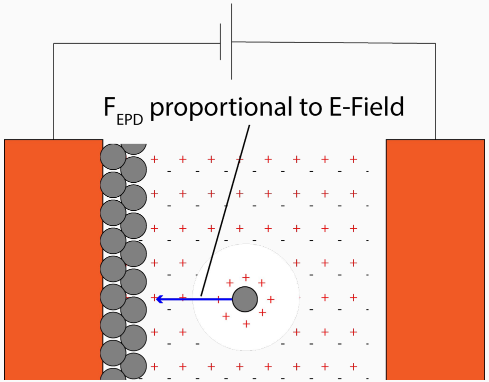
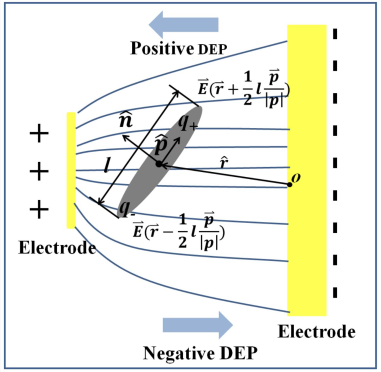
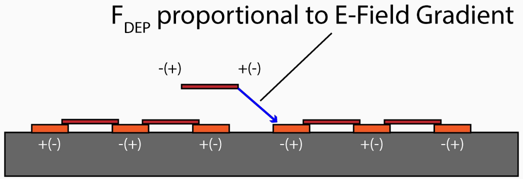
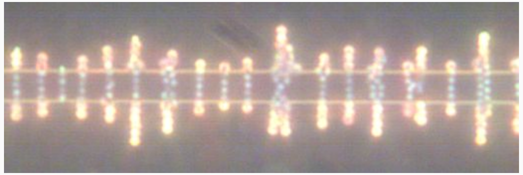
Multiphysics Nanoparticle Assembly: Design, Simulation, and Applications









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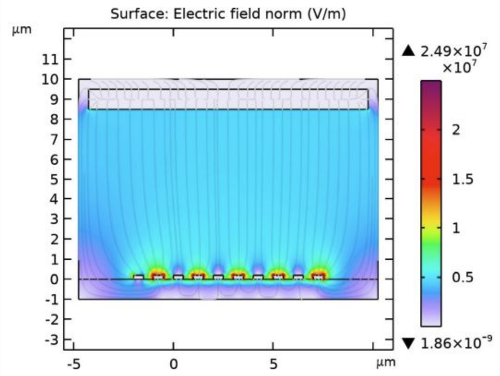

