Fabrication of a Polymeric Microfluidic Device with Inkjet-Printed Silver Electrodes for Electrokinetic Bioparticle Characterization

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Abstract

We are developing an inkjet printing technique for patterning electrodes on polymeric substrates to create microfluidic devices for bioparticle applications. Electrode deposition is important for actuating electrokinetic phenomena in microfluidic devices, and polymeric substrates are becoming increasingly common. Dielectrophoretic (DEP) forces are induced via application of a spatially non-uniform electric field and are directly dependent on the sign and magnitude of the Clausius-Mossotti factor. Accurate characterization of particle response when subject to spatially varying electric fields is essential for successful implementation of DEP-based particle sorting and manipulation techniques. We propose a microfluidic device that will (a) characterize Clausius-Mossotti factors for biologically relevant particles and media, and (b) allow for easy and inexpensive fabrication outside of a clean room environment. Particle characterization is conducted using an interdigitated electrode design in a polymeric microchannel. A Dimatix inkjet printer is used to deposit micro-scale electrodes onto Zeonor 1020R using a silver nano-ink (PChem Assoc.). Electrode resolutions of approximately 70 μm have been accomplished using these techniques, which are compatible with applications on a biological scale. The inkjetting protocols developed allow for fast, inexpensive fabrication of our device and rapid prototyping for future research.

Summary

We are developing inkjet printing techniques for the rapid prototyping and manufacture of polymeric microfluidic devices that require on-device electrodes. Microfluidic devices have been produced utilizing DEP forces for particle sorting [1]. Proper functioning of these devices requires accurate characterization of DEP mobility. We desire a DEP characterization device that is cheap and easy to manufacture outside of a clean room environment. Cyclo-olefin copolymer substrates, such as Zeonor, are ideal for this application since they are inexpensive and mechanically resilient. The deposition of highly conductive electrodes on these substrates is necessary to generate locally non-uniform electric fields.

Dielectrophoretic forces are felt by mobile, polarizable particles subject to spatially-varying electric fields. Analytical modeling of these forces is possible when idealized particles are considered. However, accurate modeling becomes difficult when dealing with biological particles such as cells, which are of non-uniform shape and composition, and are subject to multiple double-layer effects. The magnitude and sign of the DEP force is dependent on the Clausius-Mossotti factor (f_{cm}) (Figure 1). This factor measures the difference in complex permittivity ($\tilde{\varepsilon}$) between a particle and a medium in which it is suspended. The complex permittivity is a relation of the permittivity (ε) and frequency-dependent conductivity (σ) of a given material. Under a negative DEP force, a particle will be repelled from regions with a high electric field, whereas positive DEP corresponds with movement toward higher electric fields.

$$\left\langle \vec{F}_{DEP} \right\rangle = \pi\varepsilon_m a^3 \operatorname{Re}\left[f_{CM}\right]\nabla\left|\vec{E}\right|^2$$

$$f_{CM} = \frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_m}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_m}$$

$$\tilde{\varepsilon} = \varepsilon + \frac{\sigma}{j\omega}$$

Figure 1: Equations for dielectrophoresis and the Clausius-Mossotti factor.

Our proposed device for characterizing DEP mobility relies on interdigitated electrodes crossing a microfluidic channel (Figure 2). The electrodes alternate positive and negative to create a non-uniform electric field. By varying voltage amplitude at a given frequency and known flow rate, a graph of the trapping voltages against drag and sign of the DEP force can be obtained.

Electrode deposition was achieved on Zeonor 1020R using a Dimatix Materials Printer (DMP-2800), a tabletop inkjet printer. To be jettable, an ink must not have large agglomerates of particles or settle quickly, and should have low viscosity and surface tension. Modifications were made to the PFI-300 (PChem Assoc.) silver ink to produce a jetting, conducting ink. The pH of the ink was raised to 5.4 using a solution of 5:1 deionized (DI)

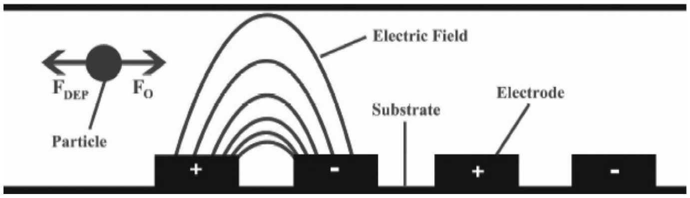

Figure 2: Side view of the proposed dielectrophoretic mobility characterization device, where F_0 denotes Stokes' drag force.

water to ammonium hydroxide, altering interparticle potentials and resulting in smaller aggregations. The ink was then filtered through a 0.8 μm filter to remove any remaining large particles. DI water could then be added to increase fluid volume and decrease concentration. Solutions of up to 5:1 DI water to ink were tested, with 1:2 yielding the best results with regards to jettability (Figure 3). The surfactant Triton X-100 was added in small amounts to later inks prior to filtering, which resulted in better electrode conductivity. A ratio of 40:1 Triton X-100 to ink resulted in the most effective jetting while maintaining conductivity.

