LONG-REACH FLYING FUNCTIONAL INKJET SYSTEM BY EMPLOYING ELECTROSTATIC ACCELERATION

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Abstract: In this paper, the authors proposed a novel idea of a long-reach flying inkjet system employing electrostatically-accelerated ink drop for the purpose of functional ink micro pattern plotting by contact-free and environment friendly. Proposed working principle was demonstrated through experiment and analysis. At the 5-mm of electrode gap and $\phi 120\ \mu m$ of nozzle, the applicable maximum voltage was 3.5kV realizing 67% up (1.67 times) of droplet flying velocity by one-step of accelerating. By $\phi 10\ \mu m$ of droplet, over 35m/s of flying velocity was promising and by 2~3 steps of accelerating further of speed increment could be expected.

Index terms: long-reach, contact free, functional ink, direct wiring, micro pattern, coating film.

1. INTRODUCTION

To fabricate a single set of personal computer, 1.8-tons of resources are being consumed according to the survey results of United Nation available in Mar. 2004 [1]. With the development of MEMS (Micro Electro Mechanical Systems) technology, recent electronic devices become miniaturized and functionally-efficient at a rapid rate. However, such micro devices are generally realized by enormous facility investments, and heavily depending on a huge equipments and manufacturing buildings having clean room, depending on excessively wasteful consumption of resources and energy, result in a serious problem of environmental load in the fabricating process [1-2]. For example, to fabricate a multilayer circuit by a traditional method, sets of photo-mask are required for the circuit patterns in every layer, and the metallic material laminated on the substrate will be eliminated except the necessary wiring patterns. In this method, metallic layer was firstly formed on the whole surface of the substrate including the unnecessary areas and then to be patterned by etching process, so that results in the problems in resource saving and emission limitation of waste fluid and materials. In place of the traditional method, recently such a research has been getting big attention as applying the characteristic of inkjet technology to the fabrication of electronic circuit wiring [2-4]. Inkjet printer could make several picoliters of ink droplet landing accurately on to the target paper by contact-free. It is exactly promising to printout micro patterns directly on to the non-planner surfaces and fine areas or flexible substrate by contact-free plotting without etching process so that make the production process become much resource saving and friendly to the environment. Originally, the printing technology was used to form photographic image, but by using a wide variety of functional ink, patterns of varied sizes can be expected and a wide range developments of new applications can be expected. In the case of electronic circuit fabrication, comparing to the traditional method of Cu-covered substrate pattern etching, if can plot wiring directly on to the substrate like inkjet printer by using electrically conductive ink, it is promising to manufacture high-mix low-volume product with much energy-saving, lower cost and quicker delivery without expensive photolithography facilities and photo mask [5-7]. Further more, by using multi nozzle and ink-sorting, it will also be prospective to printout LCR or semiconductor element with low cost like today’s color printer. In coating field, it is considerable to form a wide variety of overcoating at the micro space region, like anti-charging coating, anti-reflective coating or magnetic shield coating, as well as the photo-resist patterns for the semiconductor process.

However, comparing to the traditional ink which has been used in the offices or at home by existing inkjet printer, the functional ink generally shows higher of viscosity and specific gravity. Further, in the expected applications mentioned above, the surrounding operating condition for the direct drawing by inkjet is generally not so good but have non-planar surface. For instance, in the application of follow-on wiring after electronic packaging, there generally exist the high of bumps at the surrounding, so that a strong pumping force is absolutely necessary to make the ink droplet have higher of kinetic energy to guarantee a long distance flying and accurate drawing of micro patterns. But, existing inkjet technology has the problem of insufficient ejection power in principle when using functional ink something like metallic nano-particles.