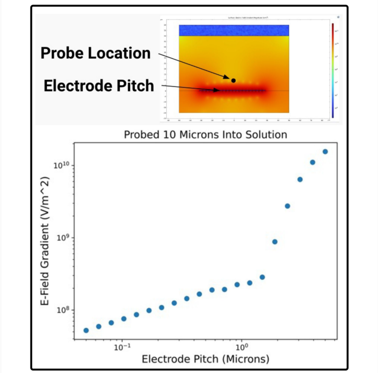

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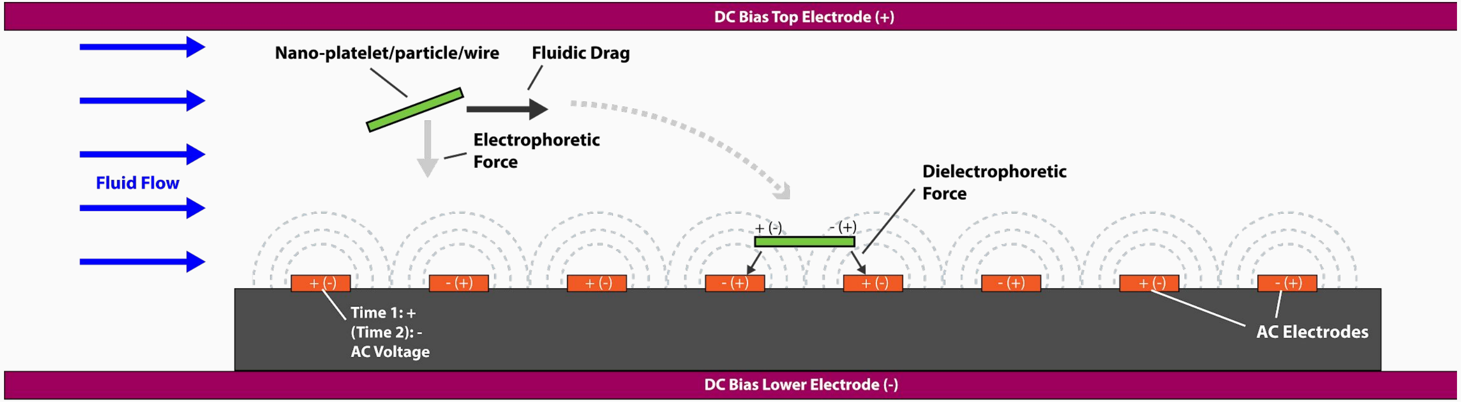
Nanoparticle Assembly

Applications
- MEMS resonators
- Biosensors
- Transistors
- Photo-emitters
- Photo-detectors
- NP quantum dots



- Many nanoparticles can be assembled in a parallelized process using electrical and fluidic forces
- Forces which will be simulated here are electrophoretic and dielectrophoretic forces
- Extended simulations in the future are fluidic forces, dipole-dipole forces, and brownian motion

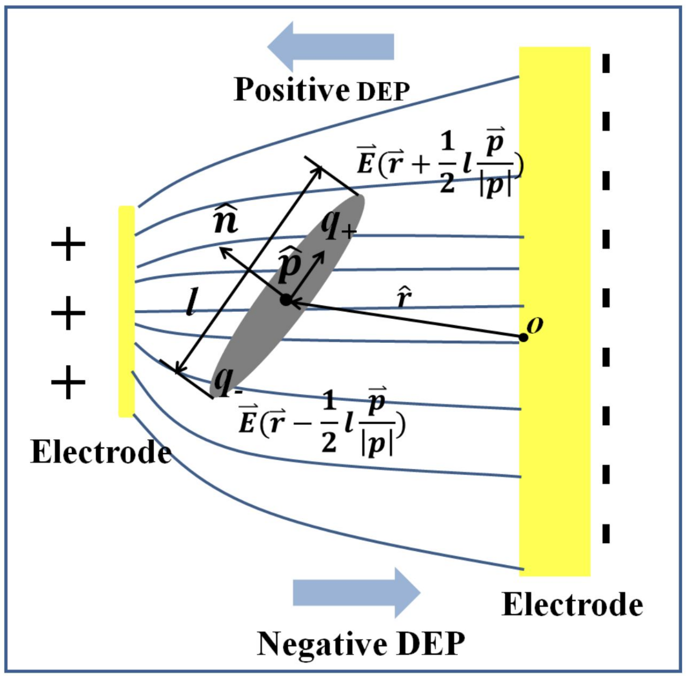
Dielectrophoresis (DEP) Background

When a particle is placed in an electric field created by electrodes its positive charges are attracted toward the negative electrode and its negative charges are attracted toward the positive electrode. The net resultant force experienced by the particle is given by:

$$\vec{F}(\vec{r}) = q_{+}\vec{E}\left(\vec{r} + \frac{1}{2}l\frac{\vec{p}}{|\vec{p}|}\right) + q_{-}\vec{E}\left(\vec{r} - \frac{1}{2}l\frac{\vec{p}}{|\vec{p}|}\right)$$

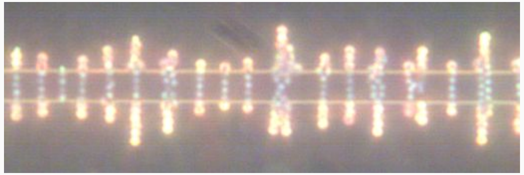
Where p is the electric dipole moment, r is the distance vector between the center of the dipole and the reference point O and l is the length of the particle. This shows that the DEP force is proportional to the difference in electric field intensity, and thus the particles will move toward the location with the highest electric field intensity.

