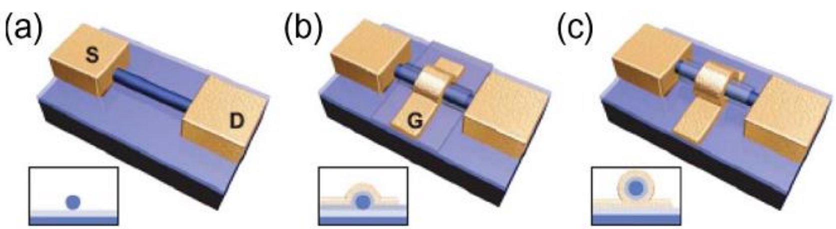
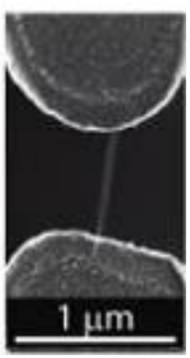
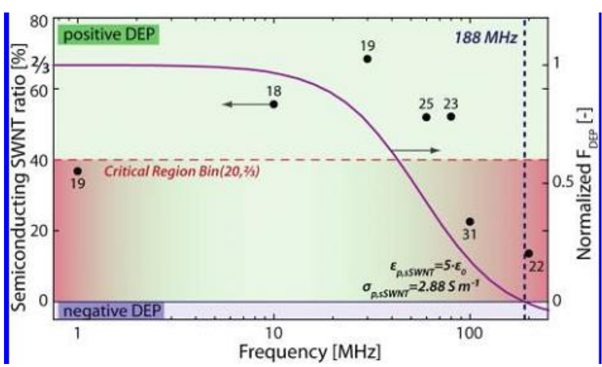
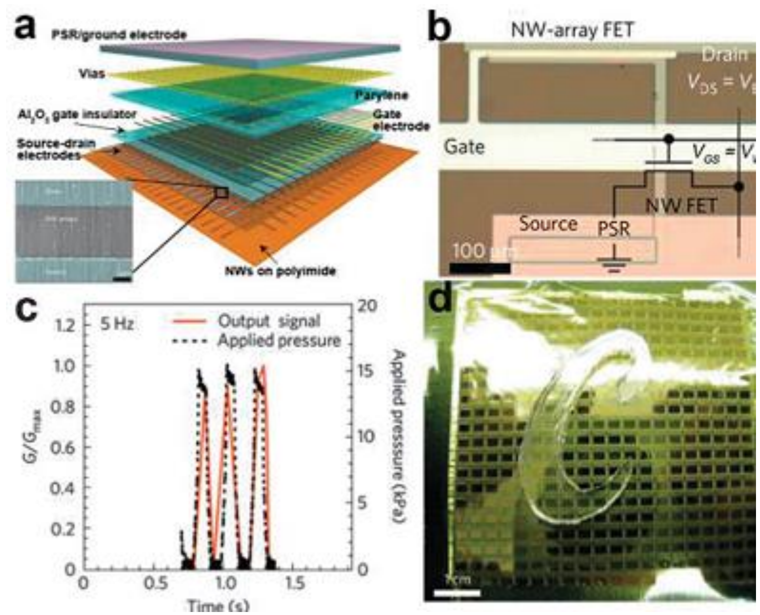
Nanowire/Nanotube Arrays Enable Flexible Electronics

- Semiconducting nanowires have **high electrical mobility**, **high sensitivity** and are **flexible**.
- For FETs, they minimize short-channel effects and enable gate-all-around configurations





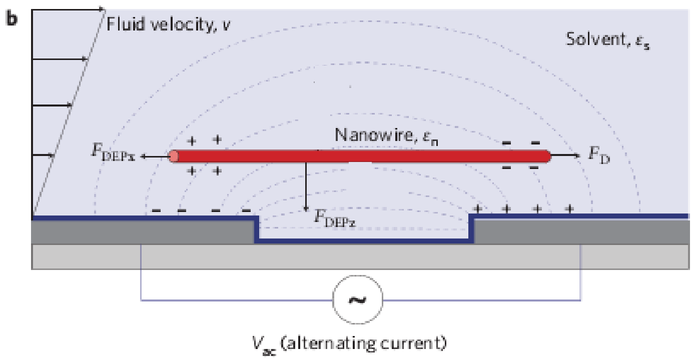


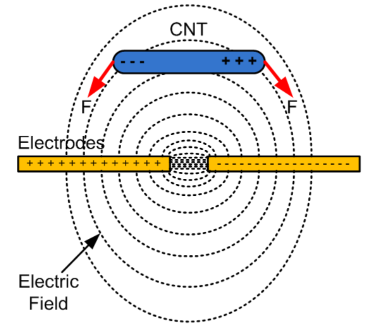


- Takei *et* al, *Nat. Mater.* 2010
- Burg *et al*, *Langmuir* 2010

Flow-Assisted Dielectrophoretic Deposition

- Suspended nanowires flow across a substrate pre-patterned with electrode sites
- Nanowires are pulled towards the electrodes via **dielectrophoresis**



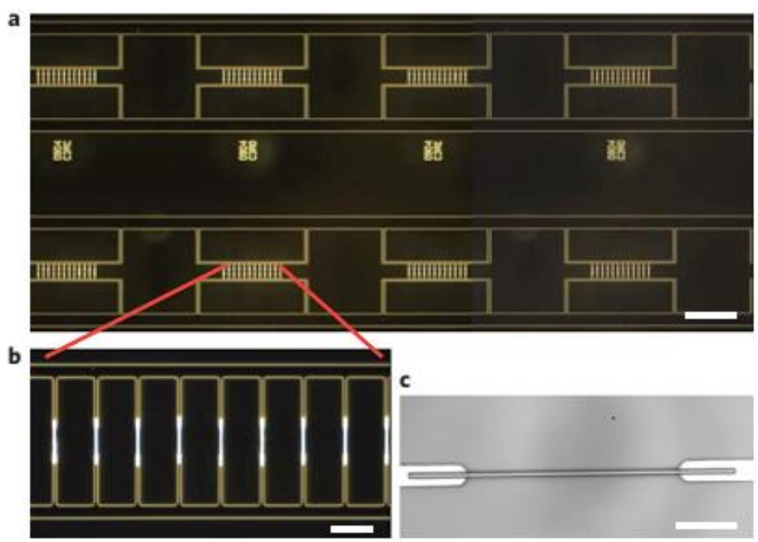


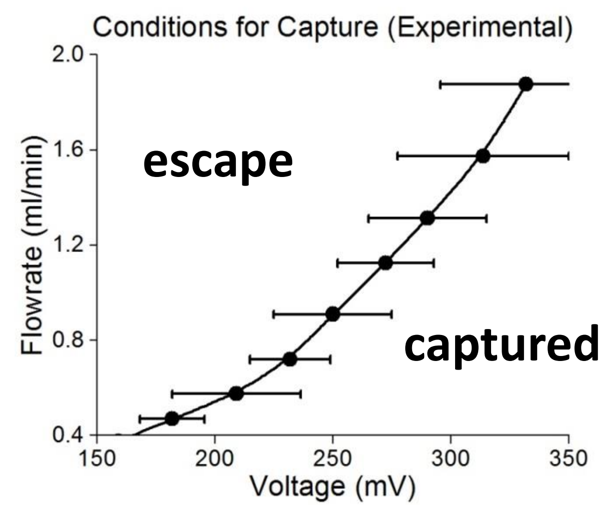
- Force direction depends on field gradient and relative polarizability

- **Under the right conditions**, individual nanowires are assembled at each electrode site

