Supporting Information for

Selective Manipulation of Biomolecules with Insulator-Based Dielectrophoretic Tweezers

Myungkeun Oh[1,‡], Vidura Jayasooriya[2,‡], Sung Oh Woo[3], Dharmakeerthi Nawarathna[2,], and Yongki Choi[1,3,*]*

[1]Materials and Nanotechnology Program, [2]Department of Electrical and Computer Engineering, and [3]Department of Physics, North Dakota State University, Fargo, North Dakota 58108, USA

Corresponding Author:

*E-mail: dharmakeerthi.nawara@ndsu.edu (D. N.) or yongki.choi@ndsu.edu (Y.C.)

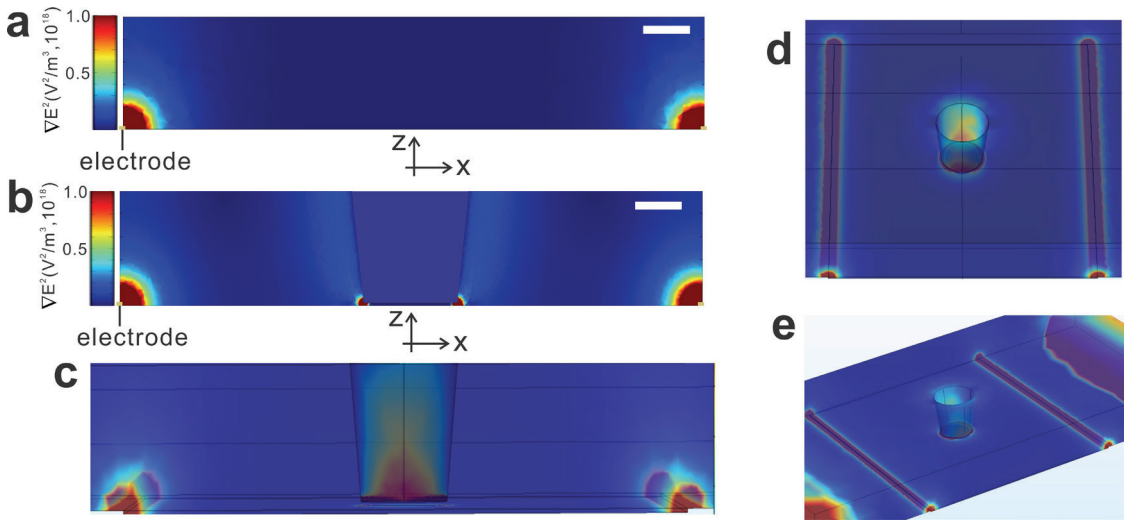

Figure S1. The distribution of ∇E^2 calculated by COMSOL simulation. (a) Localized ∇E^2 at the both electrode under AC voltage V_{ac} (7 V_{pp}, f = 50 kHz). The scale bar is 5 μm. (b) Distribution of the additional localized ∇E^2 at the tip. (c) Cross sectional view of ∇E^2 distribution. (e) Top and (e) side view of ∇E^2 distribution.

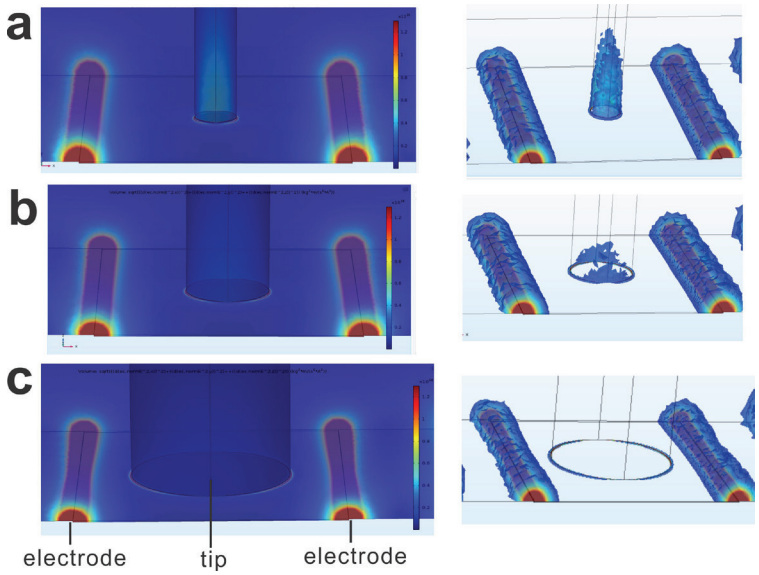

Figure S2. The distribution of ∇E^2 around the tip with its diameter of (a) 4 μm (b) 5 μm, and (c) 15 μm. For the small tip, the concentrated field at the tip is proportional to the area of the tip (πr^2). In contrast, the field partially interacts with the large tip. Thus, about a quarter of rim contacts with each electrode, and the effective trapping volume is proportional to the circumference of the tip (πr). Our experiments show that the tip diameter of 4 ~ 8 μm offers the most effective trapping of the particles and DNA in our devices.