The net DEP force is proportional to electric field gradient

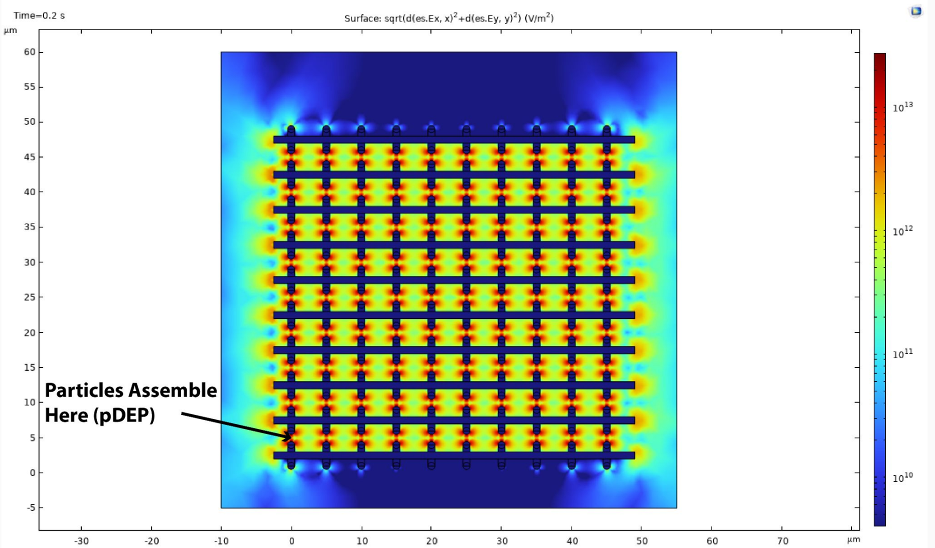


Electrode Shape Effects

- Parallel electrodes may be used where many parallel nanowires or chains of particles are to be assembled without spacing requirements
    - i.e. sensing applications
- ”Finger-like” electrodes are desired where single nanoparticles are to be assembled at specific locations
- The concentration of DEP force at the tips of the electrodes allows for chaining to be overcome by fluidic drag



