Electronic Supplementary Material (ESI) for Nanoscale.


# Supporting Information

# Electrospun Nanofiber Mat as an Electrode for AC-Dielectrophoretic Trapping of Nanoparticles

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## Electrospinning details

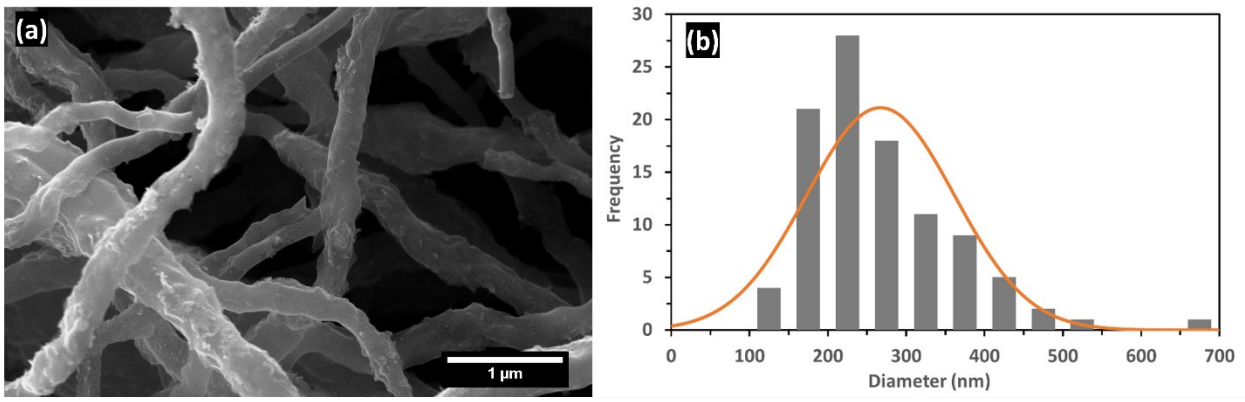


**Figure S1.** SEM image and analysis of carbon-based nanofibers. (a) 25,000X magnified SEM image of fibers. (b) Diameter distribution of the fibers of 100 measurements over the mat surface, including normal distribution curve (orange).

To electrospin CNT-embedded polyacrylonitrile (PAN) fibers, a custom-made chamber was used with humidity control to ensure proper fiber morphology. First, 0.51g of MWCNT was mixed with N, N-Dimethylformamide (DMF) to make a 2 wt.% CNT solution, using the Cole-Parmer 8891 ultrasonication bath system for 5 hours. The CNT-DMF solution was then combined with 2g of PAN and 0.39g of PTA. This solution was mixed on a hot plate stirrer for 2 hours at 60℃. The final mixture was transferred to a syringe pump (Harvard Apparatus pump 11) with 22G blunt needle and electrospun with parameters detailed in Figure 1. A 25 kV benchtop voltage supplier was used to apply high voltage, and aluminum foil served as the collector. After electrospinning, the fiber mat was left to evaporate any leftover residue for a day. The mat was then peeled off the foil and underwent a two-step heat treatment process using a 5℃/min rate of heating. Stabilization was done in air, and carbonization was done in $N_2$ atmosphere. SEM images (Figure S1a) of heat-treated CNF were taken by sputter coating the mat with a thin gold coating (approximately 10nm). The diameter distribution was calculated using ImageJ software from at least 100 measurements (Figure S1b).

