

# Electronic Circuit Printing, 3D Printing and Film Formation Utilizing Electrostatic Inkjet Technology

Hiroyuki Kawamoto; Department of Applied Mechanics and Aerospace Engineering, Waseda University; Tokyo, Japan

## Abstract

An investigation has been carried out on the control of a micro-droplet in electrostatic inkjet phenomena, because the electrostatic inkjet has a merit that the formation and locus of the droplet can be controlled by the application of the electric field and it is possible to treat highly viscous liquid. It was observed that a Taylor cone of the paste was formed at an end of a tube and the tip of the cone was broken to form a very small droplet at the beginning of the corona discharge. Droplets of paste that contains Ag nanoparticles are injected on a glass substrate to form electrode patterns. The formation of the droplet is controlled by the application of pulse voltage between the plate electrode and the fine tube that is filled with Ag paste. A multi-layered printing was realized by over-coating insulative glass paste on line electrodes. A direct 3D printing was also developed by taking advantage that highly viscous liquid can be ejected by the electrostatic inkjet system.

## Introduction

We have been developing a mask-less printing technology for microelectronic circuits, film formation for coating technology, and three-dimensional micro rapid-prototyping utilizing an electrostatic inkjet system.[1][2] In the mask-less printing, drops of paste that contains Ag nano-particles are injected on a glass substrate by electrostatic force to form electrode patterns.[3] The formation of the droplet is controlled to realize the drop-on-demand (DOD) by the application of pulse voltage between the plate electrode and a fine tube that is filled with Ag paste. On the other hand, liquid is dispersed under a certain condition due to electrostatic instability and Coulomb repulsive force between dispersed droplets. This phenomenon is investigated to utilize for the micro coating technology. The last application is a 3D printing. Because highly viscous liquid can be ejected with the electrostatic inkjet system, it is expected to be utilized for the micro rapid-prototyping and manufacturing of a micro-mold for casting. In this study, we have investigated fundamental characteristics of the system to apply for these digital fabrication technologies.

## Experimental

An experimental set-up shown in Fig. 1 was constructed to investigate characteristics of droplets formation.[2][3] A capillary tube made of silica coated by polyimide (PolymicroTechnologies, Phoenix, AZ) was equipped with a bottom of a syringe. This tube with liquid was hanged down perpendicular to a plate electrode made of stainless steel. DC voltage was applied by a DC power supply (Matsusada Precision Inc, Tokyo, HVR-10P) and pulse voltage was generated with a function generator (IWATSU, Tokyo, SG-4105) and a high voltage amplifier (Matsusada Precision Inc, Tokyo, HEOP-10B2). The voltage was measured by a digital

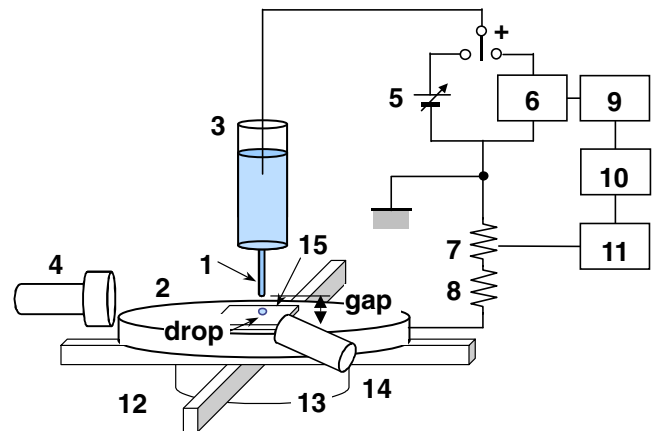


Figure 1. Experimental set-up. (1: pin electrode, insulative capillary tube filled with liquid, 2: metal plate electrode, 3: liquid tank, 4: CCD camera, 5: DC high voltage power supply, 6: high voltage amplifier, 7: shunt resistor, 400 kW, 8: resistor: 400 kW, 9: function generator, 10: oscilloscope, 11: volt meter, 12: linear motors, x and y directions, 13: mechanical z-stage, 14: light, 15: substrate)