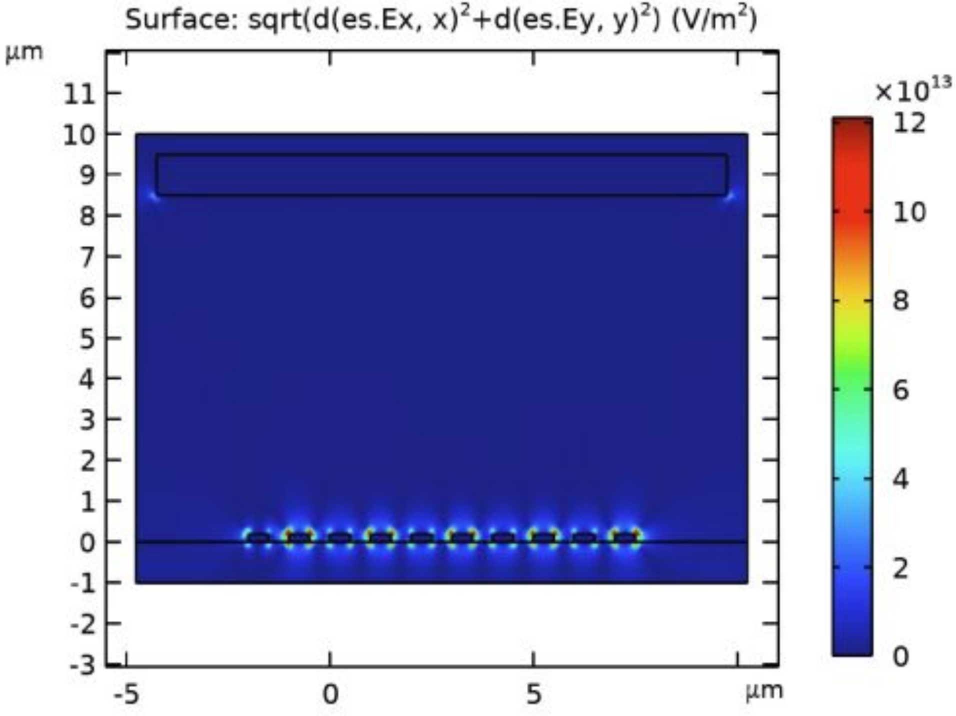
Parallel



Finger-like electrodes

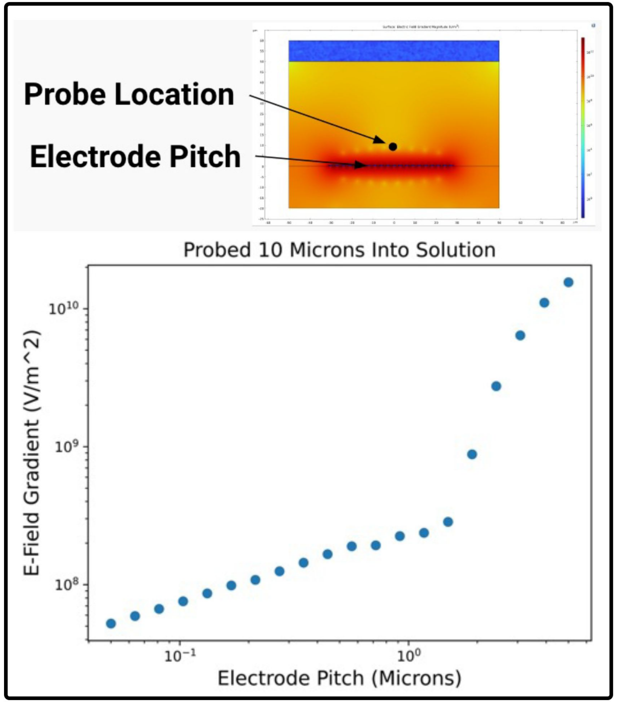
Electric Field Gradient Simulation

- The electric field gradient was simulated using finite element analysis to investigate how quickly the dielectrophoretic force decays with distance from electrodes
- In this example an 5Vpp was applied to the substrate electrodes and the electric field gradient was calculated at max voltage
- The gradient, and largest DEP force, is near the electrode edges and decays into solution



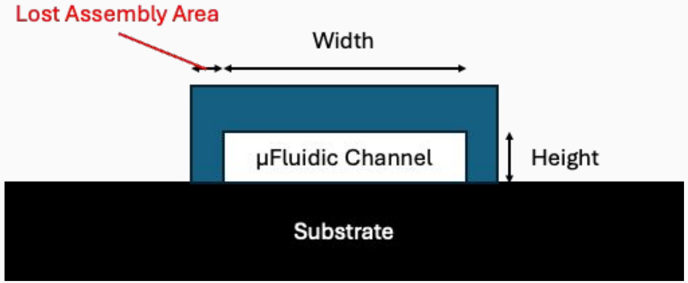
Effects of Electrode Spacing on Electric Field Gradient

- Electrode spacing may change depending on the application
  - Smaller electrode gaps are needed for smaller particles where single particle deposition is required (i.e. photonic or semiconducting wires)
  - Larger electrodes may be desired for larger nanowires or if chaining is desired (i.e. MEMS resonators, biosensing wires)
- To investigate the effect on DEP the electric field gradient was simulated with varying electrode pitch at a constant distance
  - Finer electrode pitches resulted in decreasing DEP force at a fixed distance from the substrate
- For fine pitched electrodes particles need to be moved closer to the substrate for assembly

