Flight behavior of charged droplets in electrohydrodynamic inkjet printing

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Flight behaviors of charged droplets are presented for electrohydrodynamic (EHD) inkjet printing. Three different kinds of EHD spraying techniques, pulsed dc, ac, and single potential (SP) ac, have been investigated and both conductive and dielectric target surfaces were considered. Experimental results show that the flight paths of charged droplets may deviate from their regular straight route, i.e., directly from the nozzle to the substrate. Depending on the droplet charge and applied electric field, droplets may deflect, reflect, or retreat to the meniscus. We can solve these drawbacks by SP EHD printing. © *2010 American Institute of Physics*. [doi:10.1063/1.3280077]

In recent years, inkjet printing technology has received significant attention as a micro/nanofabrication technique for flexible printing of electronic circuits[1] and solar cells,[2] as well for biomaterial patterning.[3] It eliminates the need for physical masks, causes fewer environment problems, lowers fabrication costs, and offers good layer-to-layer registration. To fulfill the requirements for use in the above applications, however, the inkjet system must meet certain criteria such as high frequency jetting, uniform droplet size, high density nozzle array, etc. Recently, an electrohydrodynamic (EHD) printing technique has been suggested and proposed as an alternative to the thermal bubble or piezoelectric devices.[4–6]

In EHD jetting, a liquid (ink) is pumped through a nozzle and a strong electric field is applied between the nozzle and an extractor plate, which induce charges at the surfaces and creates an electric stress. Once the electric field force is larger than the surface tension force, a liquid droplet is formed. An EHD inkjet head can produce droplets smaller than the size of the nozzle that produce them. This unique feature distinguishes EHD printing from conventional methods for submicron resolution printing.

In a seminal work, Choi *et al.*[7] presented drop on demand printing of conductive ink using a pulsed dc electric field between a nozzle and a target plate. Recently, Nguyen and Byun[8] demonstrated EHD printing technology based on ac voltage without a nozzle electrode. This technique is called single potential ac (SP-ac) EHD printing, and it offers various important features including a simplified nozzle fabrication technique and a short working distance between the nozzle and target without electrical breakdown.

This study reports some of the drawbacks of conventional EHD printing technology, primarily focusing on the droplet flight behavior between the nozzle and target substrate. Figure 1(a) shows a schematic of the experimental setup used for EHD printing. A micro syringe pump was used to supply liquid ink to the stainless steel nozzle. The inner and outer diameters of the stainless steel nozzle are 200 and 500 μm, respectively. The liquid ink was prepared by dissolving silver ink (TEC-IJ-020, Inktec Inc.) in ethanol at a 1:10 weight ratio. The distance between the nozzle and the electrode was kept constant at 1.5 mm.

Based on the applied electric field, three different jetting scenarios were considered here: Pulsed dc, ac, and SP-ac. For the pulsed dc [Fig. 1(b)] or ac [Fig. 1(c)] case, the target plate was connected to the ground, while either pulsed dc or ac electric potential was applied to the nozzle electrode. On the other hand, for the SP-ac case, the nozzle was electrically floating and an ac potential was applied to the target electrode [Fig. 1(d)].

Figure 2 shows time sequence photographs of a droplet when a conducting substrate is used as a target plate. For the pulsed-dc case, straight flight [Fig. 2(a)] to the substrate is observed for more than 90% of the experiments (Table I). In this case, the net charge of the droplet is always positive, and the droplet hits the target plate directly. This is the desired phenomenon for effective printing of metal ink on a substrate. However, under identical operating conditions, we also observed returning of the droplet to the nozzle (retreat) after fine spraying to the target plate, as shown in Fig. 2(b). The fine spraying phenomena may be due to very high charge density at a location on the droplet.[9] When a droplet flies in a strong external electric field, the charges are rearranged at the surface of the droplet. While the free charges are distributed across the entire free surface, the induced charges rearranged themselves based on the polarity [Fig.

