Supplementary materials

High density, addressable electrohydrodynamic printhead made of silicon plate and polymer nozzle structure

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Supplementary Data

1. Simulation model and setup

The fluid motion in the electric field is governed by the Navier–Stokes equations:

$$\nabla \cdot v = 0 \tag{1}$$

$$\rho \frac{\partial v}{\partial t} + \rho v \cdot \nabla v = - \nabla p + \mu \nabla^2 v + f_e + \gamma \kappa \nabla c \tag{2}$$

where ρ, v, p, μ and γ are the density, velocity, pressure, viscosity, and surface tension coefficient of fluids, respectively. f_e is the volumetric electric force acting on fluid. κ is the curvature (surface tension only exists at the interface between solution and air), which can be calculated by the volume fraction c in Level-Set (LS) method as follows:

$$\kappa = \nabla \cdot \left(\frac{\nabla c}{|\nabla c|} \right) \tag{3}$$

In the LS method, f_e can be derived from the electrostatic Maxwell stress tensor:

$$f_e = q\mathbf{E} - \frac{1}{2}|E|^2 \nabla \varepsilon \tag{4}$$

where $E = - \nabla U$ is the electric field and U is the electric potential. The electric potential U is calculated by Laplace's equation:

$$\nabla^2 U = 0 \tag{5}$$

Besides, the conservation of charge used here is:

$$\frac{\partial q}{\partial t} + \nabla \cdot (\sigma E + qv) = 0 \tag{6}$$

where q is the charge density.

The governing equations (1-6) are solved by the finite element method via COMSOL software.

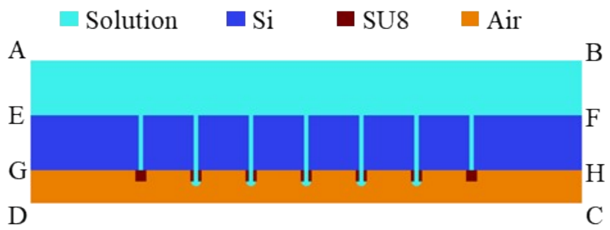

Figure S1. The schematic diagram of the calculation domain.

Figure S1 shows the calculation domain and different colors represent different materials. Table S1 gives the concrete boundary conditions, and Table S2 lists some parameters of materials used in simulations.

Table S1. Boundary conditions

Boundary	Type	Electrostatic boundary condition	Hydrodynamic boundary condition
AB	Inlet	$U = U_{on}$	$u = 0, v = v_0$
AE, BF	Wall	/	$v = 0$
CD	Ground(wall)	$U = 0$	$v = 0$
DG, CH	Outlet	/	$p = 0$

Table S2. Material parameters used in simulations

Material	Conductivity	Relative dielectric constant
SU8 nozzle	10^{-13} S/m	3.7
Air	10^{-14} S/m	1
Si	10 S/m	11.7

In addition, the current computer is difficult to support the three-dimensional arrayed EHD jet printing simulation, so we use a two-dimensional model to implement the simulation when the jets of nozzles are concerned, and a three-dimensional model to implement the simulation for accuracy when only electric field is solved.

2. Supplementary pictures

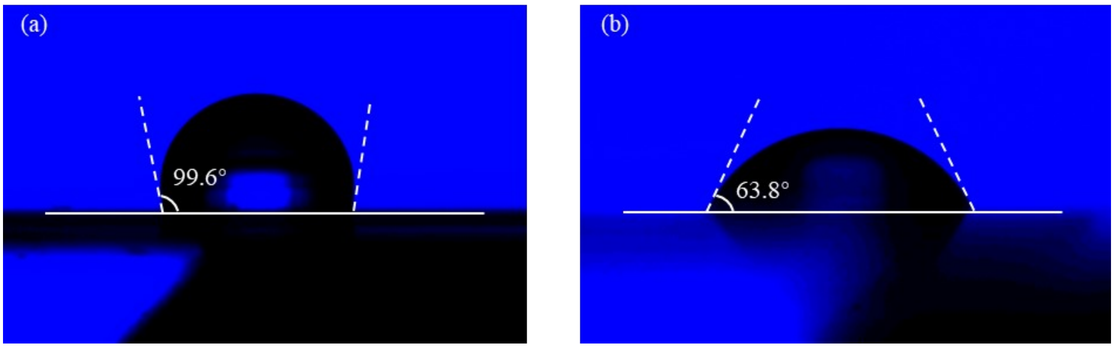

Figure S2. Contact angle of water on (a) a SU8 substrate and (b) a silicon substrate.