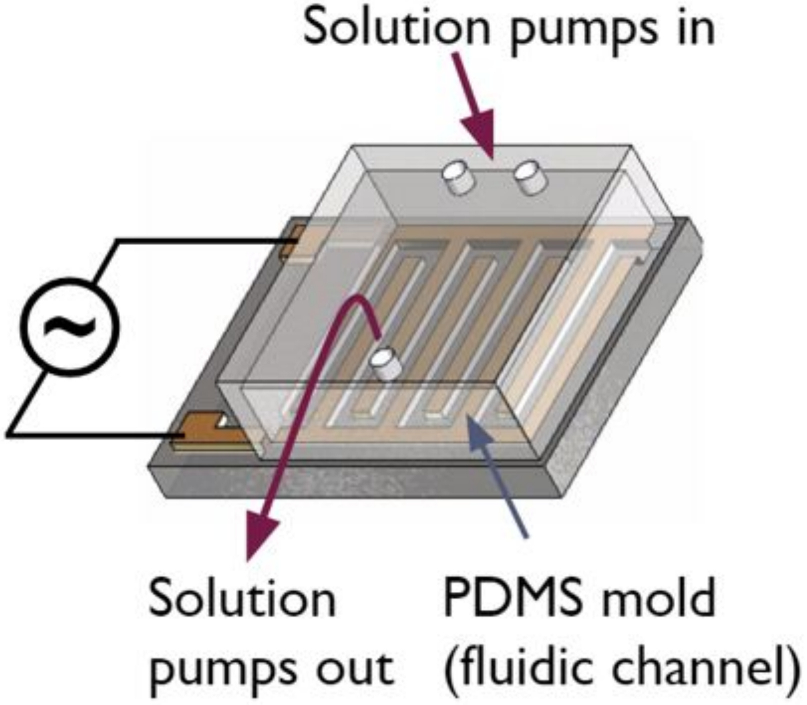


Moving Nanoparticles Within DEP Range

- Previously this has been achieved in laboratory setups using microfluidic channels, with some limitations
  - Channels contaminate substrate surface
  - Channels below a certain aspect ratio collapse
  - Channels can become detached during assembly
  - Assembly area is limited by channel width



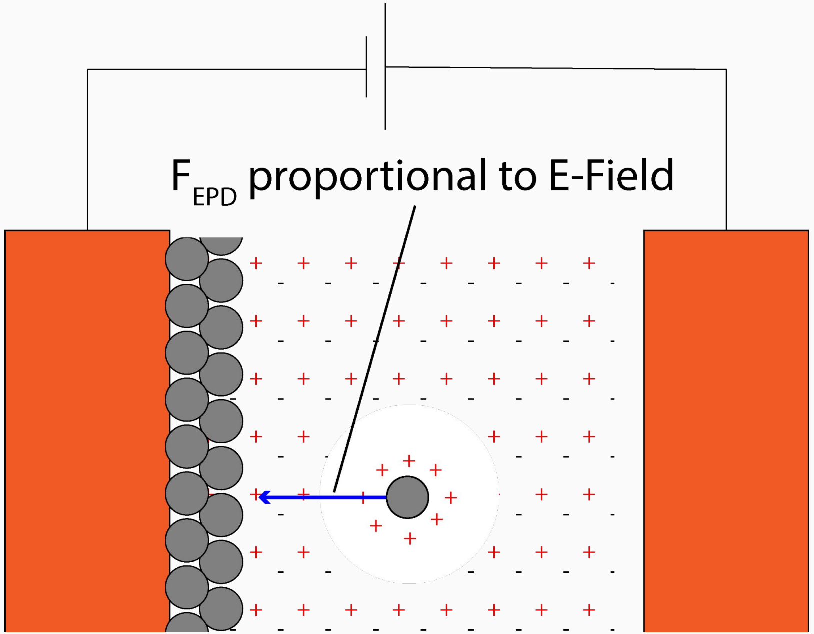
A contactless approach is needed for manufacturability