oscilloscope and the current was measured by the voltage drop in a current-shunt resistor. The formation of droplet was observed with a CCD microscope camera (Keyence, Tokyo, VH-7000). A high-speed microscope camera (Photron Inc., Tokyo, FASTCAM-MAX 120K model 1) was also used with a stroboscope light (Sugawara Laboratories Inc., Kawasaki, NP-1A) to observe transient formation and separation of droplets. The gap was adjusted by a z-stage and the plate electrode was moved in x and y directions with two linear motors. Motion of the linear motors was controlled by a PC to form print patterns.

## Fundamental Characteristics

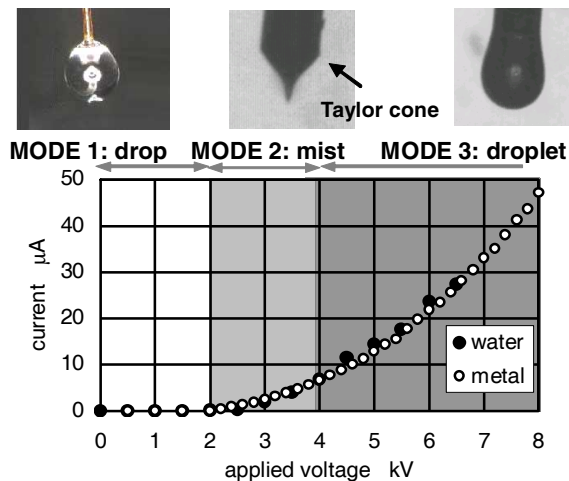
In the first place, the current-voltage characteristic of the pin electrode filled with ion-conductive water was measured and it was compared with that of the metal pin electrode of which diameter was the same with the inner diameter of the insulative tube. The results are shown in Fig. 2. In case of the water pin electrode, although pulse current was superposed on the corona current corresponding to the separation of the droplet, stable corona current was plotted in the figure. Corona current of the water electrode agreed well with that of the metal pin electrode and fundamental characteristics of the gas discharge were common. That is, no current flowed at the dark discharge region, however, when the applied voltage reached a threshold (about 2 kV), the corona discharge took place and the corona current in the order of  $\mu\text{A}$  flowed. As added in Fig. 2 the formation of the droplet was classi-

fied into the following three modes corresponding to the discharge modes.[4]

**MODE 1:** At the dark discharge region, 0 ~ 2 kV, a drop was formed at the tip of the tube. This became large gradually and drops finally. The diameter of the drop was several times larger than that of the tube diameter and the drop period was long, more than a second. A critical diameter of the drop was determined as a static balance of the Coulomb force, the surface tension, the water pressure, and the gravity. The diameter was too large and a period of the drop formation is too long for the industrial application.

**MODE 2:** At the beginning of the corona discharge, 2 ~ 4 kV, a Taylor cone [5] was formed at the end of the tube and the tip of the cone periodically separated from the cone to form a very small droplet less than several 10  $\mu\text{m}$  order diameter.[6] The voltage range of MODE 2 became wide when the air gap was large. The mechanism of the droplet formation at the very beginning of the corona discharge is assumed that the break of the force balance of the surface tension and the electrostatic force causes the separation of the droplet at the tip of Taylor cone. If the applied voltage was slightly increased, the shape of Taylor cone was unstable and the droplet did not dropped right under the tube but dispersed. Coulomb repulsive force seems to cause this instability and charged droplets of the common polarity spread along the electrostatic flux line. If the applied voltage was further increased, Taylor cone was depressed probably because the reaction force of the ionic wind became large and the concentration of the electric field at the tip was relaxed. This is a transition from MODE 2 to MODE 3.