## Numerical modeling

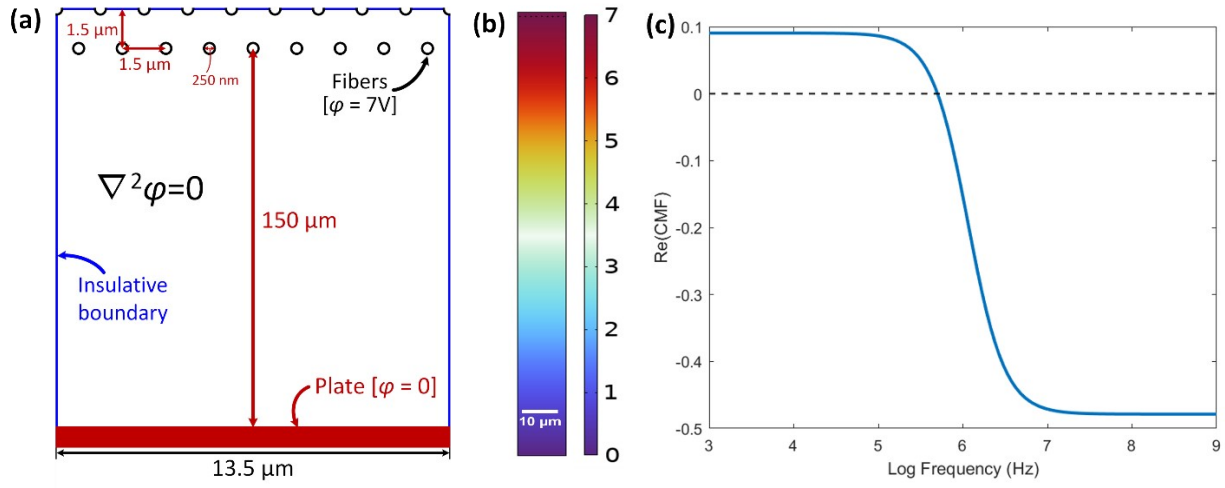


**Figure S2. (a)** Modeling schematic for an array of fibers and plate configuration. The electrode gap was chosen as 150 µm, and 7 $V_{rms}$ was applied between fiber and plate. **(b)** The electric potential distribution when 7 $V_{rms}$ is applied. (c) Real part of the Clausius-Mossotti factor (CMF) vs. log frequency in Hz.

Figure S2a presents a schematic model for numerical analysis using COMSOL Multiphysics. An array of fibers with a triangular arrangement where 250 nm diameter circle was used to represent a single fiber, and the electric field distribution around the edges of the fibers was observed. The ITO electrode was represented at the bottom as a single line. An electric potential of ϕ=7 V was applied in the fiber electrode, while the plate was grounded with ϕ=0 V. The gap between the two electrodes was chosen as 150 µm. The other boundaries marked with blue lines were insulated. The electrical properties of the medium used are mentioned in the next section where we calculate the crossover frequency. To obtain the electric field distribution, the Laplace equation was solved $(\nabla^2\varphi = 0)$. Figure 3 shows the results of electric field potential and the square of the electric field gradient. The vertical line placed in Figure S2a from plate to fiber (red in color) was used to plot the log of the square of the electric field gradient with respect to *Y* distance or height. The simulation space used was a rectangle with 13.5 µm wide and 151.5 µm height.

## Crossover Frequency & and *CMF* graph

$$\sigma_p = \sigma_b + \frac{2K_s}{a} \tag{S1}$$

For PS particles equal or smaller than 1 µm in diameter, bulk conductivity $(\sigma_b)$ is negligible, and the conductivity dominates from the surface conductance $(K_s)$ of particles and generalized value is approximately 1 nS for polystyrene particles (*a* is the

particle radius) with the medium conductivity in the range of 2-10 mS/m [1]. That will give an effective conductivity of particles $\sigma_p = 4\ mS/m$ for 1 µm particles using equation (S1) [2]. Medium conductivity was measured using (Denver Instrument Model 220 conductivity Meter) and the value is $\sigma_m = 3.08\ mS/m$.Vacuum permittivity $E_0$ is $8.85 \times 10^{-12}\ F/m$ and medium ($E_m$) and particle ($E_p$) permittivity are $E_{m=78}E_0$ and $E_{p=2.25}E_0$ respectively [3]. When we put all the values in Equation 1 from the main article, we will plot real part of the Clausius-Mossotti factor against log-frequency (Figure S2b). As the particle conductivity ($\sigma_p$) is greater than the medium conductivity ($\sigma_m$) in our set of experiments, pDEP should be observed in the low frequencies because of positive Re (*CM*). As the frequency increases, the interfacial properties related to charge relaxation will make the permittivity dominant over conductivity and the particles in the medium experiences nDEP due to a finite difference in the value of particle and medium permittivity. The crossover frequency is defined as the frequency where Re (*CM*)=0. From the graph, the crossover frequency for the medium and particle properties mentioned above is 0.52 MHz or 520 kHz. This theoretical approximation matched well with our experimental observations demonstrated in the original manuscript as well as in the supplementary movie.