An Alternative Approach, Electrophoresis

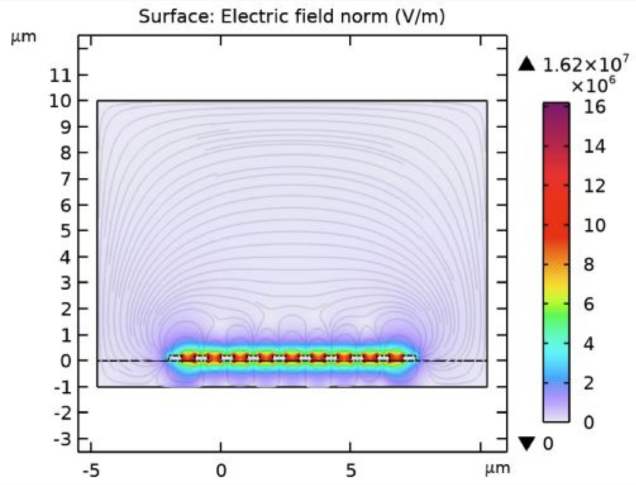
- A particle in solution can be induced to have a positive or negative surface charge by adjusting the solution pH, modifying the particles surface through functionalization, or utilizing solution additives
- Once charged the particle repels nearby particles in solution due to an oppositely charged electric double layer around the particle surface
- When placed in an electric field the particle experiences a force proportional to the electric field and near surface potential (Zeta Potential)

The net EPD force is proportional to the electric field magnitude

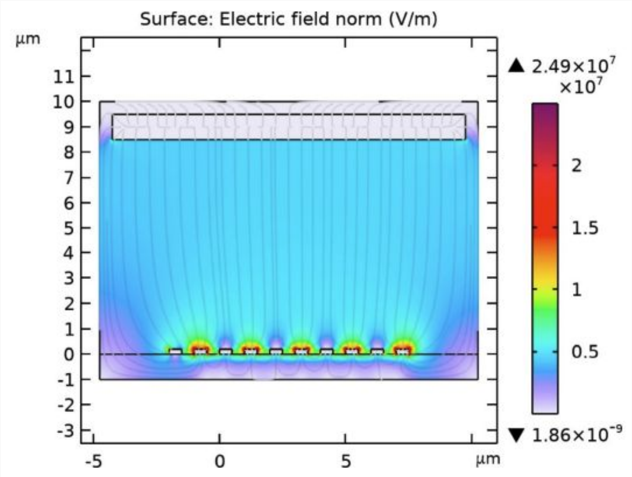


Electric Field Simulation

0V Bias

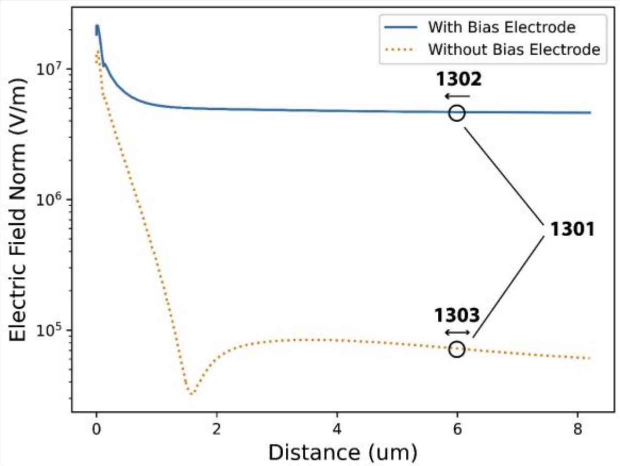


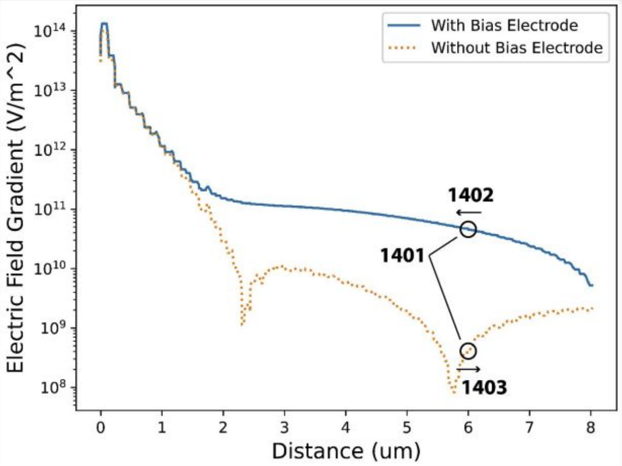
-40V Bias



- A bias voltage results in an approximately uniform electric field, and uniform EPD force far from the substrate surface
- Close to the surface the force is greatest on the AC electrodes of the opposite polarity at the time of observation
- Tuning of the bias voltage will be required, depending on the relative polarizability (DEP driver) and zeta potential (EPD driver) of the particle/solution system to prevent blanket coatings