98.5% yield over 16000 sites

18 µm long Si NWs, 12 µm long electrode gap and 10 µm pitch





•Freer *et al, Nat. Nano* 2010

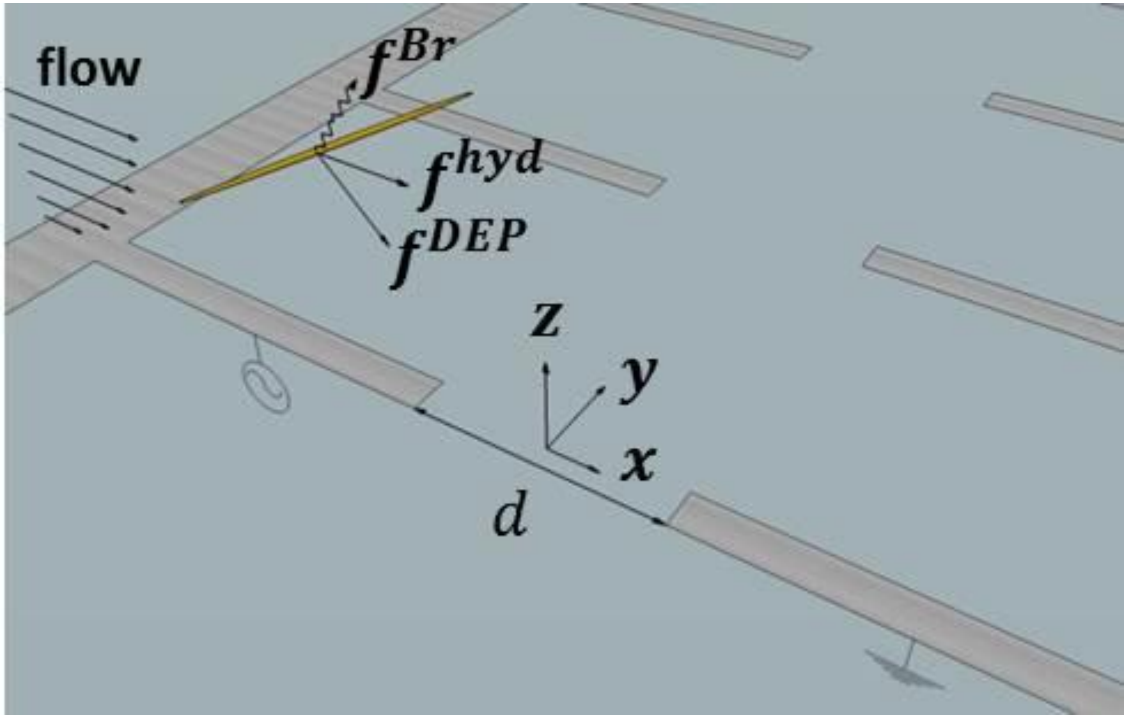
Simulation Methodology

- 3D Brownian dynamics simulations of an ***individual*** nanowire:

$$\Delta \boldsymbol{r} = \boldsymbol{R}^{trans^{-1}} . \left(\boldsymbol{f}^{DEP} + \boldsymbol{f}^{0,hyd} + \boldsymbol{f}^{Br} \right) \Delta t$$

$$\boldsymbol{r}^{*} = \boldsymbol{r} + \frac{1}{2} \boldsymbol{R}^{trans^{-1}} . \left(\boldsymbol{f}^{DEP}(\boldsymbol{r}) + \boldsymbol{f}^{0,hyd}(\boldsymbol{r}) + \boldsymbol{f}^{Br}(\boldsymbol{r}) \right) \Delta t$$

$$\Delta \boldsymbol{r} = \boldsymbol{R}^{rot^{-1}} . \left(\boldsymbol{f}^{DEP}(\boldsymbol{r}^{*}) + \boldsymbol{f}^{0,hyd}(\boldsymbol{r}^{*}) + \boldsymbol{f}^{Br}(\boldsymbol{r}^{*}) \right) \Delta t$$



Simulation Methodology

1. Dielectrophoresis

- Dielectrophoretic force is calculated via an ***averaged*** effective dipole moment (EDM):

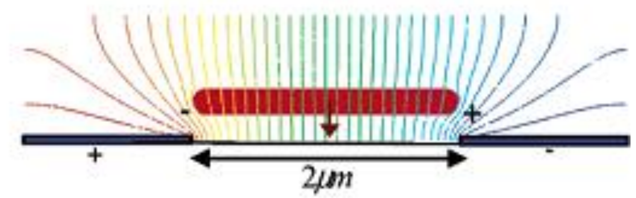
$$p_i = 2\pi a^2 l \varepsilon_s \,\mathrm{Re}(K_i) e_i$$

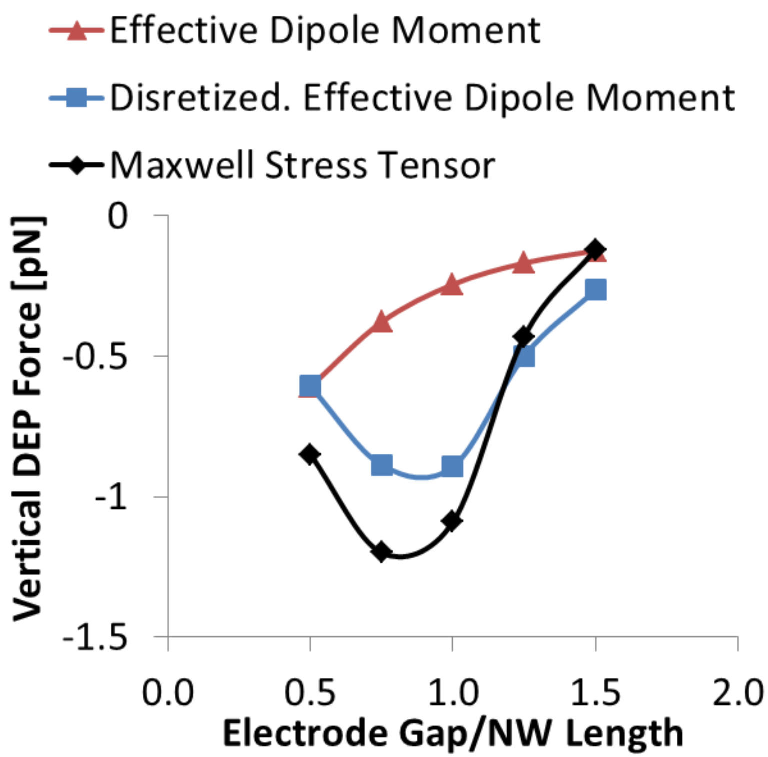
$$\boldsymbol{f}^{DEP} = (\boldsymbol{p}.\nabla)\boldsymbol{e}$$

$$\boldsymbol{t}^{DEP} = \boldsymbol{p} \times \boldsymbol{e}$$

- Electric field from finite-element solution in COMSOL

$$\nabla^2 V = 0$$



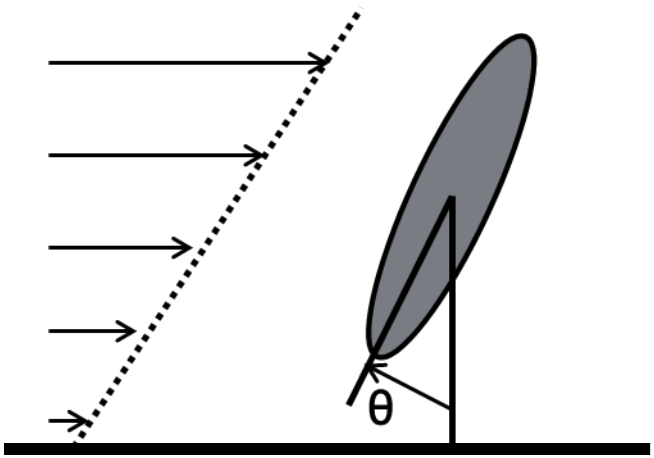


- Liu *et al*, *J. Phys. Chem. B* 2006

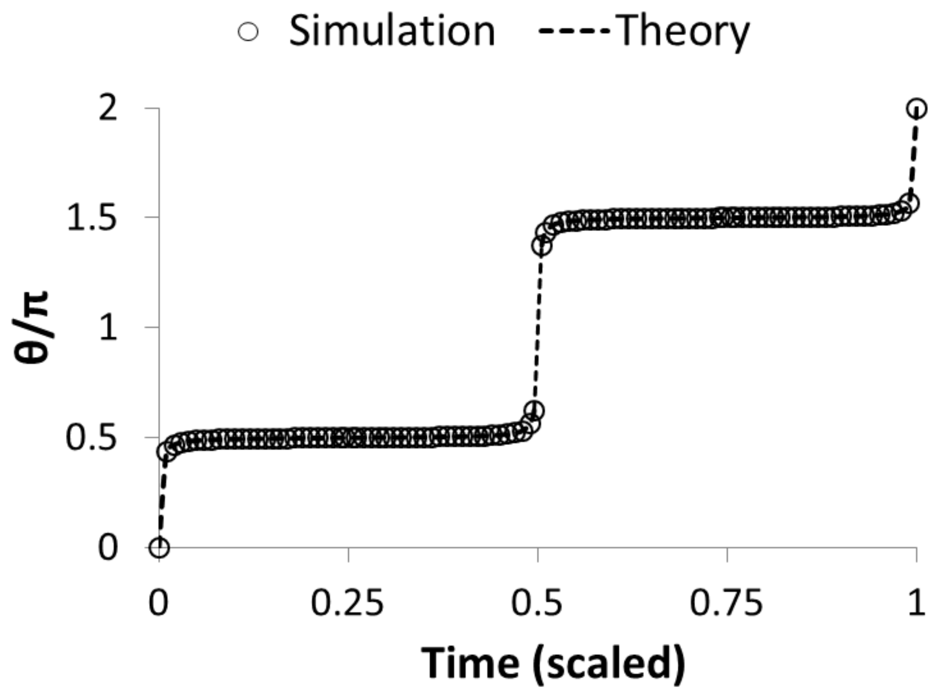
Simulation Methodology

2. Hydrodynamics

- Hydrodynamic force from Faxen's law: accounts for curvature of flow field but not for interactions with the wall.