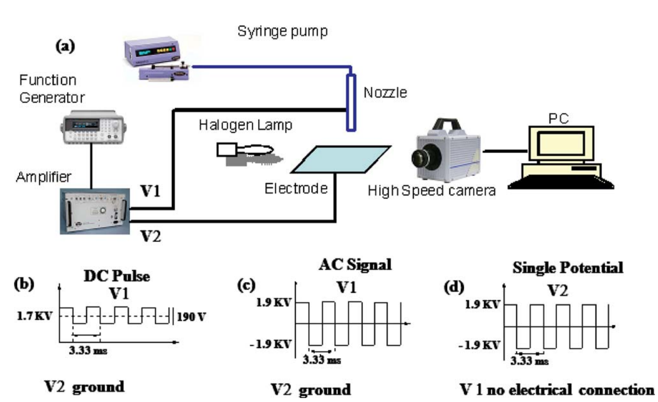

FIG. 1. (Color online) (a) Experiment set up used for EHD printing. External potentials for (b) dc case, (c) ac case, and (d) single potential ac (SP-ac) case.

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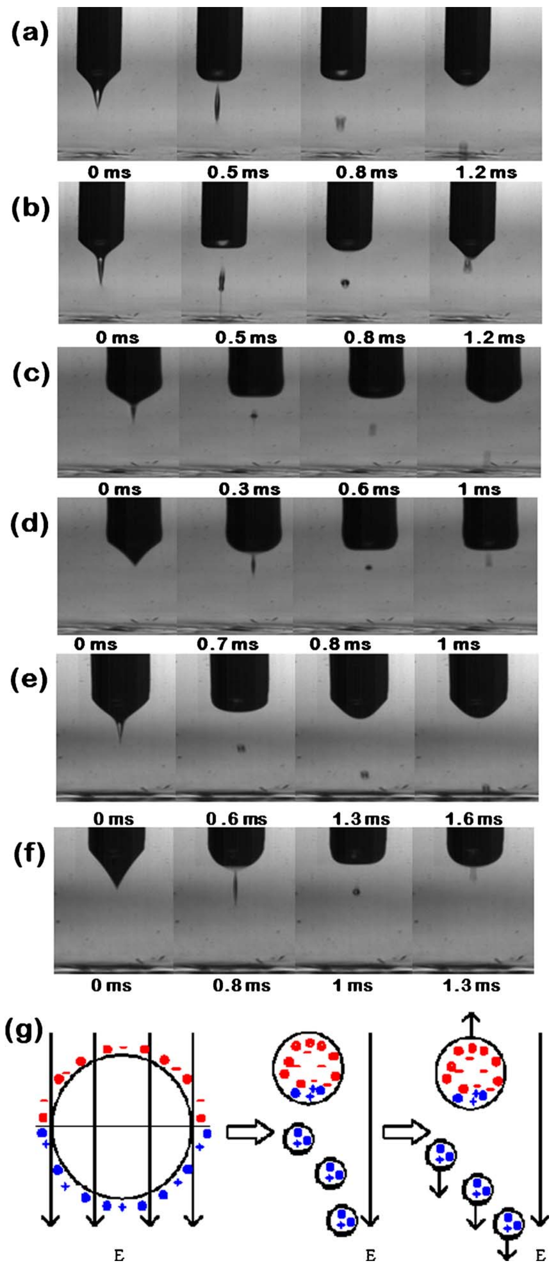

FIG. 2. (Color online) Droplet flight behavior for conductive substrate at different times after forming a droplet. (a) straight flight to the substrate with dc voltage, (b) retreat to the nozzle with dc voltage, (c) straight flight to the substrate with ac voltage, (d) retreat to the nozzle with ac voltage, (e) straight flight to the substrate with SP-ac, and (f) retreat to the meniscus with SP-ac. (g) Mechanism of charge redistribution and breaking of a droplet under a strong electric field.

2(g)]. For instance, if the net charge of the original droplet is positive, the droplet will have much higher positive charge density in the cathodic/ground side. These excess charges cause the original droplet to break up and lead to the formation of a number of satellite (smaller) droplets in addition to the mother droplet [Fig. 2(g)]. These satellite droplets are responsible for fine spraying on the substrate. The retreat of the mother droplet to the nozzle suggests that it might have attained a net negative charge. This unique retreat feature of droplet has not been observed or reported in the past.

