HIGHLY EFFICIENT ELECTROCOALESCEENCE-BASED DROPLET MERGING USING A 3D ELECTRODE
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ABSTRACT
Droplet manipulation is comprised of techniques such as droplet generation, merging, and splitting, of which droplet merging is one of the major bottlenecks in achieving high-throughput analysis. Here we present a three dimensional electrode that improves the electric field uniformity and field strength experienced by two adjacent droplets undergoing merging. We conducted a systematic comparison of planar, coplanar, dual-coplanar, and 3D electrodes under identical experimental conditions and analyzed the electric field strength and droplet merging efficiency.

KEYWORDS: Droplet microfluidics, Droplet merging, Droplet electrocoalescence, 3D electrode

INTRODUCTION
Droplet microfluidics provides the capability for highly repeatable high-throughput screening at a single-cell level. Hence, improving the primary functionalities such as droplet merging used in droplet manipulation can improve platform stability and reduce the time required to screen a large number of samples. Passive droplet merging requires the use of pillar arrays or narrowing-widening channel structures to induce a collision-relaxation force and obtain droplet fusion, but prevents the use of droplet-stabilizing surfactants [1]. Alternatively, electric field based droplet merging provides on-demand electrocoalescence of droplets while preserving system stability, throughput, and efficiency [2]. Planar electrodes often require a strong electric field and high input voltage, and even with high voltage have difficulty in reaching high merging efficiency. Here we present an on-demand high-throughput droplet electrocoalescence microfluidic chip using a 3D electrode that provides a highly uniform electric field to increase droplet merging efficiency at a lower applied voltage. A systematic study was conducted to compare the merging efficiency of the 3D electrode compared to those of planar, coplanar, and dual-coplanar electrodes.

EXPERIMENTAL
The 3D electrocoalescence device is comprised of two T-junction droplet generators to produce two droplet trains, a Y-junction to combine the two trains of droplets, a widened merging channel (300 m wide and 500 m long) to reduce the proximity between droplets, and a large observation chamber to evaluate the merging efficiency (Fig. 1). Planar, coplanar, dual-coplanar, and 3D electrodes (all 500 m wide) were combined with the PDMS channel layer to induce droplet merging. An electric field simulation analysis using Comsol Multiphysics was conducted on each electrode type to compare the field strength and uniformity experienced by the droplets. The droplet merging efficiency was characterized by comparing the ratio between one-to-one merged droplets and unmerged droplets in the observation chamber.
RESULTS AND DISCUSSION

Simulation results of the planar and coplanar electrodes showed similar field strengths with only minor changes in the field direction, while the dual-coplanar electrode showed improved field strengths (1.3 times higher) than that of the planar electrode. The 3D electrode further improved the electric field strength to 1.6 times greater than that of the planar electrode (Fig. 2). Therefore, the 3D electrode is expected to show a significantly higher merging efficiency and stronger electric field strength at the same applied voltage, as well as reduction in the voltage requirement to induce droplet merging.

Microdroplets having 120 µm diameter were produced at a total flow rate of 6000 µl h⁻¹ and merged in the presence of an electric field at applied voltages ranging from 50 V to 900 V (Fig. 3). The planar and coplanar electrodes had a maximum merging efficiency of 82% and 80%, respectively. The dual-coplanar electrode had an improved droplet merging efficiency of 85% at 900 V and the 3D electrode showed an improved merging efficiency of 95% at 150V (2 times lower voltage than previously reported voltages to obtain 95% of higher merging efficiency [3]). The threshold voltage at which droplet merging was observed for both the planar and coplanar electrodes was 300 V. The dual-coplanar electrode had a threshold voltage of 100 V. The threshold for the 3D electrode was 50 V, 6 times less than that of the planar electrode (Fig. 4A).
Additionally, we investigated the droplet merging efficiency of the 3D electrode device at flow rates varying from 100 \( \mu l \ h^{-1} \) to 4,000 \( \mu l \ h^{-1} \) per droplet generator, resulting in a final flow rate of 8,000 \( \mu l \ h^{-1} \) that corresponds to 1,300 merging events/s. At an applied voltage of 500 V, the droplet merging efficiency was consistently above 90\% regardless of the flow rates used. Above 750 V, the droplet merging efficiency was above 95\% at all flow rates greater than 500 \( \mu l \ h^{-1} \) (150 events/s, Fig. 4B).

![Graph showing droplet merging efficiency vs. voltage and flow rate](image)

**Fig. 4:** (a) Microdroplet merging efficiency for the planar, dual-coplanar, and 3D electrodes with varying input voltages \( (n=150 \text{ droplets per data point}). \) (b) Droplet merging efficiency of the 3D electrocoalescence device at varying input voltages and flow rates of up to 4,000 \( \mu l \ h^{-1} \) per droplet generator (total flow rate of 8,000 \( \mu l \ h^{-1} \), \( n=150 \text{ per data point}). \)

**CONCLUSION**

Electrocoalescence-based droplet merging efficiency of 4 different electrode designs (planar, coplanar, dual-coplanar, and 3D electrodes) were analyzed and systematically compared. The 3D electrocoalescence design outperformed all other electrode designs in terms of the required input voltage, electric field strength, electric field uniformity, and droplet merging efficiency.

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