at the trapped end but not enough to detach it totally from the surface (Fig. 5).

In the experiment, we used Nd-Fe-B magnets (Diameter = 1 cm, Height = 2 mm, 350 mT / 3500 G, Tokyu Hands) which were put on the slide glass (Fig. 6). The magnet at the bottom was used to fix the magnet at the top to prevent it from being attracted by the objective lens during the experiment. Then, we introduced nanoneedle suspension just on the magnet and covered it with a cover glass. Observations were done by an optical microscope (Olympus BX51).

Figure 7 shows an experiment observed with an x100 objective lens. The image is recorded and converted into mpeg format. Those images are taken by 2 second time intervals. It can be seen that the nanoneedle is attached to the surface at one end, and experiences rotational Brownian motion. Sometimes the rotation point shifts slightly, which reinforces the existence of a magnetic bead. These results indicate that magnetic clamping works (Fig. 5).

At the same time, we checked the magnetic bead suspension just over the magnets (Diameter=350 nm, 27.5% magnetite, 1.343 g/ml, diluted with DIW in the same ratio). In this case, the diameter was smaller with less magnetite ratio than the ones used in the experiments; which means that Brownian motion must be more effective. However, during the experiment, we observed that they just stuck to the surface of the magnet without any motion. This means that magnetic force was stronger than Brownian motion to be overcome. This further supports that the observed particle was most probably functionalized by a magnetic bead.

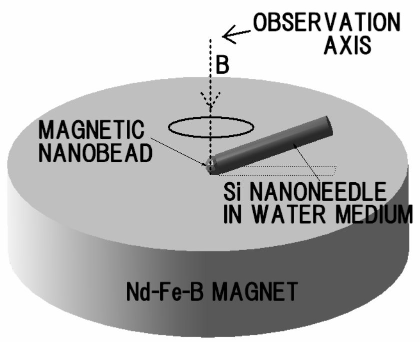

Figure 5. Conceptual view of magnetic clamping. Rotation direction is random.

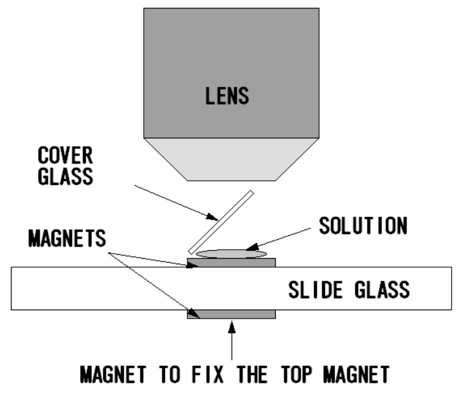

Figure 6. Experimental view.

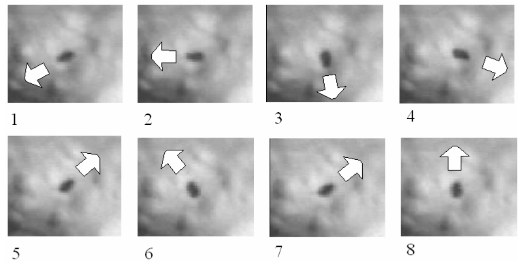

Figure 7. Optical captures of rotational Brownian motion of magnetically clamped Si nanoneedle on Nd-Fe-B permanent magnet. Arrow is the reference for the rotation. Time intervals are 2 seconds. (1 second contains 30 frames.)

4. DISCUSSIONS

When we encapsulated the Si nanoneedle properly inside a disk-shaped chamber, (Chamber diameter [6 μm] > length [3.5 μm] > chamber depth [2.2 μm]) we observed the rotational Brownian motion. The vertical degree of freedom of the needle was limited by the depth of the chamber. However, we observed translational and vertical motions. Even though those motions are limited by the PDMS chamber, we observed the translational motions due to relatively larger diameter of the chamber. The needle fluctuated in vertical direction as well. We observed the color change of the nanoneedle during the observation which proves defocusing of the needle. This means that there is vertical motion, but it is constrained by the depth of the PDMS chamber [3].

In this paper, we achieved rotational Brownian motion of a nanoneedle by clamping at one end. Magnetic field with the help of magnetic bead attached to the needle provided this by eliminating vertical or 3D motion. The rotation point was almost stationary [Fig. 8]. Furthermore, during the experiment, we did not observe any detectable and realizeable vertical fluctuations that may cause a trace above. This suggest that the needle was clamped well.

The speed of the rotation changes from time to time. In a given time period, it may experience a rapid rotation, or sometimes it may stay in a position for a few seconds. The direction of the rotation is random. It can be clockwise or counter clockwise direction. The next challenge is to bias or rectify this random rotational motion into unidirectional motion.

Using mechanical rectification can be a solution to overcome this problem. But, thermodynamics says that in equilibrium it is impossible to obtain net-unidirectional motion. There must be thermal asymmetry in the system. Above all, providing temperature differences in a small region in the microscale remains as a challenge.

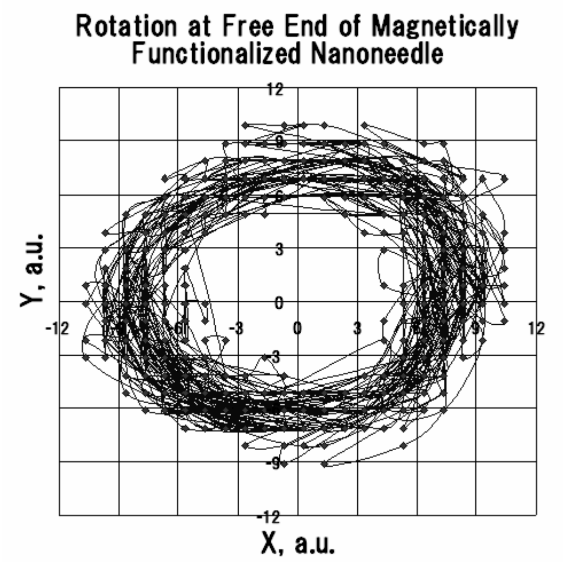

Figure 8. Trace of the rotating end of the needle. The trace reinforces the shift of the clamped point. Scales are arbitrary units. (Roughly 900 points)

5. CONCLUSIONS

We have achieved the exploitation of Brownian motion to fuel the rotation of a nanoneedle at its free end by limiting its degree of freedom using a magnetic nanobead. A magnetic field trapped the nanoneedle at its magnetic bead end. This study may lead to thermo-mechanical nano-motors fueled by Brownian motion similar to their chemo-mechanical biomolecular counterparts. We have been working on the improvement of the system and investigating to produce net-unidirectional rotation from this clamped random rotation.

6. ACKNOWLEDGEMENTS

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