2. PROBLEMS IN EXISTING INKJET TECHNOLOGY

The existing inkjet technology can mainly be divided to electro-mechanical (piezo-type) (figure 1) and electro-thermal conversion type (bubble-type) (figure 2). In the piezo-type, the pumping force is generated by the vibration dynamics of the piezoelectric element, and in that of bubble-type is by the air bubble generated by thermal energy from the heater. In the bubble type, the temperature rise of the heater might be 300~500 $°C / \mu s$ [7-10]. In order to buildup a higher of pumping force by employing the existing inkjet technology, it is necessary to increase the sizes of piezo element in piezo-type or the heater area in bubble-type. However, this will inevitably result in not only the size enlargement in ink head and high energy consumption, but also reduce the properties such as the miniaturization, reliability and durability of the inkjet device as well as its ability of the pattern refinement. Further, due to the high temperature rise in bubble type, the utilizable sort of the functional ink will be greatly limited [13]. Besides, if increase the pumping power in existing inkjet, the ink will become spray at the outside of the nozzle due to the higher of the shearing force than the surface tension of the droplet so that difficult to realize a long distance flying and the fine pattern print. In this paper, we proposed a new type of ink drop accelerating mechanism in order to realize a long-reach flying and fine pattern print when utilizing functional ink.

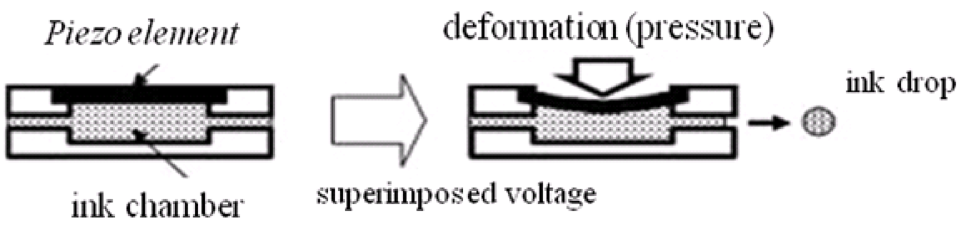

Figure 1. Piezo type inkjet printer [11, 12]

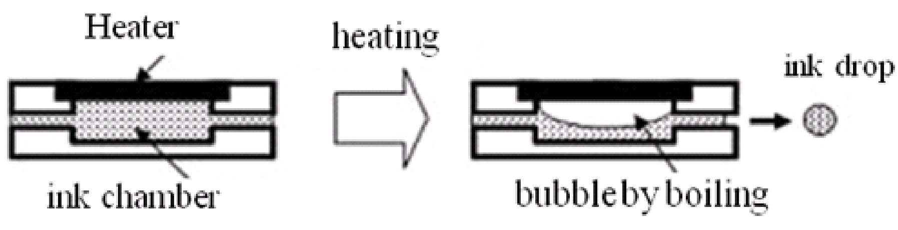

Figure 2. Bubble type inkjet printer [11, 12]

3. WORKING PRINCIPLE OF PROPOSED APPROACH

As a means of long-reach flying for the ink droplet, it is one of the thinkable approaches by increasing the size of the piezo element in piezo-type inkjet or increasing the dimension of the heater element in bubble-type to increase the pumping power. However, due to the size restriction from the structure miniaturization and the requirement of fine patterns, this approach has principle limitation and improper to the realization of a high ejecting power. In addition, because of the high temperature rise in bubble-type, the utilizable ink-sort will be greatly limited when considering employment of the functional ink in bubble-type inkjet.

In order to increase the ink droplet flying distance and to realize fine pattern print, the authors proposed for the first time to employ mechanism of electrostatic acceleration to the existing inkjet system. To be more precise, by applying a high voltage between the inkjet head and another electrode disposed in outside of the inkjet head, it is possible to accelerate a charged ink droplet and make it fly with a higher of kinetic energy to the target after ejecting out from the nozzle. The schematic illustration of proposed structure is shown in figure 3.