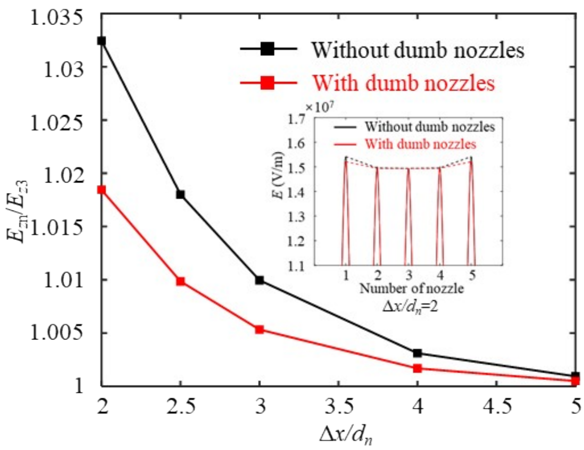

Figure S3. The effect of the dumb nozzles on the uniformity of the electric field at the tip of the nozzles.

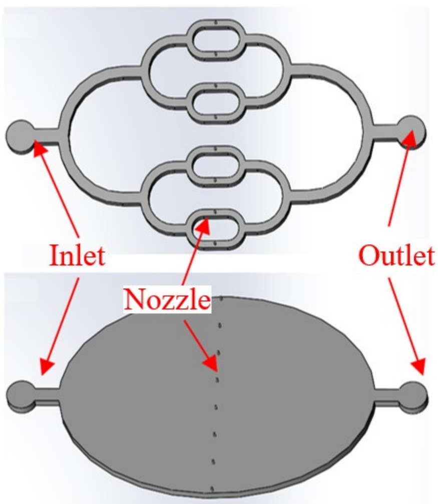

Figure S4. The microchannel structure of the printhead chip (back view in Figure 3b in the manuscript).

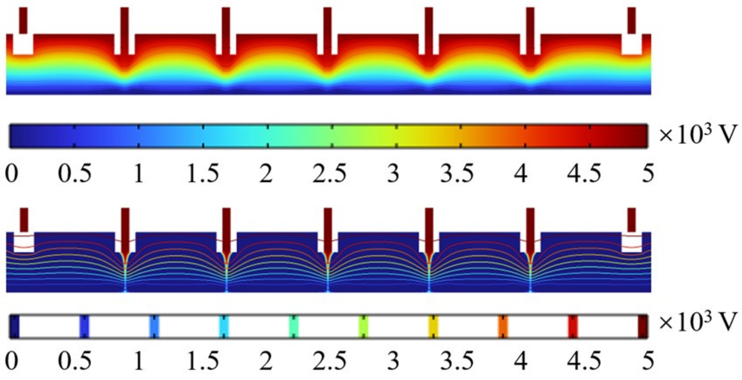

Figure S5. The simulation picture of the multi-nozzle EHD printhead with 100 μm nozzle diameter and 500 μm nozzle spacing, which demonstrates that no obvious crosstalk exists.

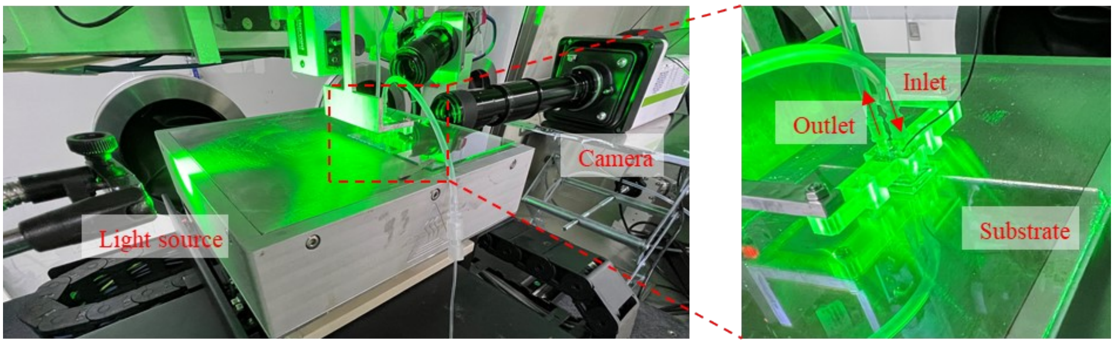

Figure S6. The picture of the experimental platform and the printhead.