**MODE 3:** At higher voltage, more than 4 kV, Taylor cone was depressed and relatively large droplet was formed. This is probably because the reaction force of the ionic wind became large and the concentration of the electric field was relaxed. Because substantially strong ionic wind was generated in this region, in the order of several m/s,[7] and it streamed to downward from the tip, the charged droplet was not broken nor spread but the single droplet reached to the center of the plate electrode.

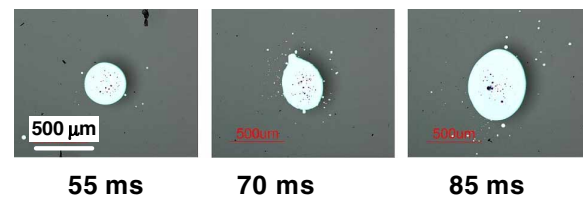


**Figure 2.** V-I curves in pin-to-plate electrode system and mode of drop formation. ( $\phi$  100  $\mu\text{m}$  inner tube diameter,  $\phi$  100  $\mu\text{m}$  metal pin diameter, 3 mm air gap)

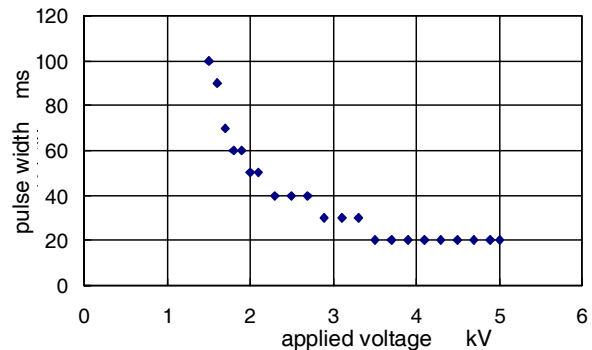
## Electronic Circuit Printing

Droplets of paste that contains Ag nano-particles are injected on a glass substrate by the electrostatic force to print electrode patterns.[8] For the mask-less printing of electronic circuits, pulse voltage was applied to control the formation of a single droplet. Figure 3 shows photographs of droplets by the application of pulse voltage. It is possible to form a small droplet and to realize the ‘dot-on-demand’ (DOD) printing by the voltage application of short pulse width. Figure 4 shows pulse width that a single droplet was formed in one pulse. This figure indicated that pulse width was short in case of the high voltage application.

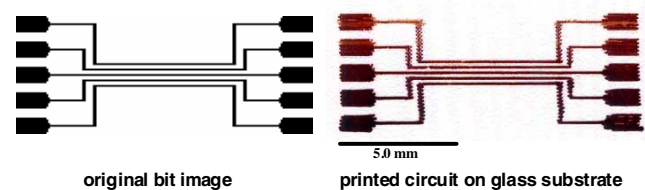
Figure 5 shows a demonstrated microelectronic circuit in the condition that the air gap was 0.5 mm and the applied voltage was 1.7 kV. A line width and pitch of this circuit was about 200  $\mu\text{m}$ . The sample was baked at 673 K to sinter Ag particles by a muffle furnace. It was confirmed that the circuit was conductive after sintering. We have demonstrated 30  $\mu\text{m}$  lines by an improved latest technology.



**Figure 3.** Droplets by application of pulse voltage of the designated pulse width. (1.6 kV applied voltage, 100  $\mu\text{m}$  inner diameter of the tube)



**Figure 4.** Critical pulse width that separates a droplet from the tip of the tube. (100  $\mu\text{m}$  inner diameter of the tube)



**Figure 5.** Original bit image and printed electronic circuit on glass substrate. (0.5 mm air gap, 1.7 kV applied voltage)

