Inlaid Carbon Nanofiber Nanoelectrode Array as Highly Efficient Dielectrophoresis Device for Bacteria Trapping
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Abstract—Dielectrophoresis (DEP) is an effective microelectronic technique for trapping and manipulating biological particles in a microfluidic environment, which relies on the highly asymmetric electric field gradient created by the microelectrodes. Here we demonstrate an AC DEP technique for single-bacteria trapping using nanoelectrode arrays (NEAs) in a “points-and-lid” configuration. The NEA is based on vertically aligned carbon nanofibers (CNFs) embedded in SiO₂ matrix. The miniaturization of the electrode size provides a highly focused electric field with the gradient enhanced by several orders of magnitude. Finite element modeling indicated that the pDEP electric field, resulting in positive DEP (pDEP). The magnitude is proportional to \(|\nabla |E(r)|^2\), determined by the electrode geometry and voltage. For a nanoelectrode (NE), \(|\nabla |E(r)|^2\) can be increased over 100 times, generating a much stronger DEP force. The large pDEP force is able to counter Stokes drag force in a high-velocity laminar microfluidic flow and effectively traps E. coli at individual NEs.

MATERIALS AND METHODS

The NEAs based on inlaid vertical CNF arrays were fabricated following the similar methods reported before: A microscope was used to observe the E. coli movement through an ITO electrode (as shown in Fig. 1a). The typical CNF array consists of 50-200 nm diameter and ~5 µm long fibers with an average spacing of ~400 nm. Each CNF was vertically aligned and freestanding on the surface. We controlled the condition so that only a small number of CNFs are exposed with an average spacing more than 1 micron. In a few samples (such as Fig. 1b), e-beam lithography was used to pattern the Ni catalysts into a well-separated hexagonal array of nanodots (~100 nm in dia.) which produced an array of individual CNFs. A layer of SU-8 was spin-coated and UV exposed to form the microfluidic channel and bind the NEA chip with the ITO counter electrode.

CURRENT RESULTS

The two-dimensional (2D) finite element modeling of pDEP trapping at a linear array of 12 CNF NEs at 26 Vpp and a flow velocity of 10 mm/s is shown in Fig. 2. Particles of 1 µm in diameter are injected at various heights simulating E. coli. The trajectories show that all particles injected below 12 µm height are trapped while others (including those near the 20 µm high ceiling) are deflected downwards. The flow velocity (10 mm/s) is much higher than those in micro- “points-and-lid” device (0.1-0.5 mm/s) and interdigitated device (0.04-2 mm/s).
reflecting the higher trapping efficiency. The $E(r)^2$ map around a NE tip shows a maximum of $\sim 1.2 \times 10^{14}$ V^2 m^-2, 200 times higher than that of the micro- “points-and-lid” device^6. At 2 mm/s flow velocity, even 9 V_pp can trap most of the particles.

The trapping of E. coli is measured by the integrated fluorescence intensity from stained E. coli by focusing at a $\sim 0.25$-mm² area at the bottom of the channel with a dimension of 500μm(W) x 20μm(H) x 2cm(L) as shown in Fig. 3a. An E. coli suspension (1 $\times 10^7$/ml) is continuously passed through the microchannel. The trap is turned on and off to observe how E. coli are captured and released from the NEA. The DEP voltage is varied between 0 to 9 V_pp in a series of experiments. At a flow velocity of $\sim 2$ mm/s, even 1 V_pp initiates evident trapping. At V_pp $> 3$ V, CNF NEs are able to generate strong DEP force to trap E. coli that instantaneously covered all exposed CNF tips.

Fluorescence images are taken before and after the 3 V_pp is turned on. When the V_pp is off at the beginning (Fig. 3b), E. coli bacteria are floating in water and generate fuzzy stretched tracks. After a 3 V_pp is turned on (Fig. 3c), bacteria are instantaneously snapped onto the exposed CNF tips, generating sharp bright spots while the extra bacteria are still floating. The trapped bacteria can be reversibly released when the V_pp is turned off.

In summary, we have demonstrated the use of embedded CNF NEA in trapping small bioparticles against strong hydrodynamic drag forces in a microfluidic channel. This new nano-DEP technique can be used either as a low-density array for registration and the study of single particles or a high-density array that is tailored as an active DEP filter for sorting, separating, and concentrating bioparticles. This approach of manipulating submicron bioparticles by highly focused strong electrical fields at NEAs, promises new capabilities for cell biology research and the development of highly integrated biochips for environmental and security monitoring.

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**REFERENCES**