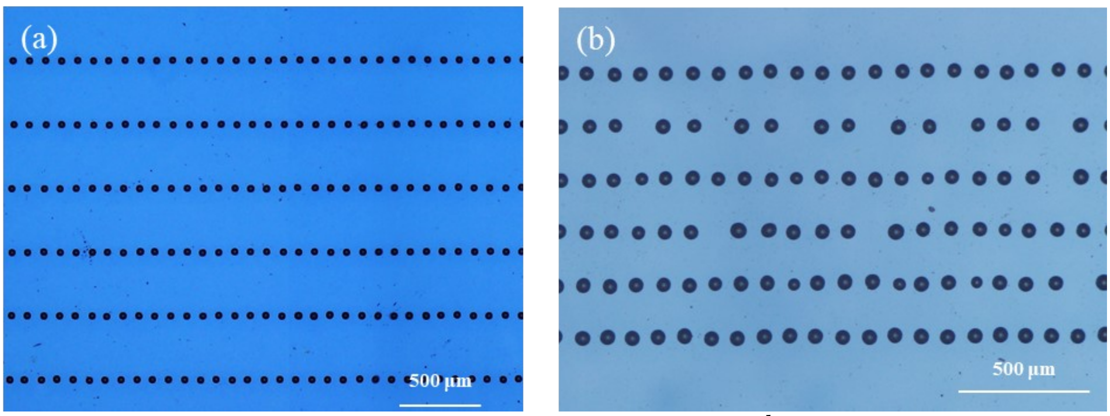

Figure S7. (a) The droplets printed by an EHD printhead with $\Delta x/d_n = 5$ (the nozzle spacing and diameter are 400 μm and 80 μm) and (b) $\Delta x/d_n = 2.5$ (the nozzle spacing and diameter are 200 μm and 80 μm).

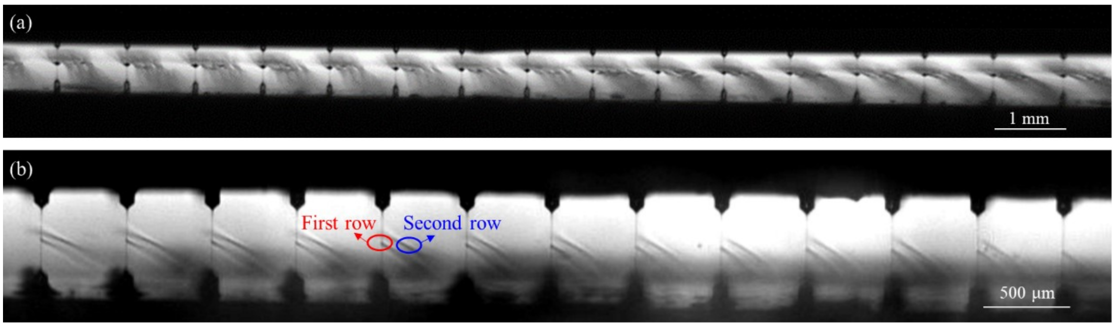

Figure S8. (a) The jetting image of an EHD printhead with 24 nozzles, the nozzle spacing is 1mm (limited by the field of vision, only 16 nozzles were photographed). (b) The jetting image of an EHD printhead with a two-row nozzle array, the nozzle spacing is 500 µm (due to the focal length of the camera, only one row of nozzles is photographed. The red and blue ellipses in the figure represent the droplets printed by the first and the second row of nozzles, respectively).

