CROSS-SCALE MANIPULATIONS OF HETEROGENEOUS COMPONENTS WITH ARBITRARY SHAPES

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ABSTRACT

Heterogeneous microcomponents were constructed on an electromicrofluidic (EMF) platform with photocrosslinkable prepolymer droplets containing fluorescent particles. The EMF platform demonstrated the features and advantages of (1) manipulating prepolymer droplets and particles, (2) photocrosslinking the prepolymer solutions with arbitrary light patterns generated by a DMD (digital micromirror device), and (3) assembling the crosslinked microcomponents. Various forces were investigated on the EMF device to drive objects on varied scales (μm particles, mm droplets and crosslinked microcomponents), in different phases (solid particle and microcomponents and liquid prepolymer droplets), and of different materials. The technique and procedure demonstrate an approach to form 3D constructs.

INTRODUCTION

Constructing 3D heterogeneous microcomponents is fundamental to recapitulation the *in vivo* microenvironment applied to cell culture and tissue engineering [1, 2] or creation of new engineered materials. Various methods have been demonstrated to form 3D microcomponents, including emulsification [3], photolithography [4], micromolding [5], and microfluidic-related means. Among the reported techniques, it is challenging to form microcomponents with heterogeneous materials and reorganized particles in adjustable patterns. It is difficult to assemble the crosslinked microcomponents on the same platform on which we form the microcomponents.

Here we demonstrate the formation and assembly of programmable microcomponents with heterogeneous crosslinkable materials, accessible embedded particles, and tunable shapes on an EMF platform using dielectrophoresis (DEP) as the main driving mechanism [6]. First, with adequate electric signals applied on the EMF platform, DEP was adopted to manipulate multiple prepolymer solution droplets that, after crosslinking, become heterogeneous, porous, and biocompatible materials ideal for 3D cell culture. In addition, before crosslinking, the appropriate electric signals were further actuate and reorganize the particles suspended in the prepolymer solutions by another DEP force excreting on the particles. With the third DEP force on the crosslinked microcomponents in solution, we further investigated the movement and assembly of the microcomponents in arbitrary shapes determined by the pattern of the illuminated light on the EMF platform.

We successfully manipulated the droplets and fluorescent particles of various prepolymer solutions and the crosslinked microcomponents in various phases and scales to assemble and form heterogeneous architectures. With the demonstrated way of building architectures, particles will be replaced with particles to construct biomimicking architectures for 3D tissue engineering applications.

PRINCIPLE

Particles, droplets, and microcomponents were driven by DEP forces on the EMF platform. Here we describe the latter two DEP forces that are less commonly employed comparing to particle DEP.

Dielectrophoresis on Liquid (LDEP)

In this paper, the prepolymer solutions were non-conductive and were driven by DEP with none or few contact angle change. As shown in Fig. 1, when applying a proper voltage (V_{LDEP}) on a driving electrode (width w) on the bottom plate and the top plate (space d), the non-uniform electric field causes a DEP force (F_{LDEP}) on the liquid-air interface and drive the droplet with a higher relative permittivity ($\varepsilon_{Droplet}$) to the air environment with a lower relative permittivity (ε_{Air}) [7]:

$$F_{LDEP} = \frac{\varepsilon_0(\varepsilon_{Droplet}-\varepsilon_{Air})w}{2d} V_{LDEP}{}^2, \quad (1)$$

in which ε_0 (8.85×10-12 F/m) is the permittivity of vacuum.

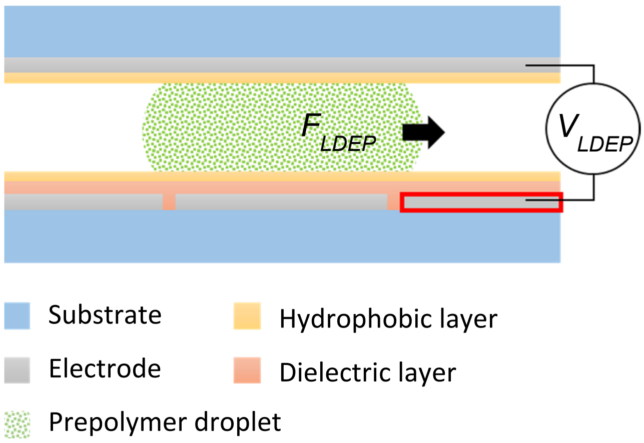

Figure 1. *Cross-sectional view of prepolymer droplet manipulation between plates on an EMF platform by LDEP.*

Dielectrophoresis of Crosslinked Microcomponent (SDEP)

Crosslinked microcomponents were driven on the EMF platform as moving a dielectric slab between electrodes. They are able to be attracted toward the stronger electric field region by positive DEP (pDEP) or expelled from the stronger electric field region by negative DEP (nDEP) depending on the electric property of the crosslinked microcomponents and the solution as shown in Fig. 2. When neglecting the voltage drop in the dielectric layer F_{SDEP} (Fig. 2) can be expressed as [7]:

$$F_{SDEP} = -\frac{\varepsilon_0(\varepsilon_{Slab}-\varepsilon_{Solution})w}{2d} V_{SDEP}{}^2, \quad (2)$$

in which ε_{Slab} and $\varepsilon_{Solution}$ are the relative permittivities of the crosslinked microcomponent and the surrounding solution, respectively.