Combining Electrical Effects

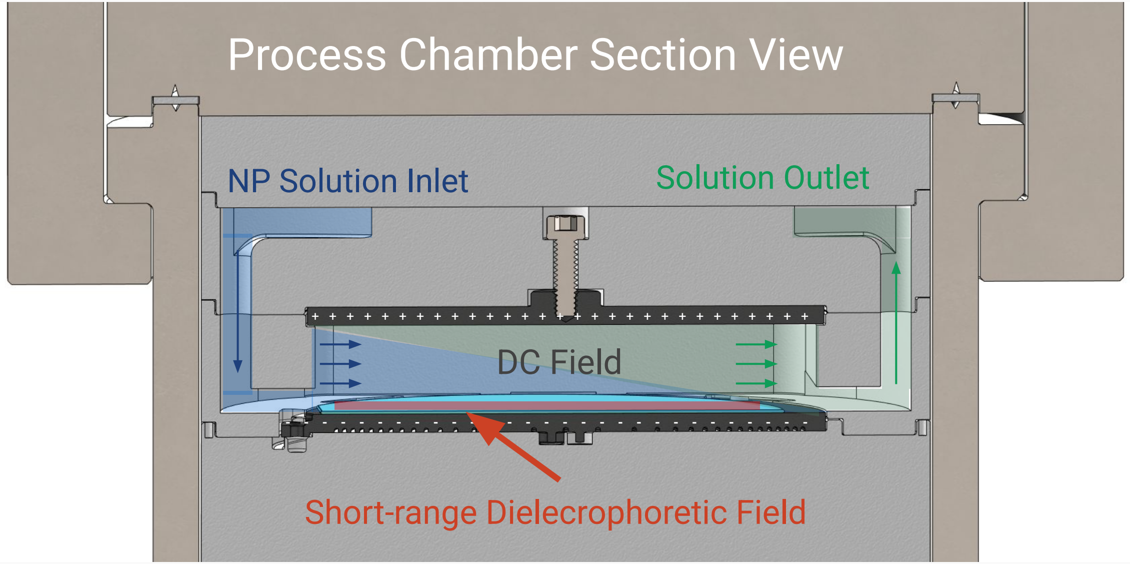




- Applying bias to a counter electrode results in a uniform electric field, and uniform EPD force to move particles close to the substrate
- This does not lead to a negative interaction with the dielectrophoretic force as the electric field gradient remains unchanged near the substrate surface

Future Work

- Computational fluid dynamic simulation will help refine the process flow internal design
  - Decrease turbulence
  - Improve uniformity of flow rate across substrate
- Dipole-dipole interaction simulation could provide insight into preventing or achieving chaining of particles
- Combined simulations could improve electrode design



Specialty Nanomaterial Deposition Equipment for Semiconductors and Semiconductor Packaging

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Directed Nanoparticle Assembly

- Semiconductor market focus
- Deterministic nanoparticle alignment and placement
- Lithographically defined
- High-selectivity assembly

Nanoparticle Deposition

- Semiconductor packaging focus
- Thick films
- High-aspect ratio fill

Novel Process

- Particle deposition from fluid suspension
- Electric field controlled deposition
- Conductors, insulators, semiconductors
- Accelerated deposition rate; 1-step full-wafer assembly
- In-situ supercritical drying
- Process scaleable to volume production

Prototype Chamber
100 mm Wafers

R&D focused

Semi-automated

Manual Load

Patent Pending