z/l = 0.6



θ/π

- Gavze & Shapiro, *Int J. Multiphase Flow* 1997

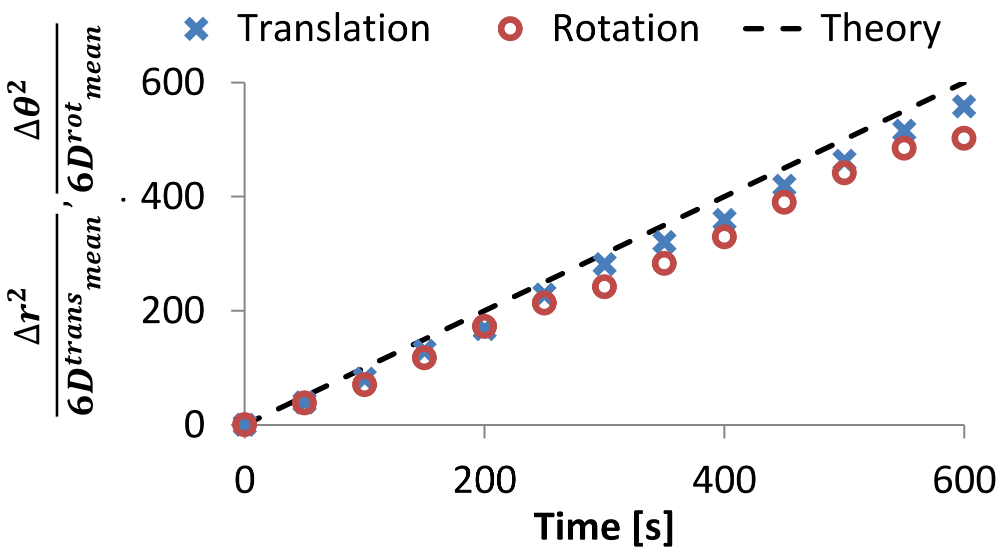
Simulation Methodology

3. Brownian Motion

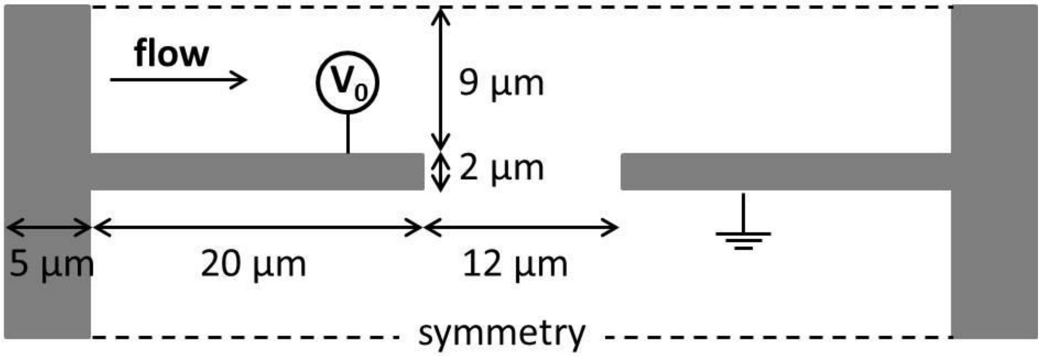
- Brownian force has the following stochastic properties:

$$\left\langle \boldsymbol{f}^{Br}(t) \right\rangle = 0$$

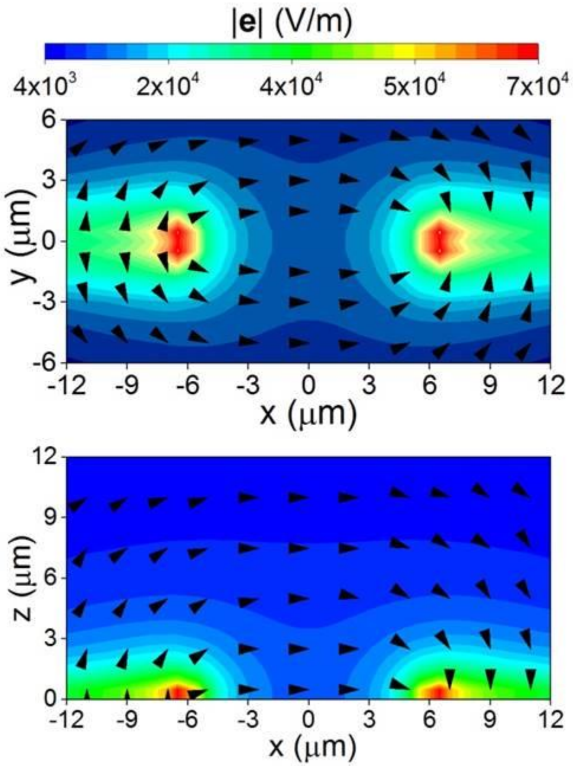
$$\left\langle \boldsymbol{f}^{Br}(0)\,\boldsymbol{f}^{Br}(t) \right\rangle = 2kT\boldsymbol{R}^{trans}\boldsymbol{I}\,\delta(t)$$



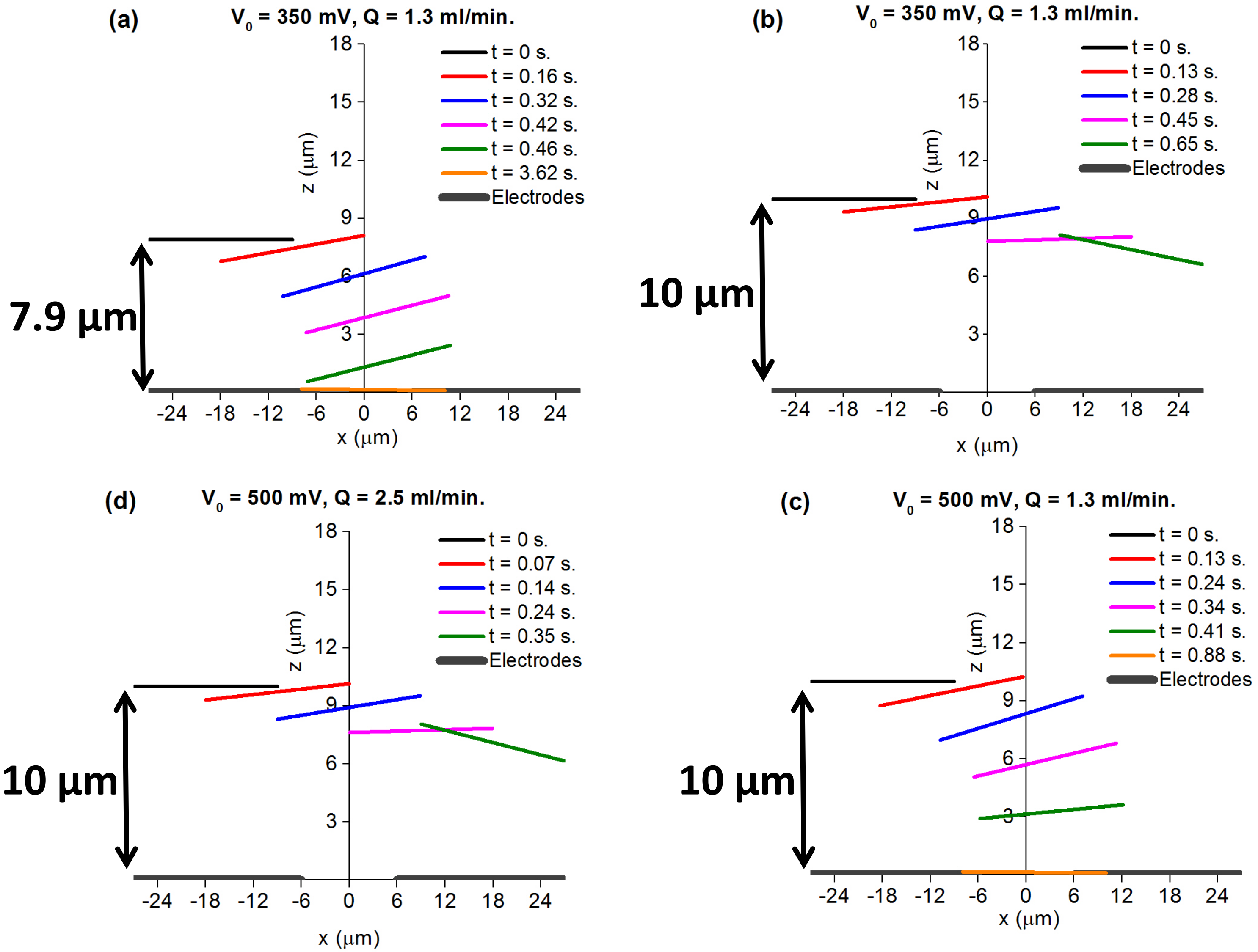
Base System



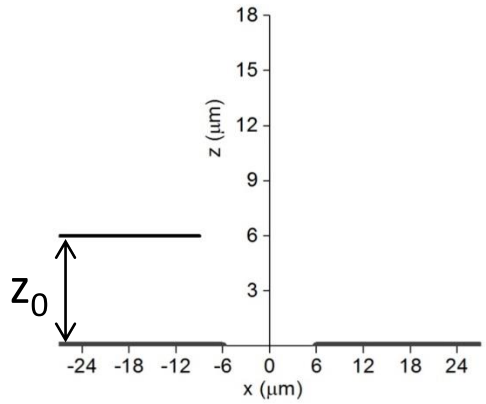
- Silicon nanowires (Boron-doped)
- IPA/H_2O 85/15%
- l = 18 µm
- 635 µm wide channel
- 12 µm long electrode gap