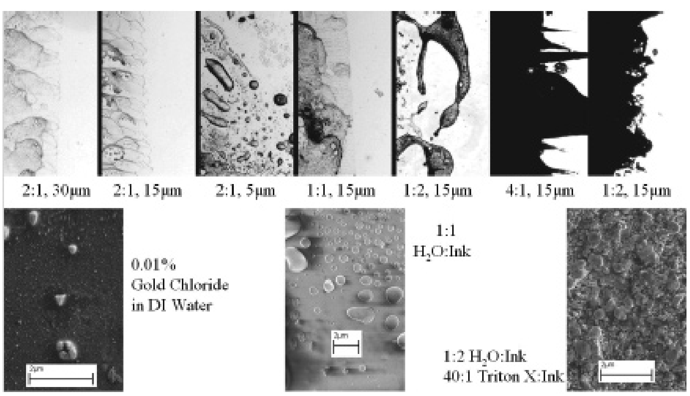

Figure 3: Various inks printed on a Zeonor 1020R substrate given in ratio of DI water to ink.

The Dimatix inkjet printer had to be tuned for functional ink jetting. Even after filtering, particle settling and ink evaporation resulted in clogging at the nozzle head. A 0.1 second purge cycle, during which a pressure increase forcefully pushed ink through the nozzles, was run every 300 seconds to remove clogs and keep the ink fresh. No heat was applied to the nozzle or to the Zeonor substrate, and voltage amplitudes were adjusted specifically for each nozzle.

Using these techniques and materials, we were able to produce promising results. Conductive silver electrodes were successfully printed onto a Zeonor substrate. We were only able to resolve the printed silver features down to about 1 mm. This was due in part to some variability in the angle at which the silver droplets would leave the print head. We hope to be able to produce smaller resolutions in the future. The device has been printed on paper using a model ink with 90 μm resolution (Figure 4), which is sufficient to actuate DEP forces in biological particles. Electrode adherence to the Zeonor substrate has been tested with several solvents, including ethanol, isoporopynol, and acetone. Adherence can be improved by depositing a 3-Mercaptopropyltrimethoxysilane monolayer onto the Zeonor substrate prior to electrode printing, though this is necessary only if the electrodes are subject to relatively large mechanical stresses. We believe that our inkjet manufacturing techniques will allow electrode-based microfluidic devices to be easily produced, paving the way for future rapid prototyping applications.

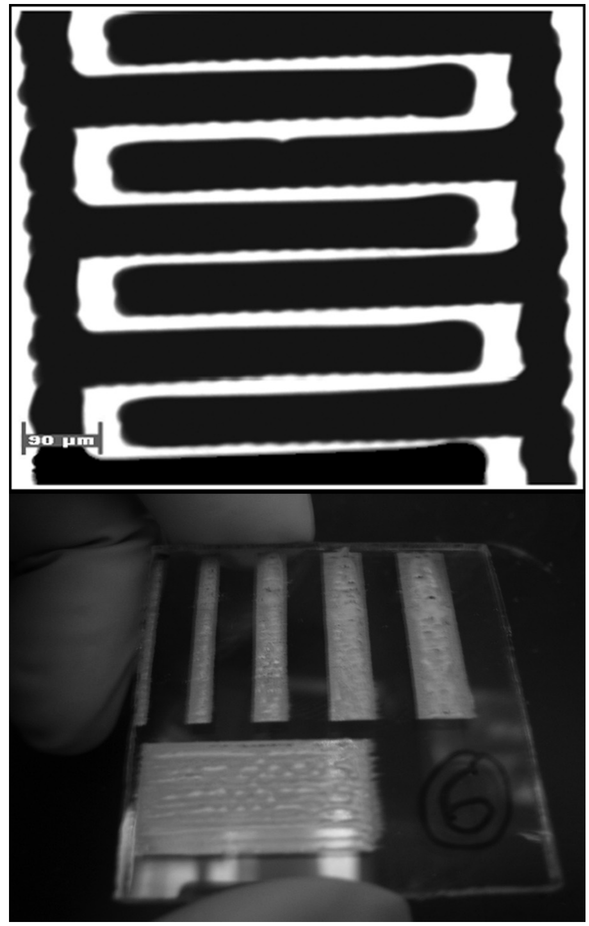

Figure 4: Top; High resolution printing of DEP characterization device with model ink on paper. Bottom; Ihe electrodes printed on Zeonor, with researcher's hand for scale. Ihe electrodes all conduct along their entire length and are of different widths. The far left is 1mm wide.

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References

[1] Hawkins, B.G., Smith, A.E., Syed, Y.A., and Kirby, B.J., Anal. Chem., 2007.