Like the pulsed-dc case, the droplet can hit the target directly (Fig. 2(c)) or retreat to the nozzle [Fig. 2(d)] for the ac case. In the ac case, however, almost half of the droplets retreat to the jetting nozzle (Table I). Here, the returning of droplets primarily occurs due to two reasons. The first is the change in electrical polarity during the flight time of a charged droplet, which depends on the frequency of the applied ac voltage. For example, during a positive cycle of electric field (V1: +ve and V2: ground), a positively charged droplet will hit the target plate. On the other hand, a positively charged droplet will return to the nozzle if the applied potential switches to the negative cycle (V1: −ve and V2: ground). And the second is the loss of the charges on the surface of the droplet. We occasionally observed the retreat phenomenon associated with fine spraying on a target plate, which is same as the dc case. This behavior was observed, when a droplet was formed at the very beginning of the cycle of applied ac current.

TABLE I. Droplet flying statistics for conductive target.

Case	Deflection (%)	Reflection (%)	Retreat to meniscus (%)	Go to substrate (%)
dc	0	0	9.6	90.4
ac	0	0	45.8	54.2
Single potential	0	0	44.8	55.2

In the SP-ac case, the mechanism of droplet flight is the same as that of the ac case, where both straight flying [Fig. 2(e)] and retreat phenomena [Fig. 2(f)] might take place. The upward or down ward movement of the droplet depends on the net charge of the droplet and the applied electric field. These results may suggest that EHD jetting of the droplet on the conducting plate will be problematic if ac or SP-ac potential is applied. However, it should be noted that the distance between the nozzle and the electrode was kept constant at 1.5 mm to observe the flight behavior at same condition. For the SP-ac case, we can reduce the distance without electrical breakdown,[8] which allows us to overcome the problem. When we kept the distance at around 100 μm, we could not observe any reflection or returning of the charged droplet.

A couple of other defects were observed when EHD printing was performed on a dielectric substrate. Printing on a dielectric surface is necessary for electronic device fabrication.[1,10] In this study, a 2.2×5 cm^2 piece of glass slide was attached on top of the electrode plate. Thus, the deposition of ink takes place on the glass surface instead of on the electrode. Therefore, charge should be accumulated on the substrate while the charged droplets are deposited on the substrate. Time sequence photographs of the droplet behavior for the dielectric case are shown in Fig. 3. Like a conductive substrate, three different cases of external electric potential were applied. Figure 3(a) shows the deposition of a charged droplet on the glass surface for the dc case. This kind of droplet behavior is observed when the target surface was electrically neutral [Fig. 3(h)] and the original droplet was very symmetric and formed from the centerline of the nozzle. Depending on the charge accumulation on the substrate, we observed deflection or reflection of the droplet.

The deflection phenomenon is demonstrated in Fig. 3(b), where a droplet starts to deviate (either left or right) from its regular straight route. A number of factors can contribute to the deflection of the droplet. First, if the droplet originates from an asymmetric meniscus, it will fly along the curved electric field line [Fig. 3(i)], because the original location of the droplet is not at the centerline. Second, if there is an