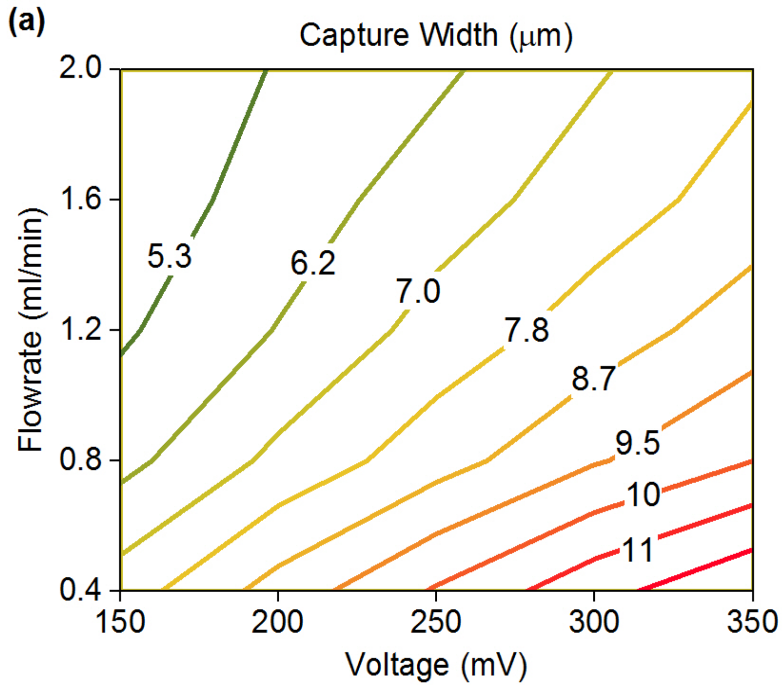


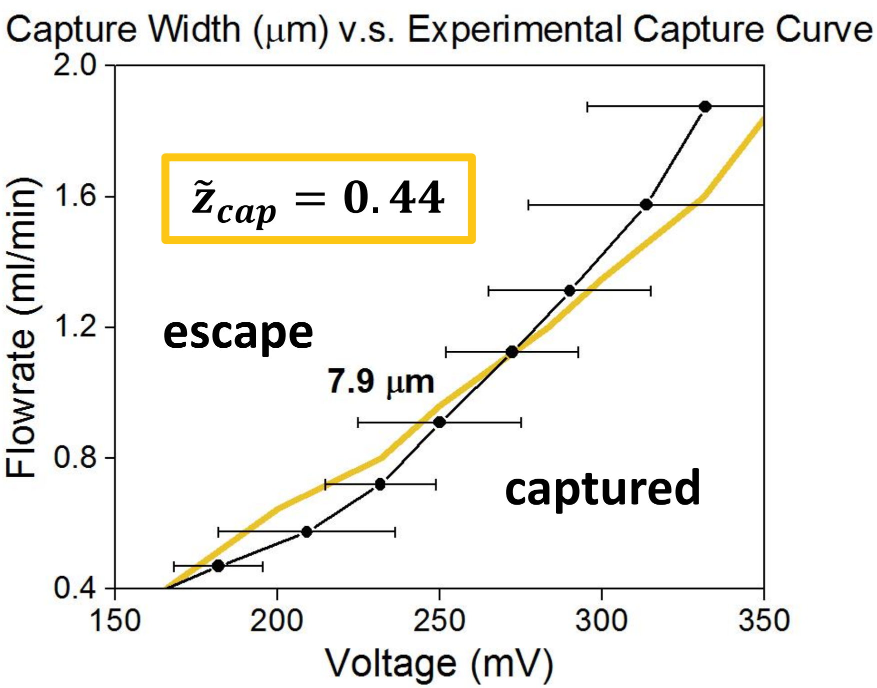
Examples of Nanowire Dynamics



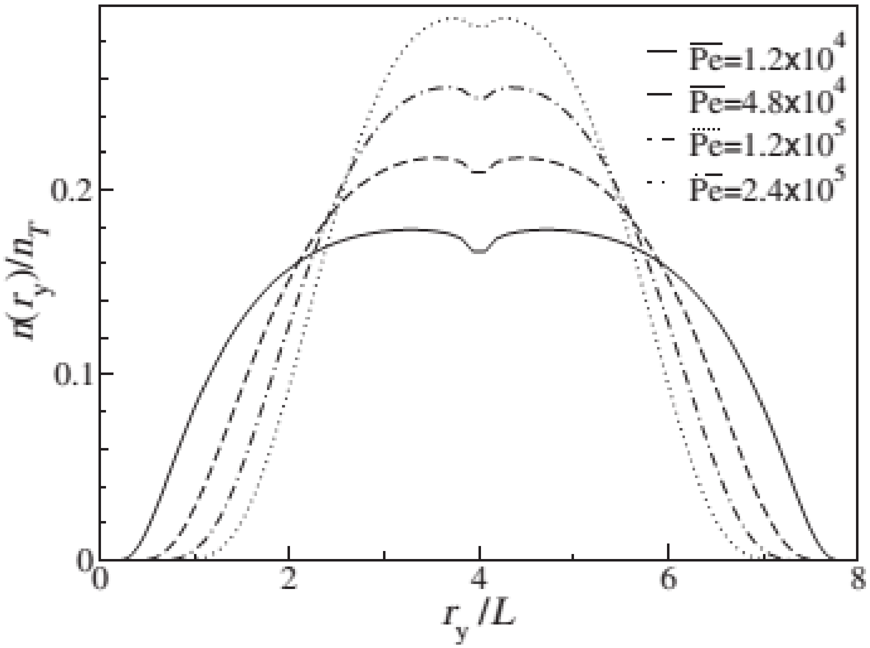
Capture Width



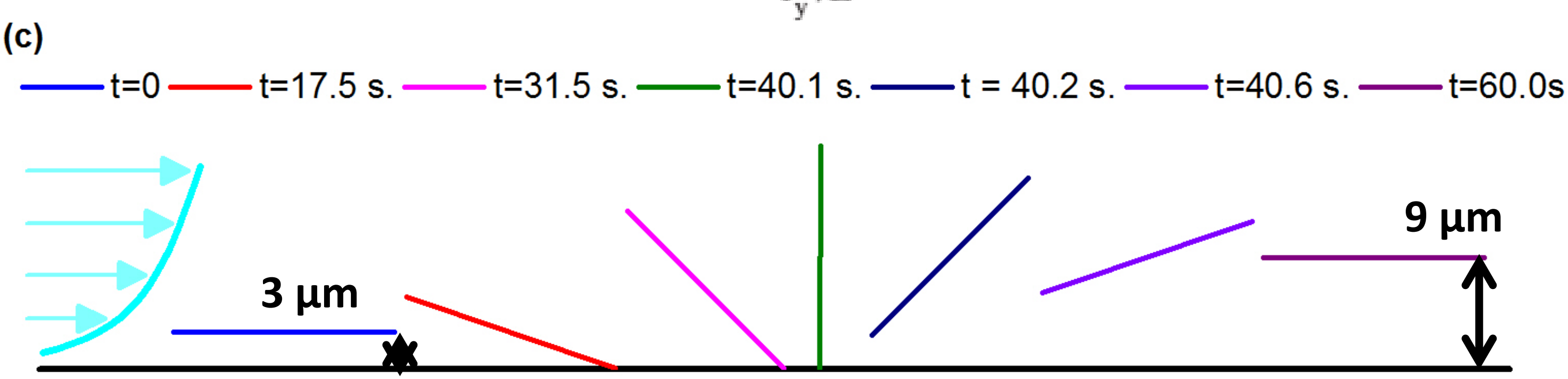




Assembly Happens when Capture Width > Depletion Width



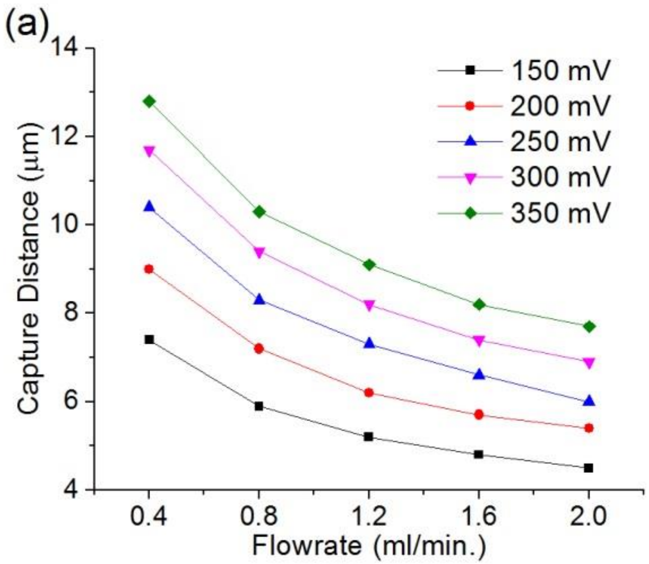
$\tilde{z}_{cap} = 0.44$



• Park *et al, Phys Rev E* 2007 •Park & Butler, *J. Fluid Mech.* 2009 • Park & Mittal, *Chromatography* 2015

