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Effect of the electrostatic focusing lens voltage on structures size in 3D printing by charged Au nanoparticles

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Abstract. The paper demonstrates a method for three-dimensional aerosol printing of charged nanoparticles using electrostatic focusing through a conductive matrix lens. The study showcases the successful printing of narrow and highly conductive structures on a silicon substrate, utilizing 20–180 nm gold nanoparticles and alternating voltage on a stainless-steel lens. The results indicate that structures significantly smaller than the lens holes were achieved, and an experimental relationship between the structure width and lens voltage was established.

Keywords: focusing nanoparticles, microstructure, inkjet printing, aerosol charging, additive manufacturing

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Материалы конференции
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Влияние напряжения электростатической фокусирующей линзы на размер структур при 3D-печати заряженными наночастицами золота

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Аннотация. В статье демонстрируется метод трехмерной аэрозольной печати заряженных наночастиц золота размером 20–180 нм на кремниевой подложке с использованием электростатической фокусировки через матричную проводящую линзу. В результате эксперимента была установлена экспериментальная зависимость между шириной структуры и напряжением на линзе. Также получены структуры до 20 раз меньшего размера, чем отверстие в линзе.

Ключевые слова: фокусировка наночастиц, микроструктура, струйная печать, аэрозольная зарядка, аддитивное производство

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Introduction

Creating narrow and conductive microstructures is a challenging yet promising field of study within printed electronics. These structures have potential applications as transparent electrode arrays, 3D interconnects, transparent heaters, optical metamaterials for light absorption or reflection, and photonic crystals. Various methods exist for focusing nanoparticles using physical forces like electrostatic [1, 2], magnetic [3], or capillary [4]. This study outlines an experimental setup for generating conductive structures through electrostatic focusing.

Materials and Methods

The process of synthesizing aerosol nanoparticles involved the electrical erosion of gold (Au) electrodes within an air-controlled environment, where the relative humidity was maintained at 34 ± 4% and the temperature at 23 ± 3 °C [5]. The airflow rate was recorded at 1 lpm. Next, the nanoparticles were sintered into spheres during the passage of a tubular furnace at a temperature of 985 °C for one second. Post-sintering, the nanoparticles were negatively charged via a unipolar charger. These charged nanoparticles were then introduced into the printing chamber for the deposition experiment, as depicted in Figure 1 of the experimental setup. The nanoparticles exhibited a log-normal size distribution, with mean size 62 nm, a GSD = 1.45, and a total number concentration of 2.8×10^6 cm^{-3}. The experimental design provided for a gap of 25 mm between the copper plate and the substrate with a dielectric layer thickness of 0.18 mm.

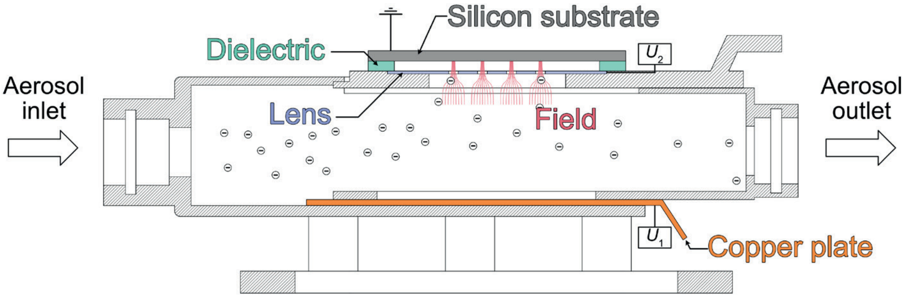

Fig. 1. The schematic of the experimental setup

The trajectory of charged nanoparticles within the focusing process is governed by a combination of forces, prominently including the Brownian force ($\overline{F_B}$), which arises from stochastic interactions with surrounding gas molecules. Additionally, the particles experience the Lorentz force ($\overline{F_L}$) and the drag force ($\overline{F_{Drag}}$) (presented in equation (1)). These forces are quantitatively represented in the Langevin equation, a fundamental mathematical model that elucidates the motion and aggregation behavior of nanoparticles under the influence of these forces during the focusing operation.

$$m\frac{d\overline{V_p}}{dt} = \overline{F_B} + \overline{F_{Drag}} + \overline{F_L} \tag{1}$$

In equation (1), m represents the nanoparticle mass, and $\overline{V_p}$ represents the nanoparticle velocity.

Издатель: Санкт-Петербургский политехнический университет Петра Великого.

Results and Discussion

The experimental outcomes showcase the ability to manipulate the dimensions of the printed structures by varying the voltage applied to the lens, designated as U_2. This control over size is quantitatively captured in Table, which summarizes the experimental data. The visual representation of this relationship is further depicted in Figure 2, offering a graphical interpretation of the effect of the applied voltage on the resulting structure size.

Table

The effect of lens voltage on the structure size

Plate voltage U_1, V	Lens voltage U_2, V	Lens hole size d_L, µm	Structure size d_S, µm
–25	–5	280	100
	–10		82
	–15		70
	–20		61
	–25		52
	–30		37
	–35		18
	–37		14

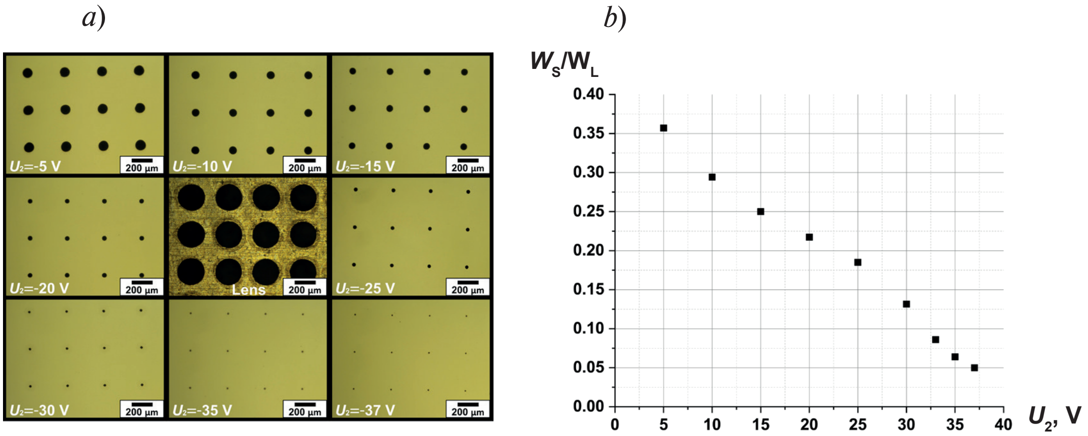

Fig. 2. Images of structures obtained at various lens voltage U_2 (image of the lens in the center) (*a*); Experimental dependence relative size of the structure on the absolute value of the lens voltage U_2 (*b*)

Elevating the voltage U_2 results in a heightened repulsive force acting on the nanoparticles at the periphery of the lens, altering the electric field distribution within the printing chamber. Notably, when the absolute voltage U_2 exceeds 30V, a marked reduction in printing velocity is observed, culminating in a complete cessation of printing at voltages surpassing 37V. This phenomenon is attributed to the nanoparticles being repelled from the lens surface towards the copper plate, thereby augmenting their distance from the substrate.

Conclusion

The paper discusses a test chamber designed for printing charged nanoparticles, featuring an optimal geometry that enables control over the size of the d_S structure. By adjusting the voltage on the U_2 electrostatic lens from −5 V to −37 V and maintaining a lens hole size of d_L = 280 µm, the size of the structure can be varied from 100 µm to 14 µm.

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