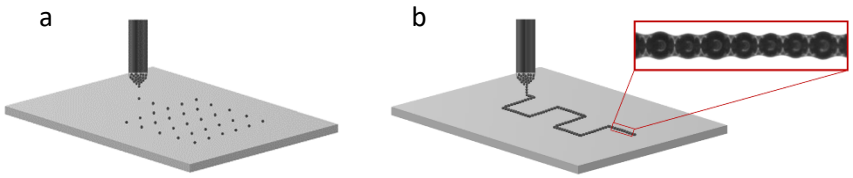
Method for efficient particle deposition on a substrate using electric field and capillary interactions

Zbigniew Rozynek,[1,2,#] Agnieszka Magdziarz,[1,2] and Yaroslav Harkavyi[1]

[1] Cadenas, Uniwersytetu Poznańskiego 2, 61-614 Poznań, Poland
[2] Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland
[#] PoreLab, The Njord Centre, Dept. of Physics, University of Oslo, Blindern, N-0316 Oslo, Norway (guest researcher)



Graphical abstract: *The electric method facilitates efficient deposition of particles upon various kinds of substrates using a variety of particle materials. It enables formation of, for example, (**a**) particle arrays, (**b**) 1D micropaths made of aligned one-by-one particles on substrates (as shown in the inset image), and many more particle structures.*

Abstract

Over the years, many approaches for depositing nano- and microparticles on substrates and assembling them into different patterns, such as particle arrays or 1D beaded micropaths, have been developed and significantly improved. These include electrohydrodynamic (EHD) particle deployment,[1] optical tweezers,[2] dip-coating techniques,[3] magnetic[4,5] or electric field–assisted methods,[6–9] self-assembly on lithographically patterned substrates,[10–16] capillary flow–assisted assembly,[17, 18] and mechanical manipulation with the use of microrobots, tapered fibres, or metallic micro-needles connected with hydraulic micromanipulators.[19–22] However, each of the methods has one or (commonly) more of the following disadvantages: its expensive, time-consuming, or inefficient (only a limited number of particles can be manipulated in one step, e.g., when using optical tweezers or micro-manipulators), requires access to advanced tools and laboratories (e.g., cleanrooms for producing templates or patterned substrates using electron beam lithography), involves immersion of a substrate in liquids, enables formation of only one kind of particle structures (particles separated from one another or 1D beaded paths), or works only for a narrow range of particle sizes and/or types. Thus, the efficient deposition of particles on different types of substrates to form particle arrays, 1D particle micropaths, or other structures that require single-particle resolution precision is still a great challenge.

In this seminar, I will be presenting an electric method for the particle deposition on a substrate that we have been developing for a while now. The route enables formation of particle arrays, 1D particle microstructures (as shown in the graphical abstract), and many other structures, such as particle micro pillars or binary structures (e.g., paths composed of two different particle types or sizes). The method overcomes several of the above-mentioned limitations, and facilitates the continuous production of single-particle-thick micropaths (linear and nonlinear patterns) using a variety of particle materials (such as hard or soft particles, solid or hollow particles, core-shell particles, microcapsules, hydrogel particles, and more) of different shapes (spherical, oval, cylindrical), with a wide size range (from around 10 μm to around 1 mm) and a high production rate (up to several thousand particles per second). It also enables deposition of particles on geometrically uneven and flexible substrates, as well as on substrates with cracks, wells or steps, which makes it remarkable and unique.

For a moment, only several experiments with rather large particles have been performed, and more thorough and comprehensive studies are required. We need to understand the physics behind the process to be able to perform scaling analysis to find out the limitations of the method. There are plenty of scientific questions to be answered and engineering problems to be tackled. Below I am listing examples of the unanswered questions. The main motivation for giving this talk is to get your feedback that will help us to understand the physics of the process, and receive suggestions regarding the possible applications for our method.