Scaling Arguments for Reduced Dimensionality

- $\bar{F}^{DEP} \equiv (2\pi a^2 l)\left(\varepsilon_s \mathrm{Re} K_{long})\right)(V_0^2/d^3)$
  - $\bar{F}^{hyd} = \dot{\gamma} R_{long} l/2$
  - $Di \equiv \dfrac{\bar{F}^{DEP}}{\bar{F}^{hyd}}$



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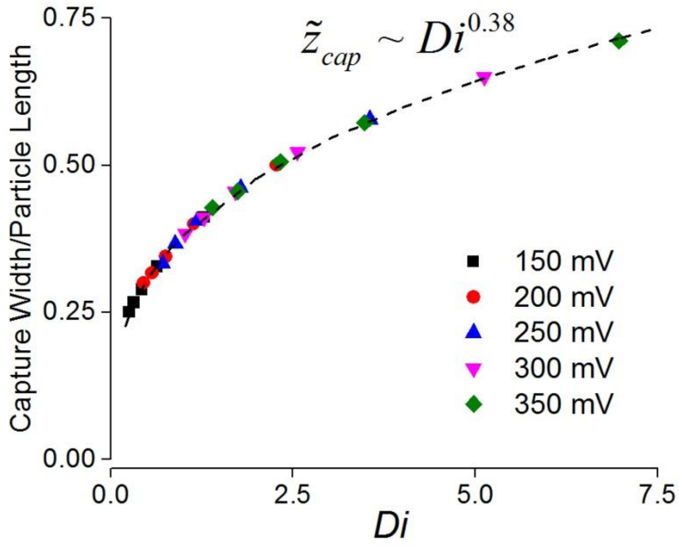
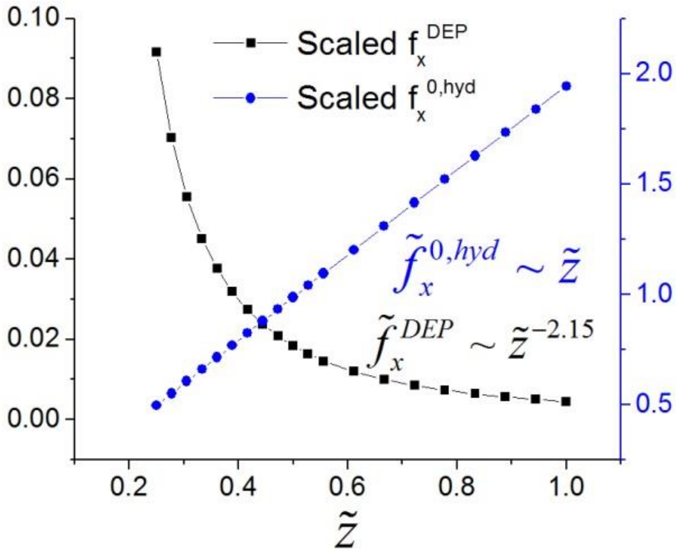


$$f_x^{\;DEP} = f_x^{\;hyd}$$

$$\overline{F}^{DEP} \tilde{z}_{cap}^{-2.15} = \overline{F}^{hyd} \tilde{z}_{cap}$$

$$\Rightarrow \tilde{z}_{cap} \sim Di^{0.32}$$



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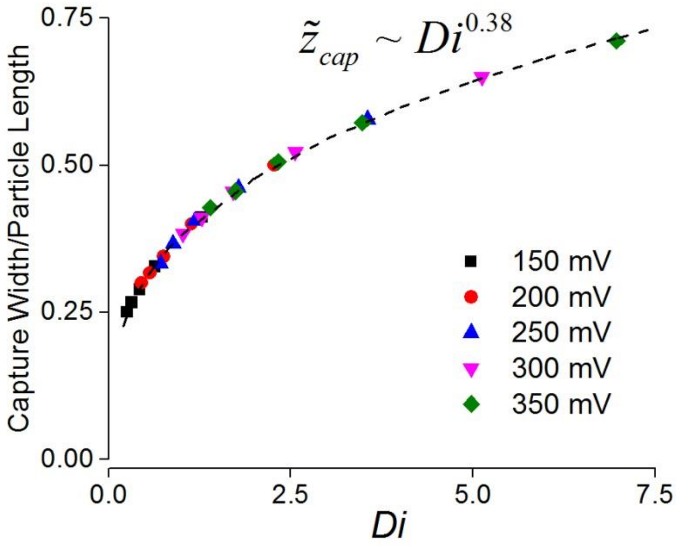
  - $\bar{F}^{hyd} = \dot{\gamma} R_{long} l/2$
  - $Di \equiv \frac{\bar{F}^{DEP}}{\bar{F}^{hyd}}$

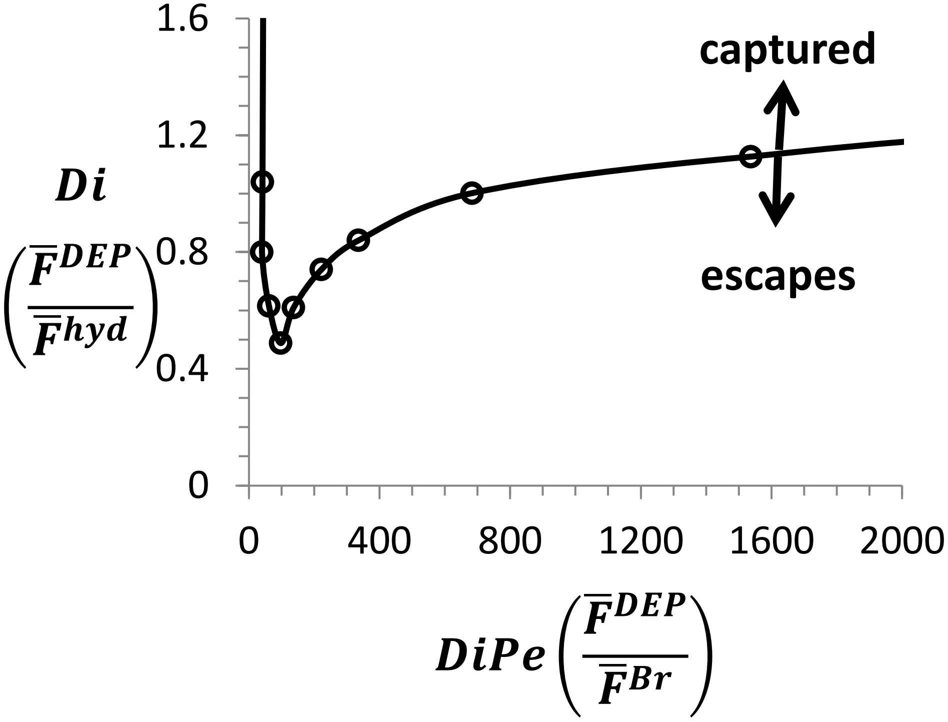


- $\bar{F}^{Br} \equiv kT/d$
- $DiPe \equiv \frac{\bar{F}^{DEP}}{\bar{F}^{Br}} \left(Pe \equiv \frac{\bar{F}^{hyd}}{\bar{F}^{Br}}\right)$

$$\Delta\tilde{\boldsymbol{r}} = \tilde{\boldsymbol{R}}^{trans^{-1}} \cdot \left(\boldsymbol{f}^{DEP} + \frac{\boldsymbol{f}^{0,hyd}}{Di} + \frac{\boldsymbol{f}^{Br}}{DiPe} \right) \Delta\tilde{t}$$