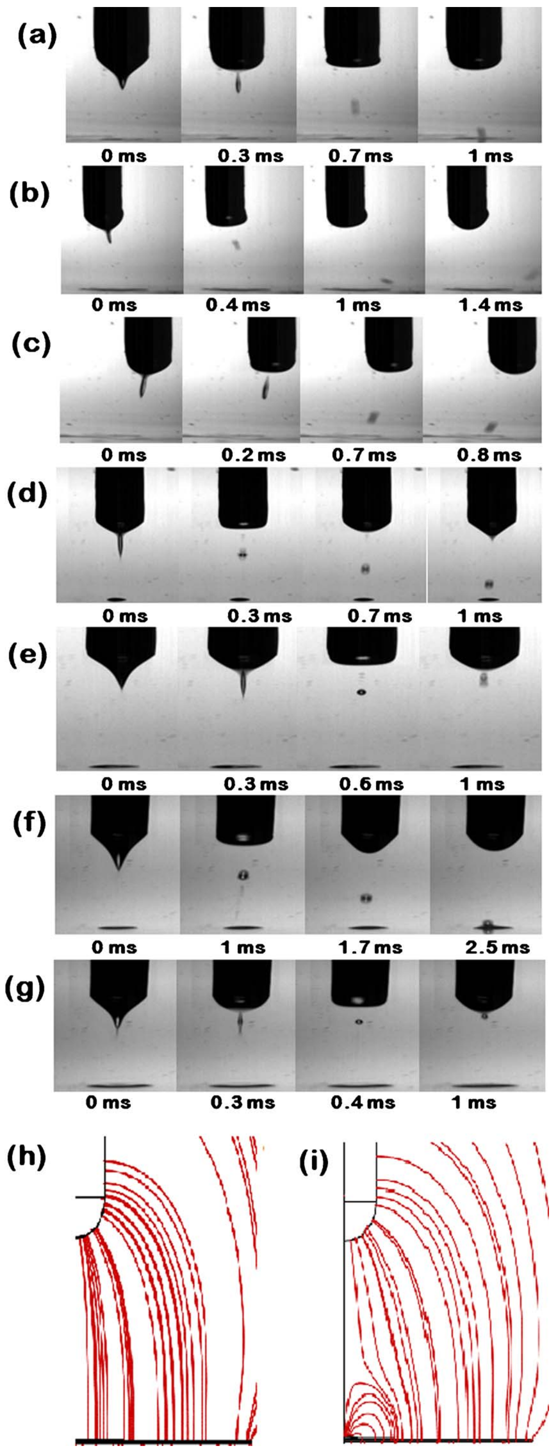

FIG. 3. (Color online) Droplet flight behavior for dielectric (glass) substrate at different times after forming a droplet. (a) Straight flight to the substrate with dc voltage, (b) reflection with dc voltage, (c) deflection with dc voltage (d) straight flight to the substrate with ac voltage, (e) retreat to the nozzle with ac voltage, (f) straight flight to the substrate with SP-ac, and (g) retreat to the nozzles with SP-ac. Electric field distribution (h) without and (i) with accumulative charge on the glass substrate.

asymmetric charge distribution in the droplet, the drop will take curved electric field lines. Third, if the droplet shape is asymmetric, charge polarization may cause deflection of the droplet. It is important to note that an asymmetric shape droplet can form due to vibration of the ink meniscus.

The reflection phenomenon is very similar to deflection, but in this case the deflected droplet comes very close to the target surface and finally reverses its flight path [Fig. 3(c)]. The reversal in the flight path is primarily due to the charge interaction forces between the flying droplet and accumulated charges of previously deposited droplets. In the case of reflection, the charge interaction force is stronger than the electric field force, especially in the region very close to the dielectric surface. It has also been observed that the formation of two droplets in quick succession contributes to the deflection or reflection of the droplet.

TABLE II. Droplet flying statistics for dielectric (glass) target. (* this can be 0 by decreasing the distance between the nozzle and the substrate.)

Case	Deflection (%)	Reflection (%)	Retreat to meniscus (%)	Go to substrate (%)
dc	44.7	31.7	0	23.6
ac	0	0	15.2	84.8
Single potential	0	0	11.8*	88.2

The deflection or reflection of droplets was not observed for the ac [Figs. 3(d) and 3(e)] or SP-ac [Figs. 3(f) and 3(g)] case due to a shift in the polarity. The phase change resulted in alternative deposition of positively and negatively charged droplets. In the ac and SP-ac cases, droplets mostly hit the dielectric surface directly (Table II). We occasionally observed the interesting retreat phenomena for the ac and SP-ac cases, and the retreat mechanism is very similar to that described for the conducting case. However, for the SP-ac case, we can overcome this problem by reducing the distance between the nozzle and the substrate. In conclusion, we observed a number of deviations in droplet flying behavior that can cause problems in high precision printing. Depending on the type of applied electric field and net electric charge density of the droplet and surrounding area, the droplet can fly directly to the substrate, retreat to the meniscus, deflect from the original vertical line, or reflect after coming very close to the substrate in a deflected route.

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