The electric method: In short, in the method (sketched in **Fig. 1**), the particles' deposition on a substrate resembles the traditional ink printing or direct writing additive processes used in 2D or 3D printers, in the sense that a printing unit containing a material is translated against the substrate on which the particles are to be deposited. There are two modes of particle printing proposed. In the first mode (Mode 1), the single-particle deposition is achieved via turning on and off an electric tension provided to the conductive nozzle, as show in **Fig. 1a–e**. The pattern (of separated particles) is formed by a step-by-step translation of the nozzle and the application of the electric field for a short time at each step. In the second mode (Mode 2), the electric tension is maintained all the time during the horizontal translation of the microcapillary. I will mainly be talking about the Mode 2 of the method. The Mode 2 enables fabrication of 1D beaded paths on a substrate, as presented in **Fig. 1f–j**. This process is continuous, as the particles from the dispersion meniscus continuously 'feed' the primary 1D structure (see **Fig. 1h**) created between the meniscus and the substrate, and the shape (a line or a 2D pattern) of the particle structure is governed by the motion of the nozzle.

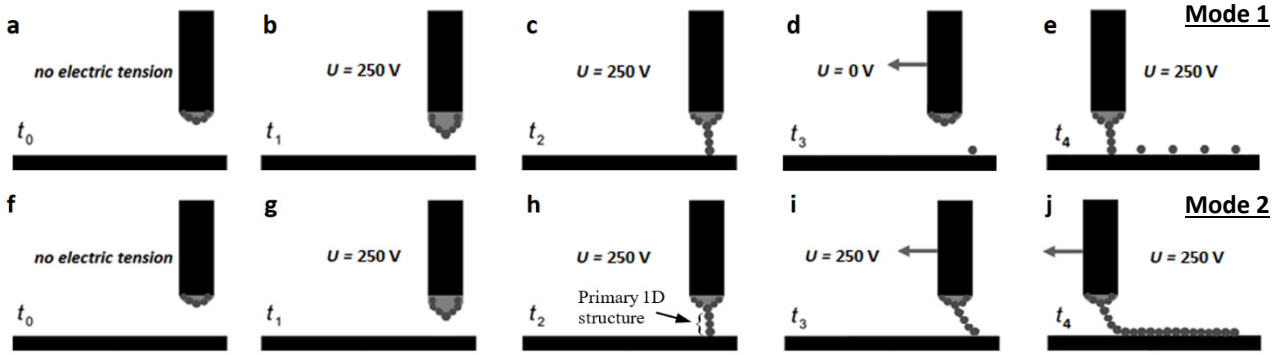


Figure 1: Schematics of two modes of particle deposition. **(a,f)** Particle dispersion is supplied through a microcapillary so that a dispersion meniscus is formed at its one end. **(b,g)** Application of an electric tension to the microcapillary deforms the meniscus, and **(c,h)** guides particles towards the substrate forming the primary 1D particle structure. In Mode 1, the electric tension is turned off as soon as the particle reaches the surface and then the microcapillary is translated to the new position **(d)**. Repeating the steps presented in panels b-d leads to the formation of a particle array. In Mode 2, the electric tension is on once the microcapillary is translated, and **(i–j)** the particles nearest to the substrate are attracted to it by the electrostatic force, forming a 1D particle micropattern on the substrate.

The studied system is very rich in physical phenomena and there are several questions to be answered.

Q1: What is the role of the parameters of applied electric tension (frequency, voltage, signal shape) in the mechanism of the formation of the primary 1D particle structure?

Q2: What is the bottom limit of particle size for the method to work?

Q3: What is the upper limit regarding the deposition rate for each operating mode?

Q4: How does the particle deposition on a substrate depend on parameters of the electrode, such as its geometry, position above the surface of a substrate)?

Q5: What is the role of the parameters of the dispersion liquid (such as, viscosity, ionic conductivity, wettability) on the mechanism of the particle deposition?

Q6: How important is the cohesion force between the deposited particles and the substrate in the general performance of the method?

Q7: How do parameters of particles and a substrate affect the ordering of deposited 1D particle paths?

Q8: How does force distribution within the primary 1D structure change as its length grows?

Q9: What are the electric requirements of the surface of a substrate for the method to work, for example, will the method work for electrically highly conductive substrates?

Q10: In principle, the method should work on a substrate covered with a thin film of liquid. If yes, how do ensure the anchoring of deposited particles to the substrate so that the particles are stable on it.

Q11: What is the role of the coupled electric and capillary interactions in the mechanism of the formation of the 1D particle structure? Can the thickness of that primary particle structure be controlled?

Q12: To what degree the bending stiffness of the primary 1D particle structure be controlled by *E*-field and capillary forces? How do the mechanical properties of the structure scale with particle size?

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