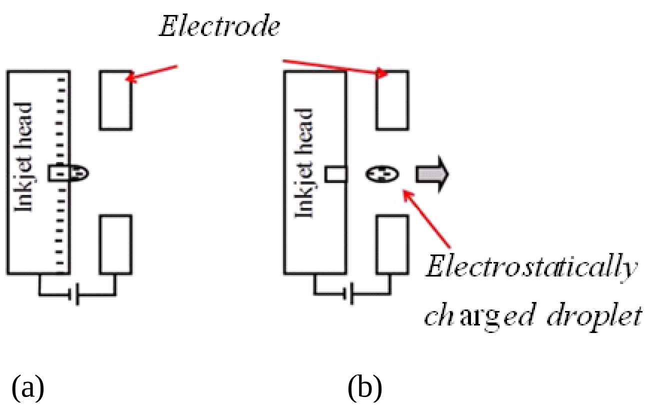

Figure 3. Working mechanism of electrostatic acceleration for the charged ink droplet: (a) Before the ink liquid ejecting out from the nozzle; (b) After ejecting out from the nozzle.

As shown in figure 3, by applying a high voltage to a grid patterned electrode disposed in front of the nozzle, an electrical field between the electrode and the nozzle was generated. In this way, an electrode polarization is generated on the ink liquids inside of the nozzle, and electrical charge will be stored on the surface of the ink droplet until the ink droplet to be ejected from the nozzle. The ejected ink droplet from the nozzle will be accelerated by the electrostatic force and flying to the electrode with a high kinetic energy. At the moment when the droplet is passing through the grid patterned electrode, by switching off the applied voltage the charged droplet will be flying to the target with the accelerated terminal velocity, or by inverting the polar character of the electrode, that of droplet will be accelerated further and got higher of kinetic energy to flying to the target so that a long-reach flying and fine pattern plotting could be realized with a general pumping power by utilizing the existing inkjet system.

It is Dr. Harold Kaufman in NASA who proposed ion electrostatic acceleration first in 1950s as a rocket engine for the deep space propulsion [14-16]. Later, this mechanism was employed in the applications of semi-conduction fabricating devices such as ion milling or sputtering etc. The working principle on the most general Kaufman-type ion gun is shown in figure 4. The electrostatic accelerating grid was made by thickening holes (diameter: several mm) on a less than 1mm-thick of plate, and closely arrange 2~3 plates with a less than 1mm of the gap. These grids were named as screen, accelerating and decelerating grid as shown in figure 4.

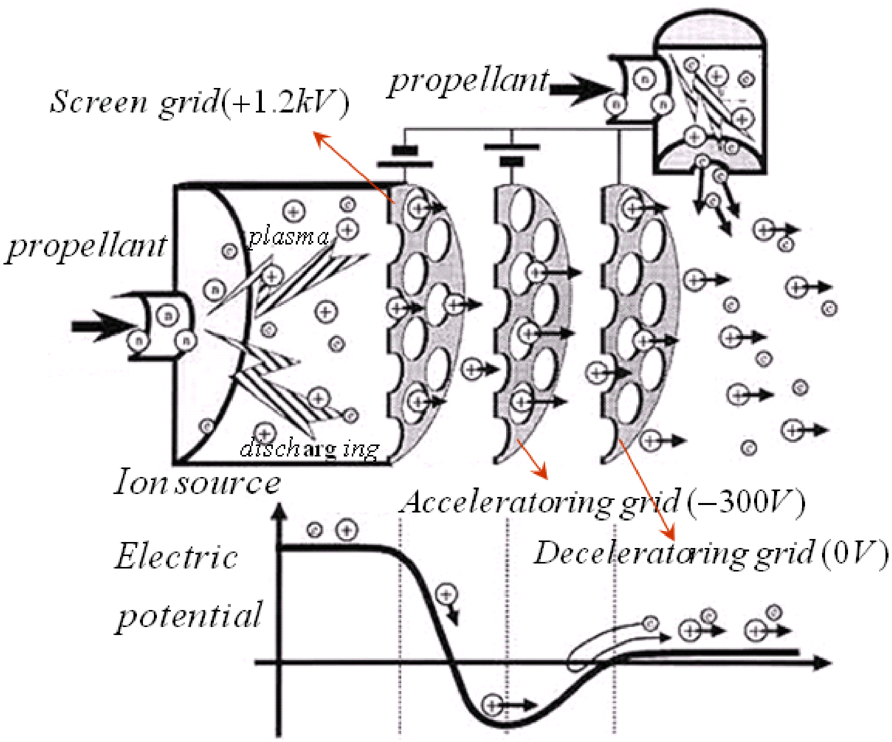

Figure 4. Working mechanism of Kaufman-type ion gun [16]