## Coating

Mist is dispersed in MODE 2 under a certain condition.[6] This phenomenon will be utilized for the film formation.[9][10] Figure 6 shows experimental results on the effect of the applied voltage and the gap for the mist formation. It is clearly recognized that the mist is widely dispersed under condition of relatively high voltage and the large gap. Because electrostatic charge of the drop just separated from the tip of Taylor cone is large under condition of high applied voltage, it is electrostatically unstable and disrupted based on Rayleigh or Vonnegut limits. That is, it is assumed that the break of the force balance between Coulomb repulsive force and the surface tension causes the separation of the droplet at the tip of the Taylor cone. This condition is called Rayleigh limit.[11] Another model was established by Vonnegut and Neubauer based on the energy minimization principle.[12] The Vonnegut charge is half the Rayleigh limit. In case of large gap, because split droplets are charged the same polarity, they repulse each other due to Coulomb force and thus spread as shown in Fig. 6.

Although single printing is not enough to cover the substrate completely, uniform coating is possible by repeating the spraying. Figure 7 shows that the thickness of the coating thickness is almost linearly increased to the number of spraying. A multi-layered printing was also demonstrated by overcoating glass paste on the circuit electrostatically printed with Ag paste and insulation between layered electrodes was confirmed.

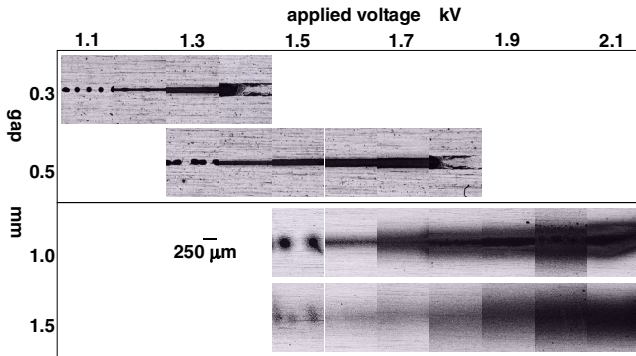


Figure 6. Effect of applied voltage and gap for mist formation.

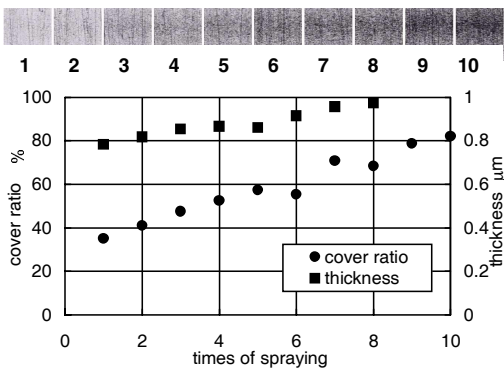


Figure 7. Cover ratio and thickness of coated film measured by Atomic Force Microscope (AFM) with respect to spraying times. (2.3 kV applied voltage, 1.5 mm gap)

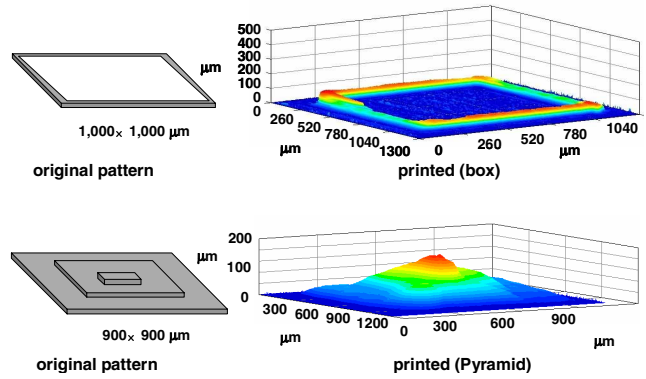


Figure 8. Demonstrated 3D printing models.