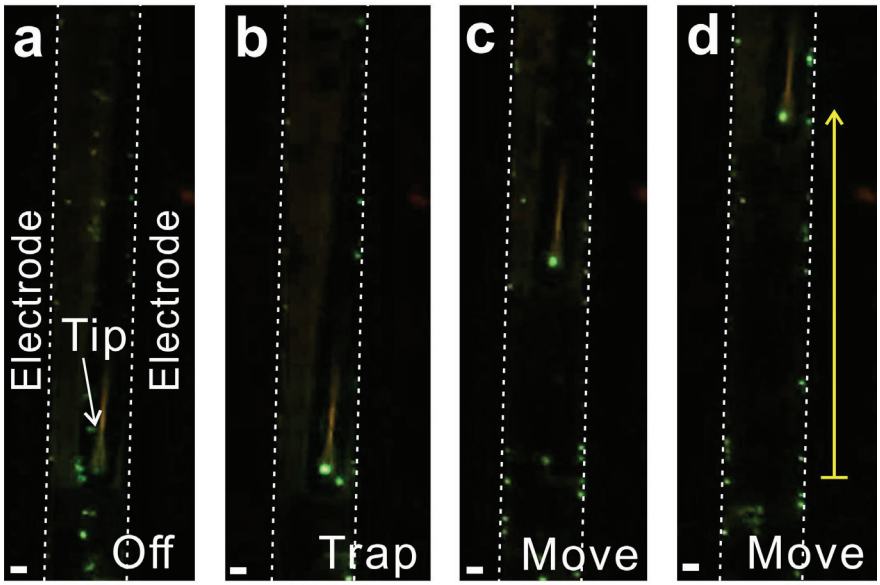

Figure S3. Additional example of nanoparticle manipulation. (a) No AC bias. (b) – (d) Trapping and repositioning of the particles at the tip with the pDEP bias (5 V, 20 kHz). The yellow arrow is 112 μm. The scalar bar is 5 μm.

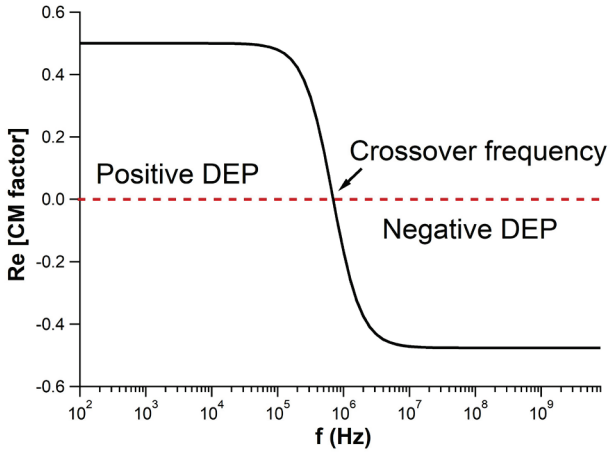

Figure S4. Real part of the CM factor of the spherical particle. In calculating this plot, the following parameters were used: $\varepsilon_p = 2.5\varepsilon_o$, $\varepsilon_m = 78\varepsilon_o$, $\sigma_p = 4 \times 10^{-3}$ S/m, $\sigma_m = 1 \times 10^{-3}$ S/m.

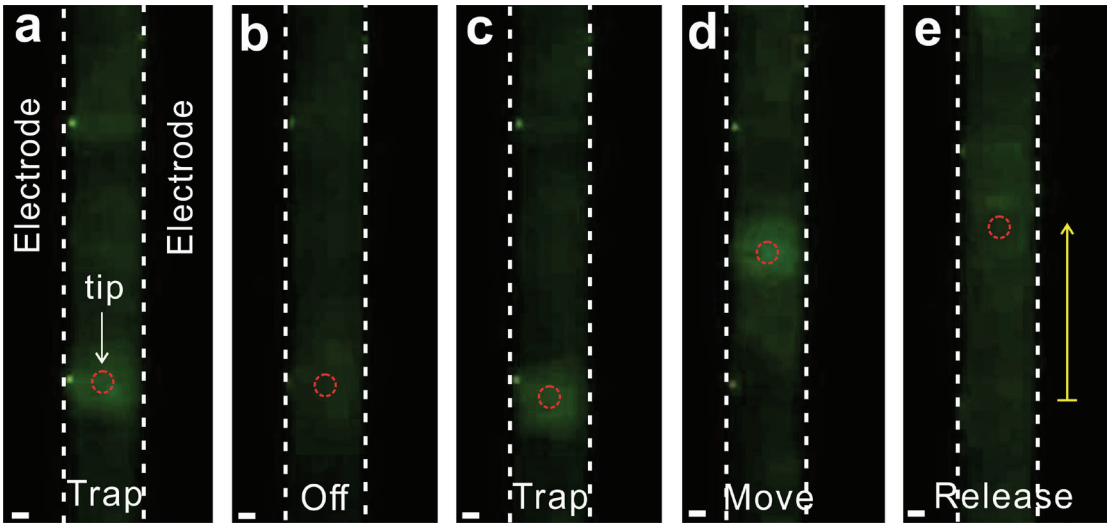

Figure S5. Additional example of homogeneous (48,502 base pairs) DNA manipulation under the pDEP bias (7 V_{pp}, f = 200 kHz). (a) Tapping, (b) releasing, (c) re-trapping, (d) repositioning, and (e) releasing of DNA at the tip (the red circle). The yellow arrow is 56 µm. The scalar bar is 5 µm.