In figure 4, by applying +1.2kV, -300V, and 0V of voltage on to the screen grid, accelerating and decelerating grid respectively, the ion can be drawn from the ion source, and then ejecting to out side as an ion beam lastly with the energy of electric potential difference between the screen and the decelerating grids. The minus field formed by accelerating grid, will make the ion to be drawn from the ion source easily due to the enlarged electric field between the screens and accelerating grids. Further more, it can also deter the backward flow of the ion from the downstream of the decelerating grid. In order to avoid the drawn and accelerated ion bumping to the grids directly, it is important to design and arrange the holes on the grid definitely.

4. EXPERIMENATAL RESULTS

The built quantity of electric charge on the ink droplet is related with many parameters such as the size of nozzle diameter, the distance between the nozzle and the electrode, the viscous force of the ink droplet, the surface tension and the interfacial aspect as well as the amount of applied voltage etc. In addition, there exists a limitation in the built quantity of electric charge on the ink droplet because of the bursting spray phenomenon. When the related parameters mentioned above such as the nozzle diameter etc. are decided, at the condition of no pumping force and zero of the ink liquid initial velocity, by gradually increasing applied voltage between the nozzle and the electrode, the realizable maximum charge on the ink droplet till the droplet pulled out from the nozzle could be understood. In order to evaluate the possibility of applying electrostatic accelerate principle to the long reach flying inkjet system, such an experimental setup was built up as shown in figure 5. It is composed of a camera DMK-31BF03 made by Imaging Source Co., and a magnetic valve INKX0517500A (Very high speed micro dispense valve) made by Lee Co. having $\phi 127\mu m$ of nozzle as well as driving circuit IECX0501350A.

Figure 6 shows one of the experimental results of stroboscopically-illuminated photograph at the condition of $8\mu s$ of light-emitting time with the intervals of $100\mu s$. From the photographic images got by the first photogenesis and the second one, the droplet flying velocity could be calculated.

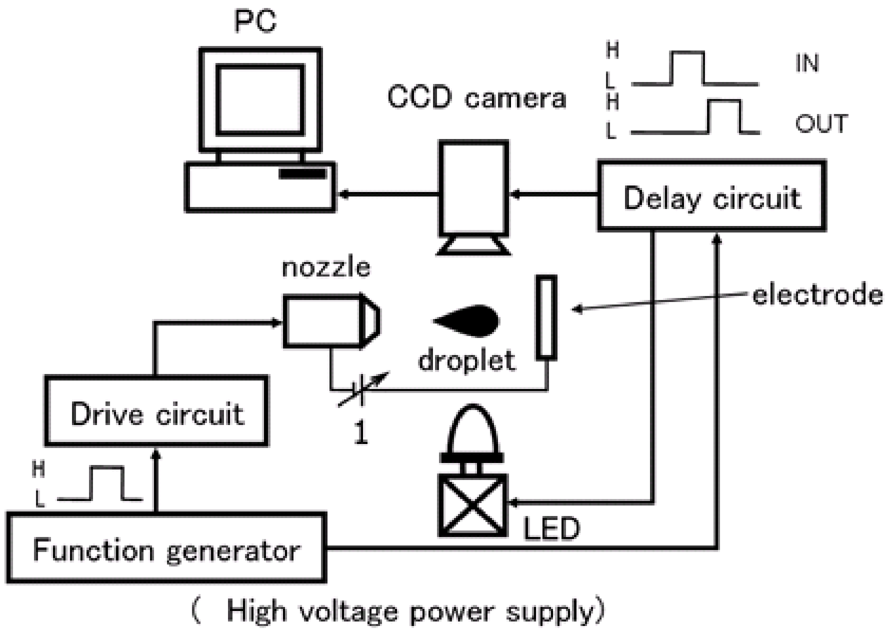

Figure 5. Experimental setup for the evaluation of long reach flying inkjet system by employing electrostatic acceleration mechanism on to ink droplet.