Diffusion Helps … Up to a Point

$Di \mid \tilde{z}_{cap} = 0.44$



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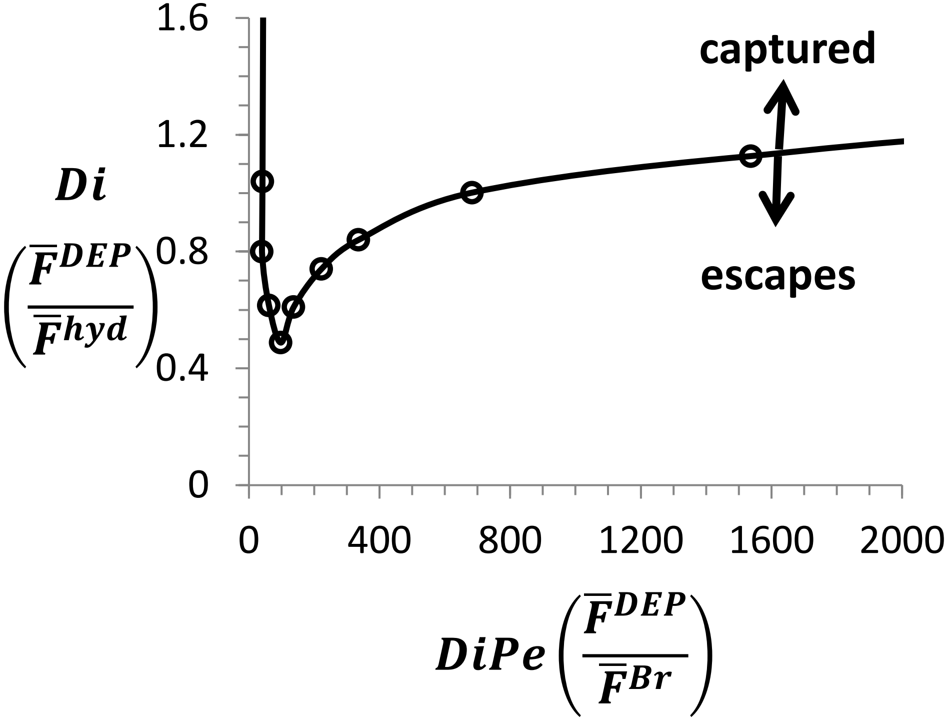

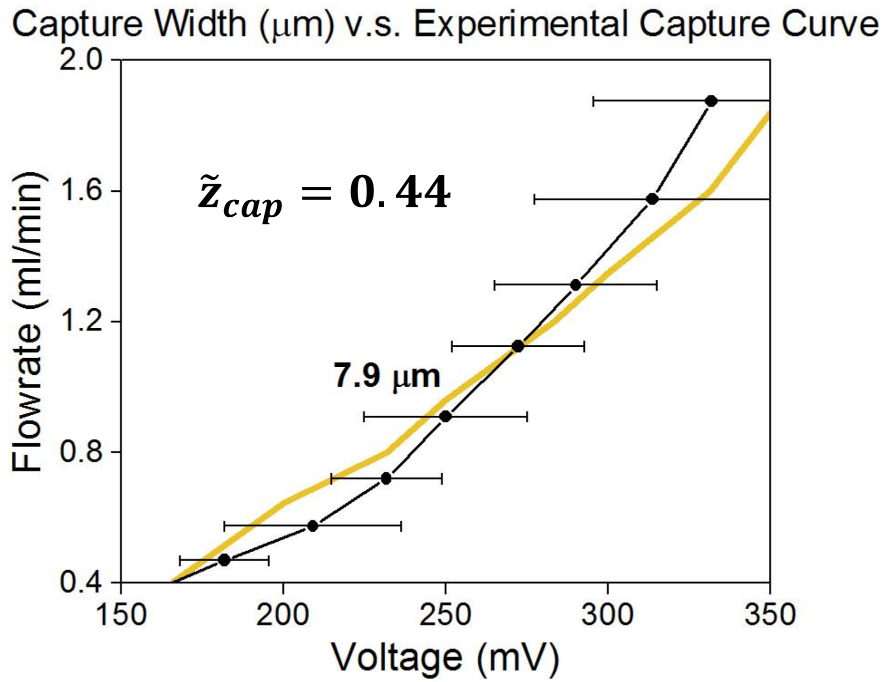

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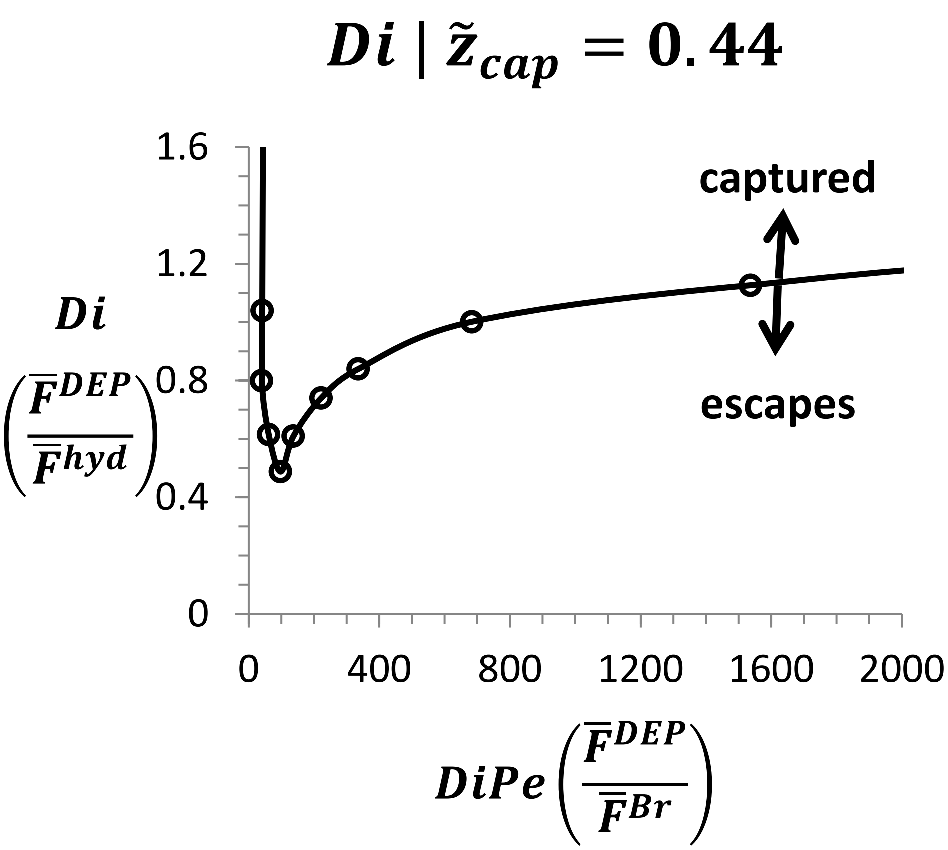