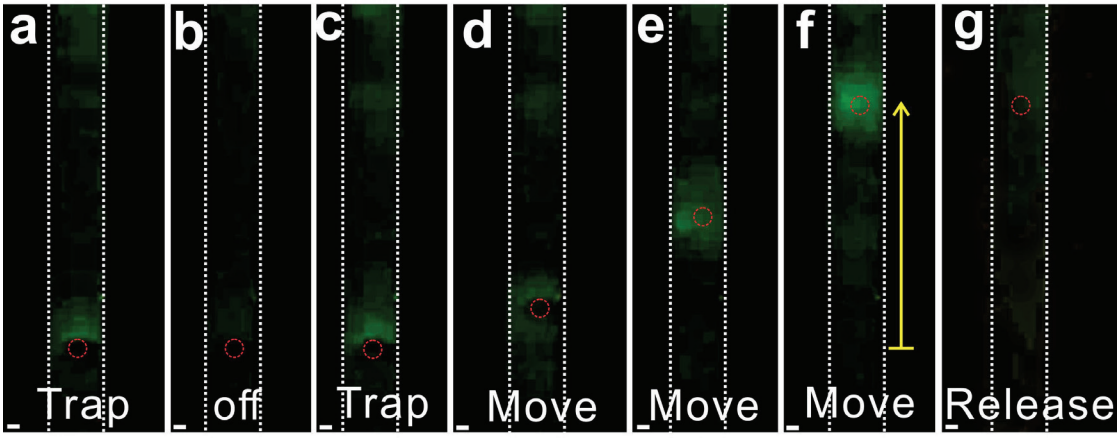

Figure S6. Spatial manipulation of nonhomogeneous mixed DNA containing 6 fragments from 3,550 – 21,226 base pairs under the pDEP bias (7 V_{pp}, f = 200 kHz). (a) Tapping and (b) releasing of DNA at the tip (the red circle). (c)-(f) The motion of the tip with trapped DNA along the y-axis. The yellow arrow is 100 µm. (g) Instant release of DNA at the tip by turning off the trap bias. The scalar bar is 5 µm.

Estimation of various forces acting on a particle in a fluid environment

We have calculated the magnitudes of various forces including electric thermo flow force, resistive drag, gravity, and buoyancy acting on a moving object in a fluid and compared to iDEP. We have used the DNA (R = 600 nm) and velocity of 1 mm/s, which are comparable to our experimental conditions.

First, we estimated gravitational force acting on DNA, $F_g = mg = 5 \times 10^{-19}$ N, which is negligible compared to iDEP estimated by the CM factor model (18 nN and 41.5 nN) in the main text.

Second, buoyant force can be calculated by $F_B = \rho g V$, where ρ is the density of the buffer (water), and $V = 4\pi r^3/3$ is the volume of DNA in the spherical model in buffer. F_B in this assumption is 2.8 $\times 10^{-15}$ N, which is not comparable to iDEP.

Third, we estimated drag force by $F_{drag} = 0.5 C_d \rho A v^2 + 6\pi\eta r v$, where C_d is drag coefficient ranging from 0.1 to 1, A is the cross section of an object moving in liquid, v is the velocity of an object, and η is viscosity[1-2]. The drag force is estimated to be 1.02×10^{-11} N, which is less than 1 % of iDEP.

Finally, we estimated the electric thermo flow force induced by applying AC voltage between two parallel electrodes. The time average force acting on a unit volume is described by, $< f >= -M(\omega, T)\left(\frac{\varepsilon\sigma {V_{rms}}^4}{2k\pi^3 r^3 T}\right)\left(1 - \frac{2\theta}{\pi}\right)$, where M is a dimensionless factor depending on applied frequency with its value $|M| < 7$ at the frequency less than 1 MHz[3]. Here, ε is permittivity, σ is conductivity, k is thermal conductivity, and T is temperature. θ and r are cylindrical coordinates, respectively, and the origin is located at the middle of two parallel electrodes. We calculated the maximum force by using the maximum of $M(\omega,T) \sim 6.5$ and $\theta = 0$. At r = 10 μm, the maximum value of electro thermal fluid force is estimated as $< f >_{max} \sim 6.5\left(\frac{\varepsilon\sigma {V_{rms}}^4}{2k\pi^3 r^3 T}\right) = 9.65 \times 10^{-17}\ N/\mu m^3$, which is not comparable to iDEP.

Taken together, our iDEP tweezers enable us to spatially manipulate objects in a fluid, and therefore, our DNA manipulation experiments with iDEP are justified.

References

(1) White, F. *Fluid Mechanics*, 7th ed.; McGraw Hill: 2011.
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(3) Ramos, A.; Morgan, H.; Green, N. G.; Castellanos, A. Ac electrokinetics: a review of forces in microelectrode structures. *J. Phys. D Appl. Phys.* **1998,** *31* (18), 2338.