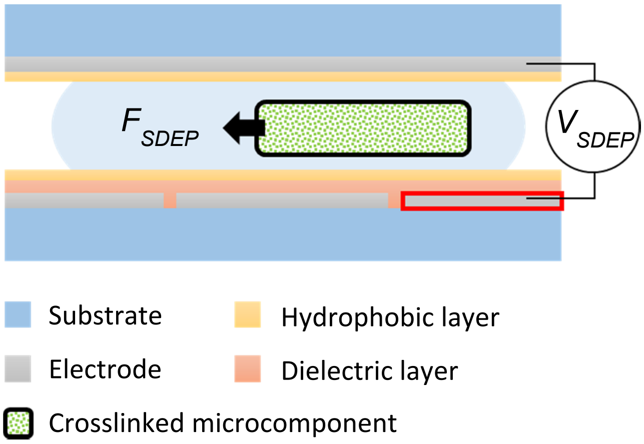

Figure 2. Manipulation of crosslinked microcomponents by DEP on the EMF platform.

DESIGN

The EMF platform was designed to provide the functions of (1) manipulation of prepolymer droplets and particles, (2) photocrosslinking of the assembled droplets with arbitrary light patterns through a DMD, and (3) assembly of the crosslinked components. The EMF platform was composed of top and bottom glass plates. The top glass plate consisted of a conductive ITO layer and a hydrophobic Teflon layer. The bottom plate held ITO driving electrodes with designed patterns coated by SU-8 as a dielectric layer and Teflon (Fig. 1 and Fig. 2). On the EMF platform, the crosslinkable prepolymer droplets were first assembled to form a heterogeneous structure with multiple prepolymer materials as shown in Fig. 3(a). The particles suspended in the prepolymer droplets were then further addressed and reorganized as shown in Fig. 3(b). After the droplets and particles were manipulated to their designed positions and arrangements, UV light (320-340nm) with programmable patterns was formed with an illuminator (Polygon400, Mightex Systems) using the embedded DMD to crosslink and to accomplish the exposing process (Fig. 3(b)). As shown in Fig. 3(c), the photocrosslinked microcomponents were then ready for following assembly process.

To efficiently drive and assemble the hexagonal microcomponents, we designed an array of hexagonal driving electrodes on the bottom plate. After crosslinking, the hexagonal microcomponents were harvest from the EMF platform containing square driving electrodes for microcomponent formation to another EMF platform with hexagonal driving electrodes for microcomponent assembly.

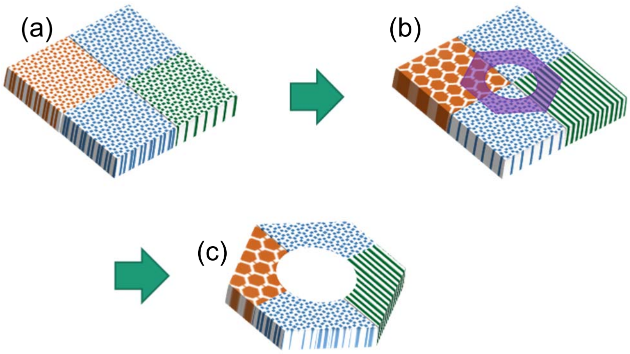

Figure 3. Microcomponent preparation with prepolymer droplets assembly, particle reorganization, crosslinking with a programmable light pattern (shown hexagon with a center hole.

EXPERIMENT

Crosslinking Prepolymer Solutions

For the advantages of biocompatibility and easy crosslinking, we adopted non-conductive poly(ethylene glycol) diacrylate (PEGDA, Mn 575) with photoinitiator I-819 (1 w/v%) as the crosslinkable material and mixed it with fluorescent particles (red, green, and blue) as the manipulating solution as shown in Fig. 4(a).