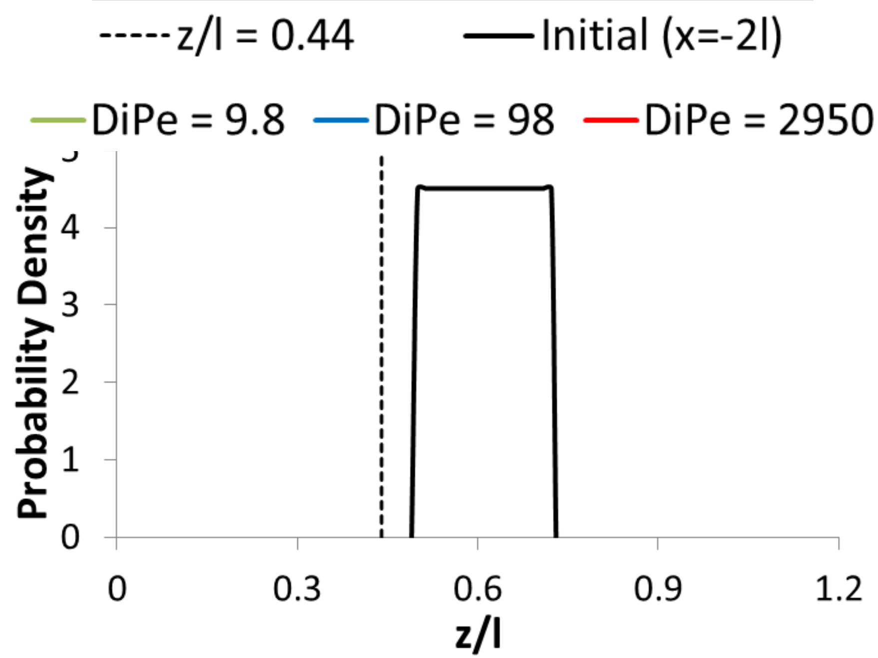

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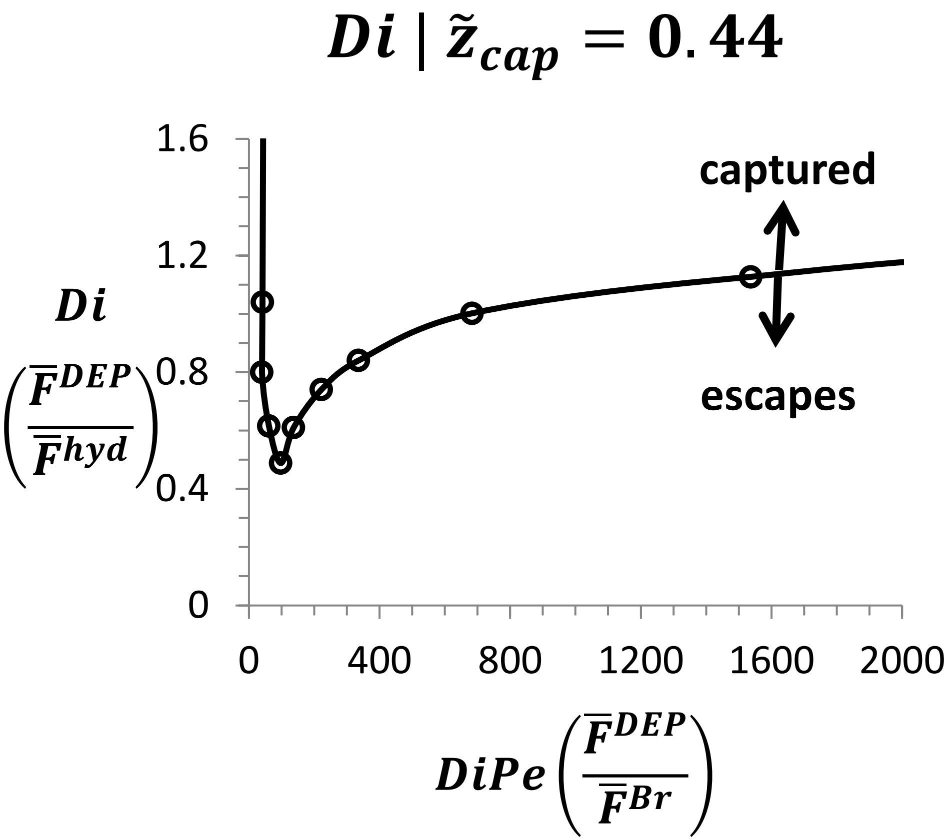
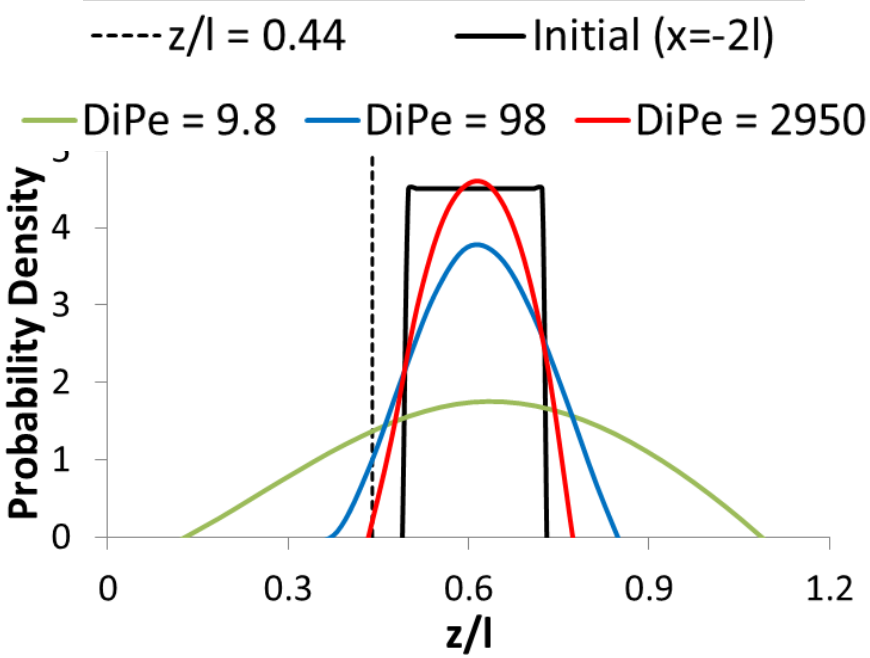
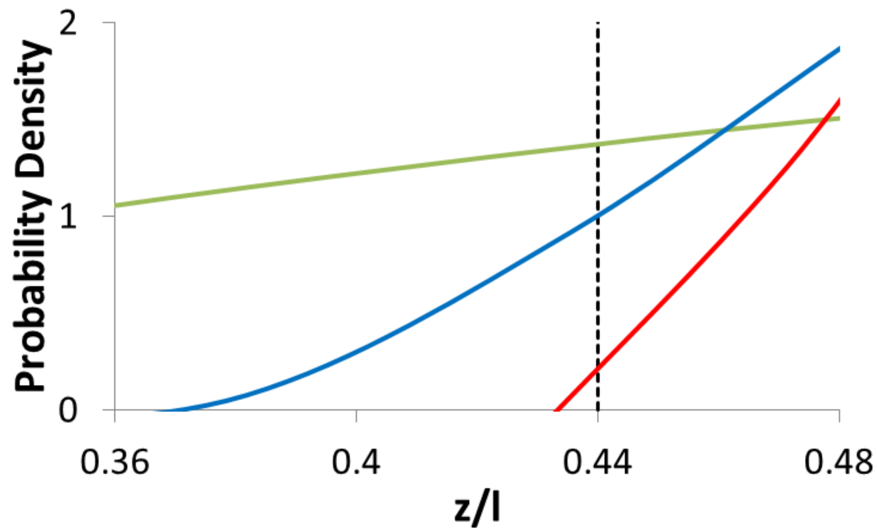
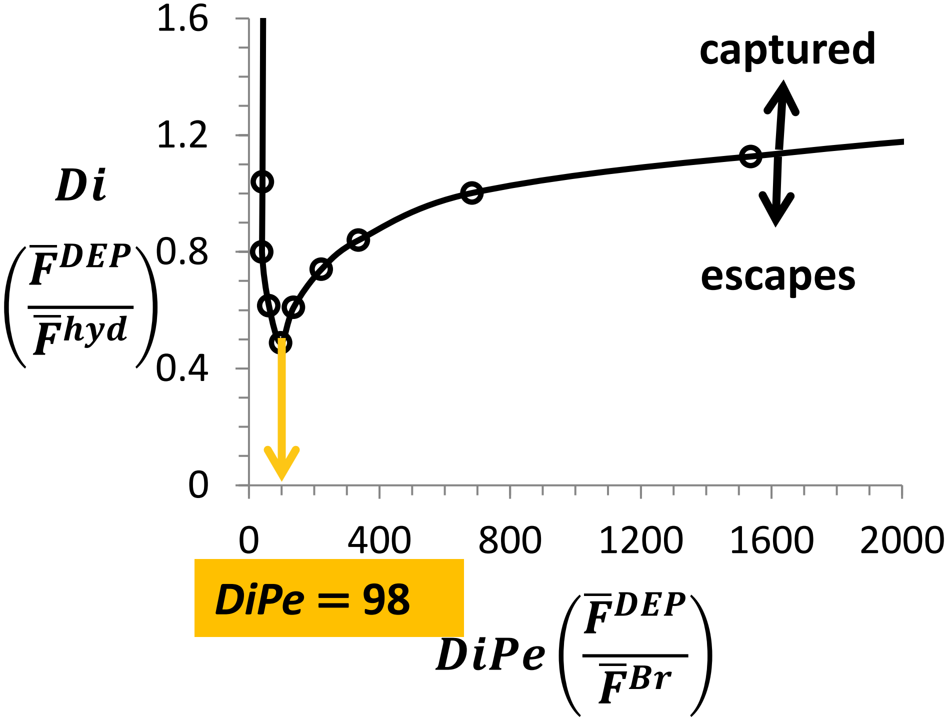