## 3D Printing

The electrostatic inkjet system has a potential to realize three-dimensional printing with emulsified liquid that consists largely of nano-particles, because highly viscous liquid, more than 30,000 mPa.s, can be ejected by the system. It will be applied for the micro rapid prototyping or a micro mold for casting.[13]-[15] Compositions of liquid we have synthesized for the 3D printing are 20 % alumina nano-particles (440 nm), 3 % binder (PVA), 0.2 % dispersing agent, and 77 % water. The viscosity was 12 mPa.s and the contact angle was 70 deg. Figure 8 shows demonstrated 3D patterns.

## Concluding Remarks

We have developed digital micro fabrication technologies, electrostatic circuit printing, film formation, and 3D printing, utilizing the dot-on-demand electrostatic inkjet technology. Although demonstrated models are elemental and not satisfactory for practical applications, they have a potential to realize new technologies for micro fabrication.

The author wishes to express his thanks to Dr. Shinjiro Umez, Mr. Tomomichi Ota, Mr. Masato Nishiura, Mr. Ryosuke Nakazawa, and Mr. Kentaro Tanabe for their help with carrying out experiments. This work is supported by The Foundation for Technology Promotion of Electronic Circuit Board and Grant-in-Aid for Scientific Research, Japan Society for the Promotion of Science.

## References

- [1] A. Bailey, *Electrostatic Spraying of Liquids*, Research Studies Press (1988) pp.60-90.
- [2] H. Kawamoto, S. Umez, and R. Koizumi, *J. Imaging Sci. Technol.*, **49**, 1 (2005) pp.19-27.
- [3] S. Umez, R. Nakazawa and H. Kawamoto, *ASME/JSME Joint Conf. on Micromechanics for Information and Precision Equipment (MIPE 2006)*, Santa Clara (2006).
- [4] M. Cloupeau and B. Prunet-Foch, *J. Aerosol Soc.*, **25** (1994) pp.1021-1036.
- [5] G. Taylor, *Proc. Roy. Soc. London, A*, **280** (1964) pp.383-397.
- [6] J-D. Moon, J-G. Kim and D-H. Lee, *EEE Trans. Industry Applications*, **34**, 6 (1998) pp.1212-1217.
- [7] H. Kawamoto, H. Yasuda and S. Umez, *J. Electrostatics*, **64** (2006) pp.400-407.
- [8] D.Y. Lee, E. S. Hwang, T.U. Yu, Y. J. Kim and J. Hwang, *Appl. Phys. A - Materials Science & Processing*, **82**, 4 (2006) pp.671-674.

- [9] H. Nomura, S. Parekh, J. R. Selman and S. Al-Hallaj, *J. Appl. Electrochem.*, **35**, 1 (2005) pp.61-67.
- [10] J. Lu, J.R. Chu, W. H. Huang, Z. M. Ping, *Sensors and Actuators A-Physical*, **108** (2003) pp.2-6.
- [11] L. Rayleigh, *Proc. R. Soc.*, 14 (1882) pp.184-186.
- [12] B. Vonnegut and R. L. Neubauer, *J. Colloid Sci.*, **7** (1952) pp.616-622.
- [13] R. Noguera, M. Lejeune, and T. Chartier, *J. European Ceramic Soc.*, **25**, 12 (2005) pp.2055-2059.
- [14] B. Derby and N. Reis, *MRS Bulletin*, **28**, (2003) pp.815-818.
- [15] J. Wang and J. Evans, *Physical Review*, E **73**, 2 (2006).

## Author Biography

*KAWAMOTO, Hiroyuki holds a BS degree in Electrical Engineering from Hiroshima Univ. (1972) and a Dr. degree in Mechanical Engineering from Tokyo Institute of Technology (1983). From 1972 to 1991 he was a Senior Engineer at the Nuclear Division of Hitachi Ltd. In 1991 he moved to Fuji Xerox, and had been engaged in the research of imaging science and technology as a Research Fellow. In 1999 he left Fuji Xerox and he is now a professor of Waseda Univ. He was selected a Fellow of the IS&T in 1999 and awarded Chester F. Carlson Award in 2007.*