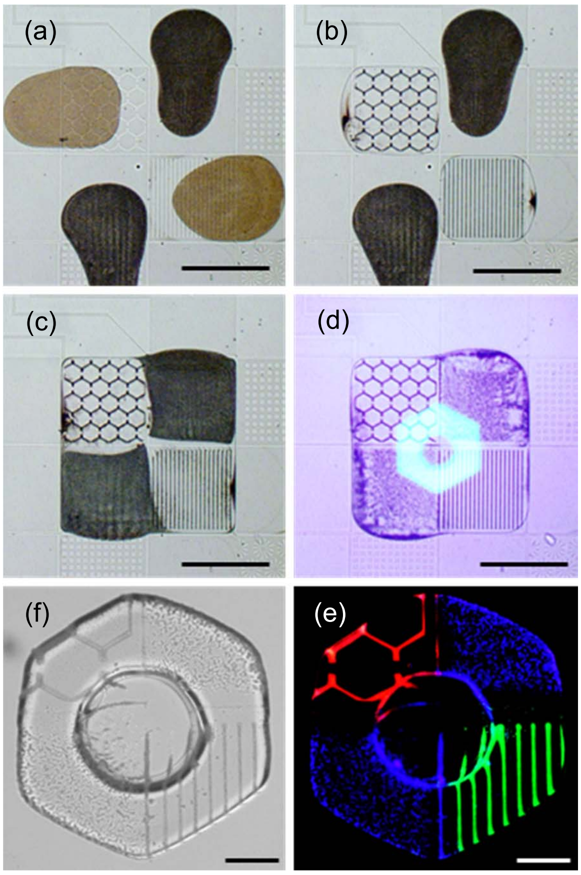

Figure 4. Formation of the hexagonal microcomponents. ***(a)*** *Prepolymer droplets manipulation.* ***(b)*** *Fluorescent particles within droplets reorganization.* ***(c)*** *Prepolymer droplets assembly.* ***(d)*** *Photocrosslinking with patterned light (Polygon 400). (scale bar: 1 mm)* ***(e)*** *Bright field and* ***(f)*** *fluorescence images of the crosslinked microcomponent. (scale bar: 250 μm)*

With the appropriate AC electric signal (20-80 Vpp, 1 kHz) applied between the two plates (space 100 μm), the prepolymer droplets were first driven by the square electrodes (1 mm × 1 mm), and the suspended fluorescent particles were then reorganized (Fig. 4(b) and 4(c)). A hexagonal microcomponent was crosslinked using programmable light patterns from the Polygon 400 as shown in Fig. 4(d). Fig. 4(e) and 4(f) show the bright field and fluorescence microscope images of the crosslinked microcomponent.

Assembling Microcomponents

The photocrosslinked microcomponents with the thickness of 100 μm were then harvested and transferred to another EMF platform with hexagonal driving electrodes and driven in another PEGDA (Mn250) prepolymer solution between top and bottom plates spaced with 300 μm. As shown in Fig. 5, the microcomponents were assembled by DEP when applying a 30 Vpp and 1 MHz AC signal. As can be seen from Fig. 5, the prepolymer solution was also deformable by the applied electric signal. After moving all the microcomponents to their designed positions (Fig. 5(d)), the second exposure was performed to secure and crosslink the entire architecture.

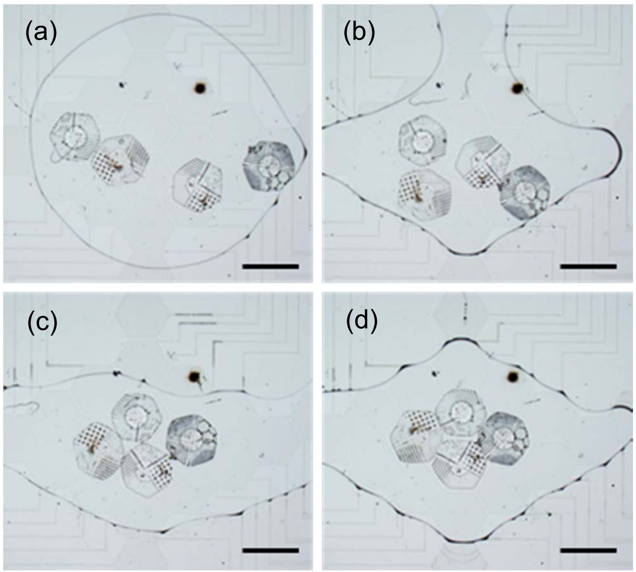

Figure 5. *Crosslinked hexagonal microcomponents assembled in another prepolymer solution on the EMF platform. (scale bar: 1 mm)*

CONCLUSIONS

We demonstrated the formation and assembly of microcomponent on the EMF platform on which the prepolymer solution droplets, particles, and crosslinked microcomponents were successfully manipulated on varied scales and in liquid or solid phases. Programmable light patterns were investigated to crosslink the microcomponents into the hexagonal shape with multiple prepolymer solutions containing different fluorescent particles reorganized by DEP. The reported technique and procedure is an alternative way to form 3D architectures and would be applied to tissue engineering when replacing the particles and prepolymer solutions with hydrogels and cells in the future.

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