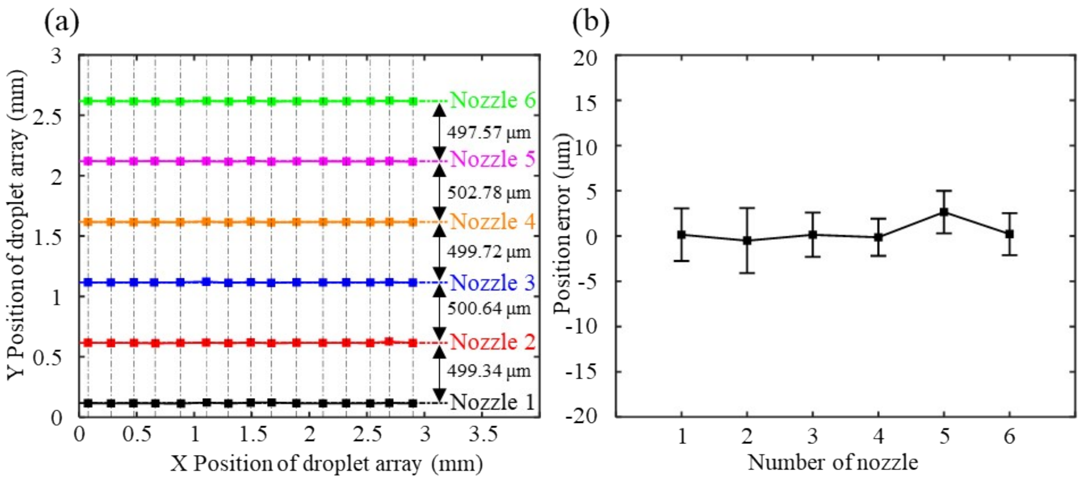

Figure S9. (a) Position analysis diagram of droplets in Fig. 4d in the manuscript. (b) Position error analysis of droplet array in Y direction. Take the middle position of nozzles 3 and 4 as the coordinate origin.

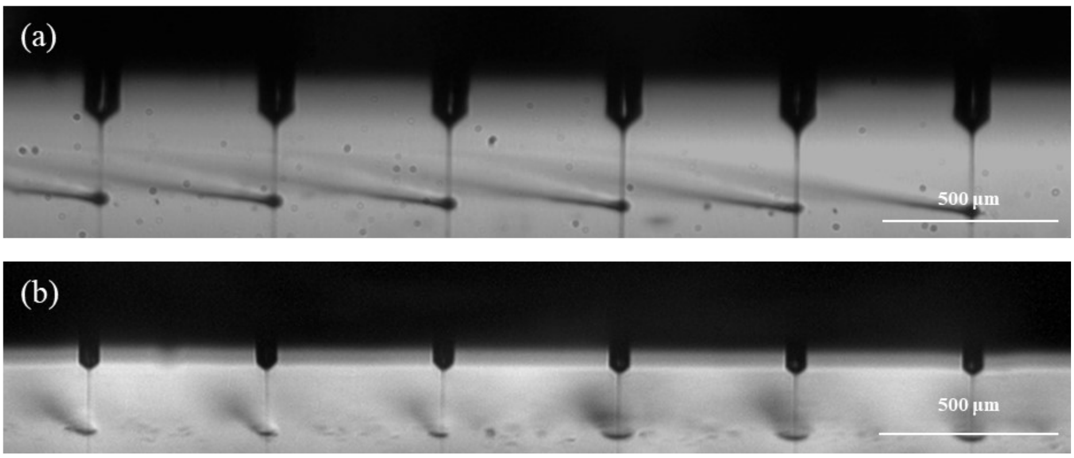

Figure S10. The same printhead is capable of printing with different inks. (a) The solution is triethylene glycol; (b) The solution is ethanol.