## Time-lapse sequence of 20 nm particles

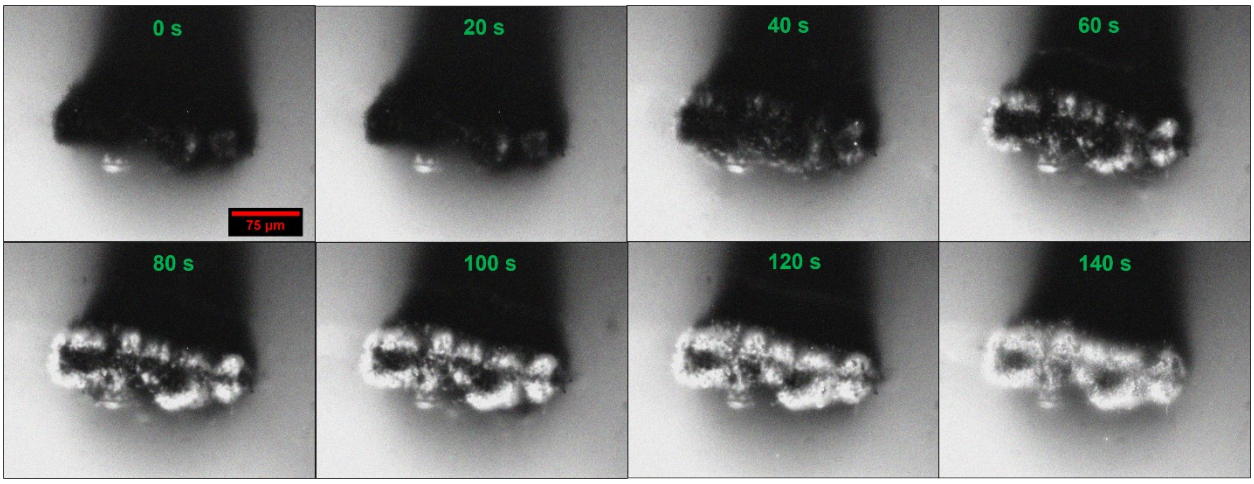


**Figure S3.** Fluorescence microscope image with 20 nm particles. Time lapses series after applying electric potential from 0 sec to 140 sec which is around two and a half minutes as described in the main text.

In this section, we have included a time-lapse sequence (Figure S3) featuring 20 nm particles to better show how nanoparticles get trapped over time. The scale bar is placed in the first image and remains the same for all subsequent images.

For the supplementary movie footage, we used a Canon EOS Rebel T7i camera (instead of the PCO camera) to effectively capture the vibrant colors emitted by the red fluorescent particles in the movie.

## Electrothermal flow

The time average electrothermal fluid body force is given by[4]:

$$F_e = \frac{1}{2}\varepsilon\left[(C_\varepsilon - C_\sigma)\frac{(\nabla T.E)}{1+(\omega\tau)^2}E - \frac{1}{2}C_\varepsilon\nabla T|E|^2\right] \quad \text{(S2)}$$

Where $\varepsilon$ is the permittivity of the fluid, E is the electric field, $\tau = \frac{\varepsilon}{\sigma}$ is the charge relaxation time of the fluid, The applied AC frequency is $\omega = 2\pi f$. Constant $C_\varepsilon$ and $C_\sigma$ are the linear approximations of the temperature dependence of the electrical permittivity and conductivity, respectively. The force density depends on the AC frequency and has two different limiting cases. For low frequencies $(\omega\tau \ll 1)$ the Coulomb force, which is the left term of equation S2 dominates, and for high frequencies the dielectric force dominates which is the seconds term of the equation. Typically, these two forces act in different directions based on the crossover frequency (520 kHz in our case), resulting in a changing flow pattern.

These flow patterns have been sketched in Figure S4 around the conductive fibers we used based on the theoretical background shown in this section.

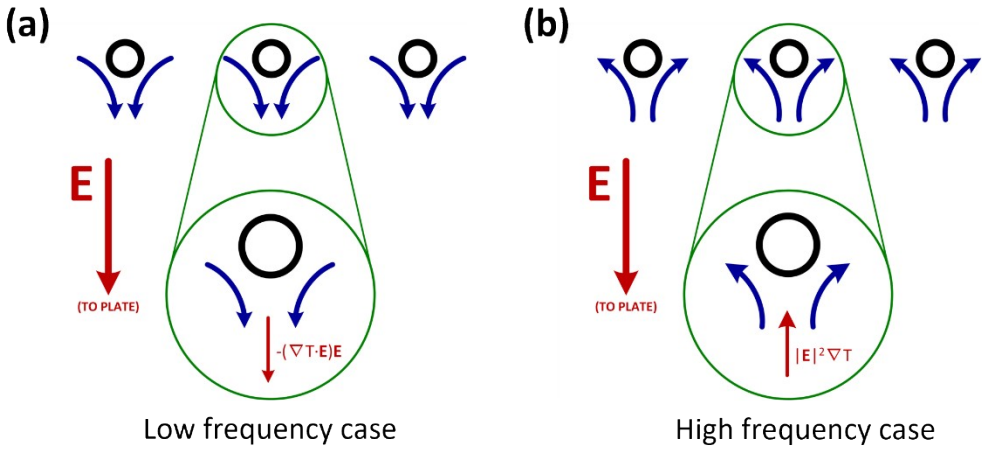


**Figure S4:** Electrothermal flow around the fiber (a) low-frequency case (b) high-frequency case.

## References

1. M. D. Vahey and J. Voldman, *Analytical chemistry*, 2009, **81**, 2446-2455.
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3. J. Cao, P. Cheng and F. Hong, *Journal of Electrostatics*, 2008, **66**, 620-626.
4. S. J. Williams, *Electrophoresis*, 2013, **34**, 1400-1408.