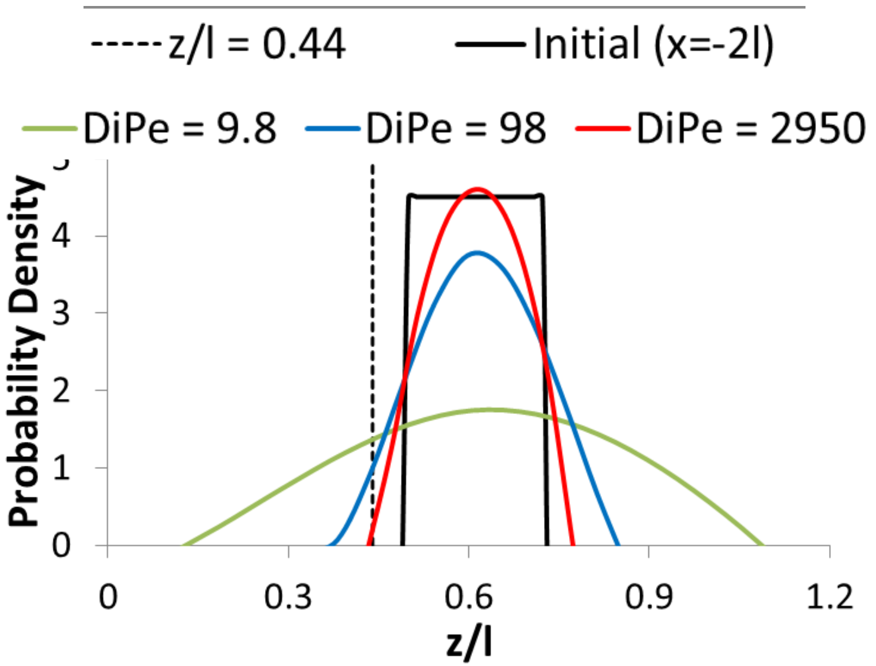


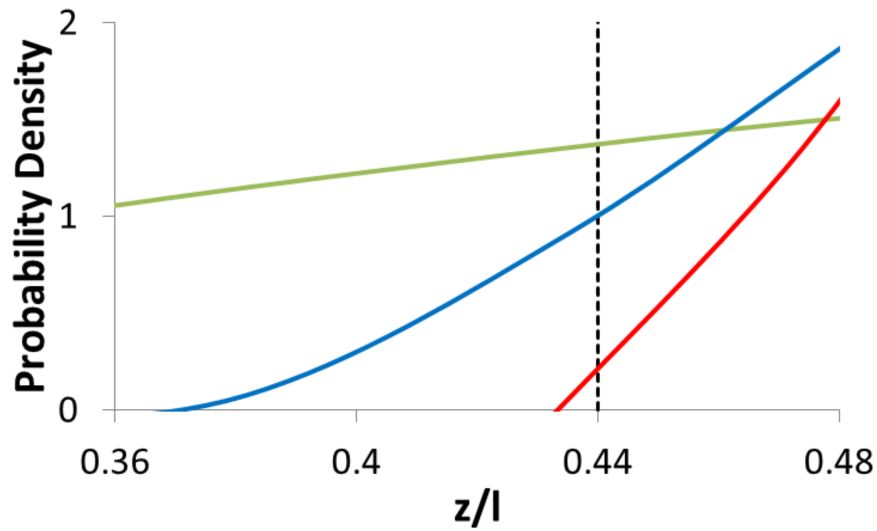


Diffusion Helps … Up to a Point

$$Di \mid \tilde{z}_{cap} = 0.44$$



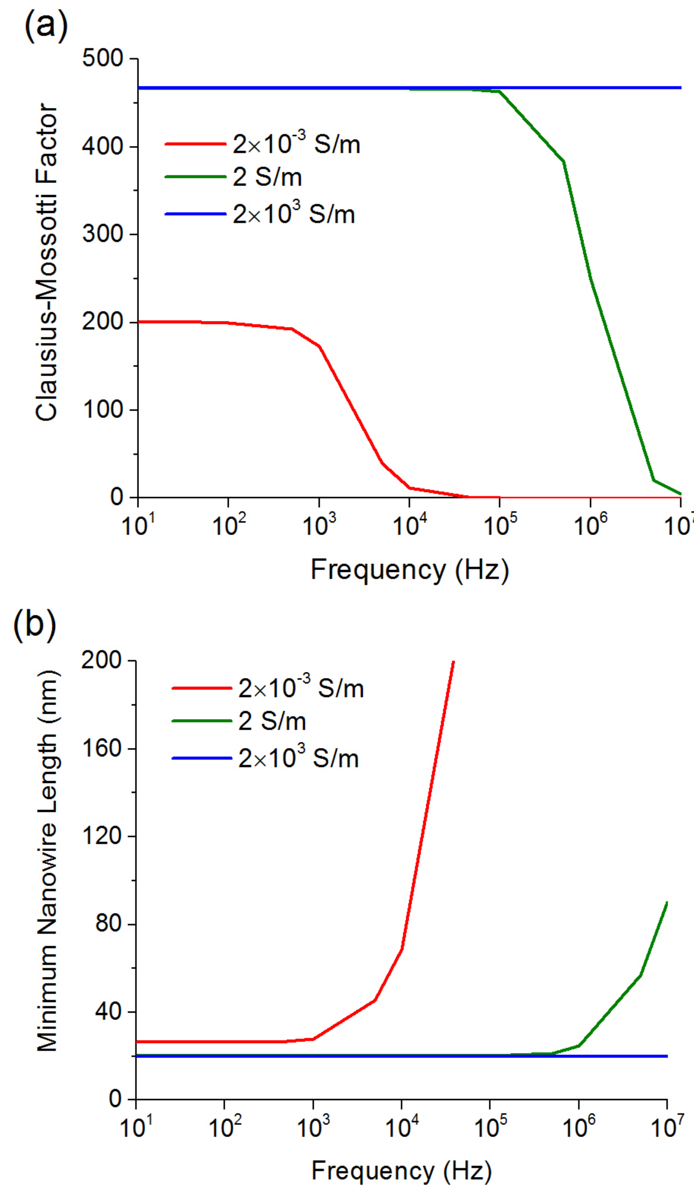




Increasing Pattern Density

With decreasing gap length, the electric field strengthens for a fixed applied potential

- We want $DiPe \geq 98$
- $DiPe \propto Re(K)(V_0/d)^2 l^3$
- $V_0/d < 60\ MV/m$ (dielectric breakdown)
- $\Rightarrow l^3 \propto \frac{DiPe}{Re(K)(V_0/d)^2}$



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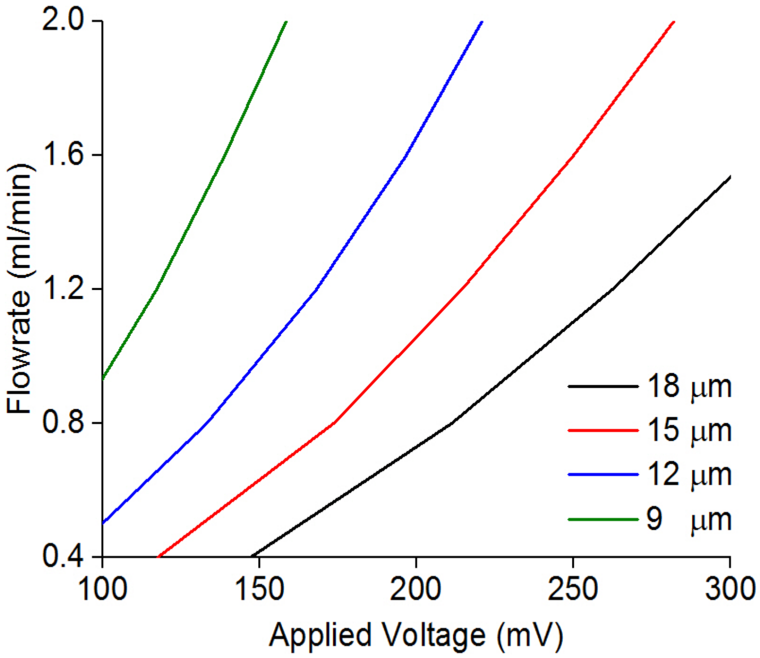

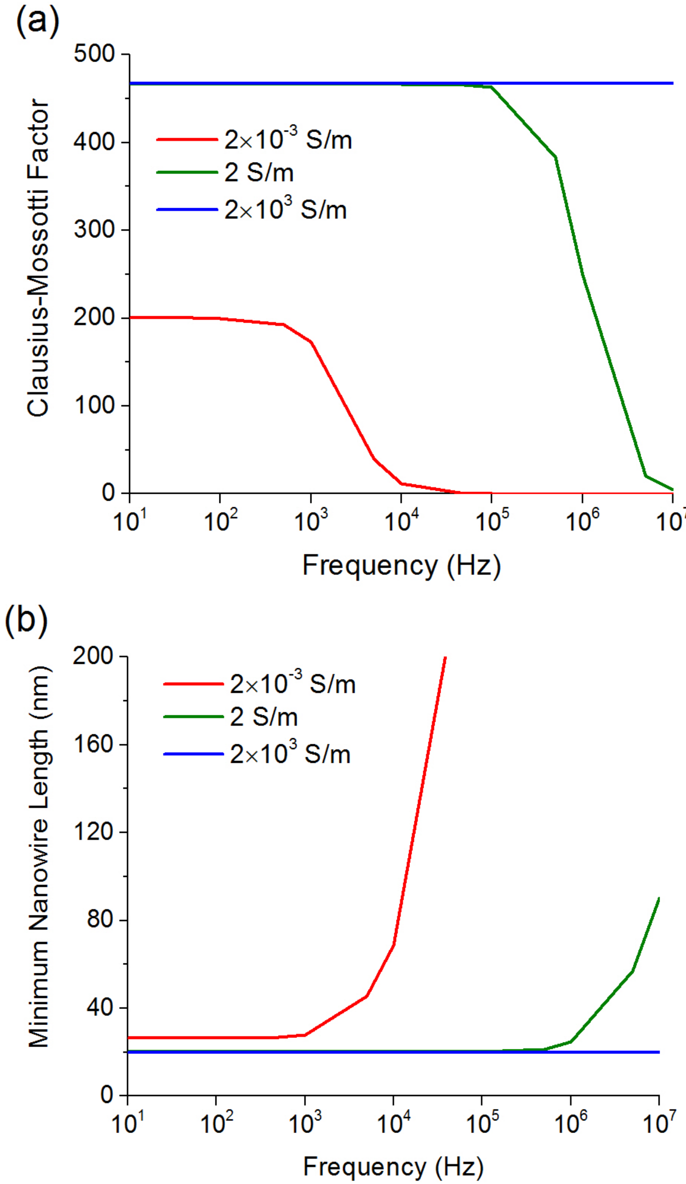

Conclusions

Flow-Assisted DEP Deposition

- Successful capture happens when capture width > depletion width.
- *Di* and *DiPe* describe how dynamics are effected by experimental parameters and material properties.
- Diffusion aids capture by reducing the depletion width, but sets a minimum size ~ 20 nm for which flow-assisted dielectrophoretic assembly is feasible.