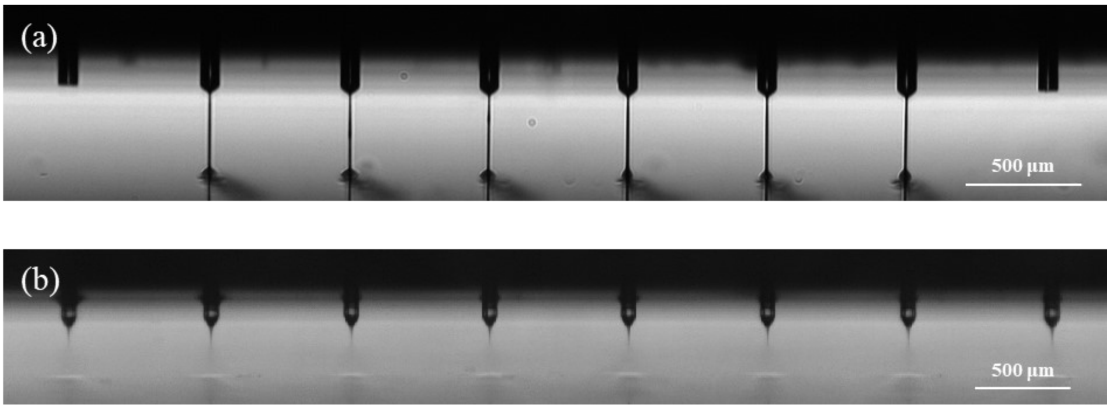

Figure S11. The jetting image of an EHD printhead with different solutions. (a) The solution is DMSO with polymer PVP dissolved (the concentration of PVP is 500mg/g). The printing height is 350 μm, the rectangular pulsed voltage is 1600 ± 200 V, 50 Hz, 5%; (b) The solution is silver ink containing silver nanoparticles. As the ink used is with high conductivity and low viscosity, the jetting mode is electrospray. The printing height is 300 μm, the rectangular pulsed voltage is 1100 ± 200 V, 50 Hz, 10%.

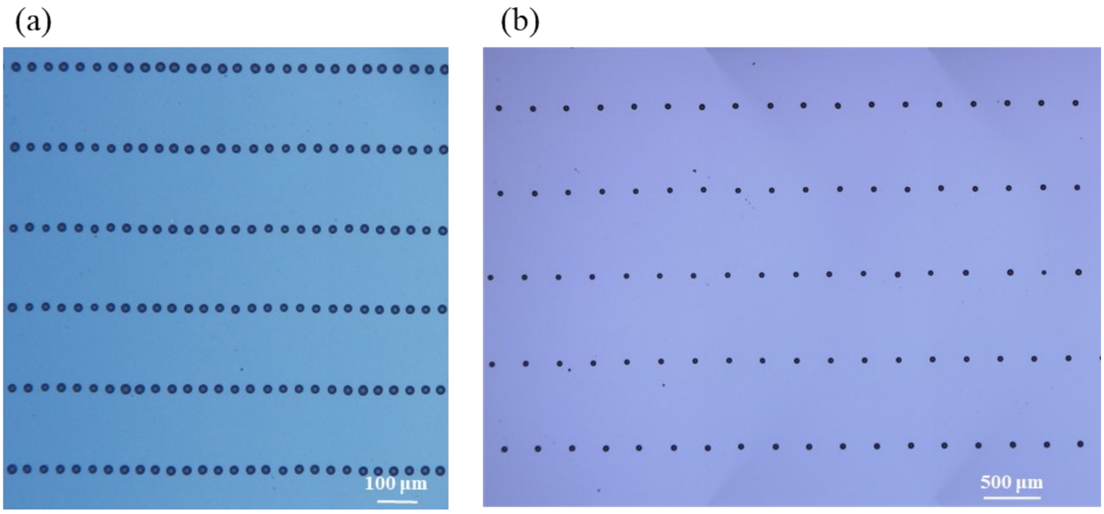

Figure S12. (a) Small size droplets (< 20 μm) printed with triethylene glycol. The printing height is 250 μm, the rectangular pulsed voltage is 1600 ± 300 V, 1000 Hz, 20%; (b) The printed droplets of glycerol. The printing height is 250 μm, the rectangular pulsed voltage is 1400 ± 200 V, 50 Hz, 8%.

3. Supplementary videos

1) Video S1: the printing height is 300 μm, the rectangular pulsed voltage is 1000 ± 500 V, the injection frequency is 100 Hz, and the duty cycle is 50%. The spacing of nozzles is 500 μm. The solution used in the video is triethylene glycol. The video was shot at 5000 fps.

2) Video S2: the printing height is 250 μm, the rectangular pulsed voltage is 1500 ± 350 V, the injection frequency is 2500 Hz, and the duty cycle is 40%. The spacing of nozzles is 500 μm. The solution used in the video is triethylene glycol. The video was shot at 15000 fps. The video playback rate is 4 fps.

3) Video S3: the printing height is 250 μm, the rectangular pulsed voltage is 1500 ± 350 V, the injection frequency is 2500 Hz, and the duty cycle is 40%. The spacing of nozzles is 500 μm. The solution used in the video is triethylene glycol. The video was shot at 15000 fps. The video playback rate is 100 fps.

4) Video S4: the printing height is 320 μm, the rectangular pulsed voltage is 1400 ± 400 V, the injection frequency is 10000 Hz, and the duty cycle is 60%. The spacing of nozzles is 500 μm. The solution used in the video is ethanol. The video was shot at 40000 fps.