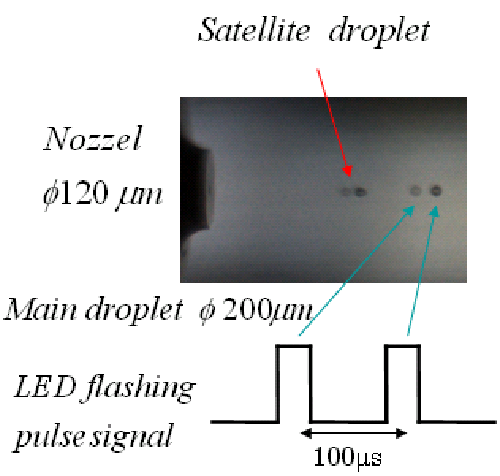

Figure 6. Stroboscopically-illuminated ink droplet flying measured by multiple exposure.

Figure 7 shows the continuously shot photographic imagery of the droplet flying during the period of discharge from the nozzle to the desorption from the nozzle at the condition of 10 μs of serial shoot duration without electrostatic acceleration. It was clear that the ink droplet did not immediately become a ball shape but stay flying carrying in a long tail.

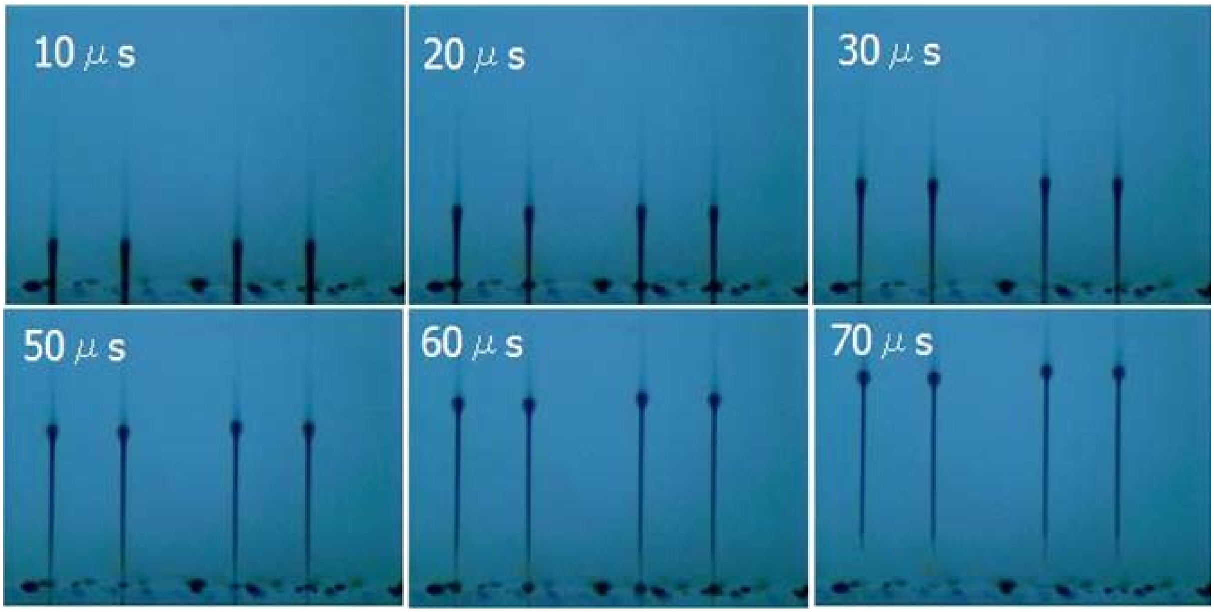

Figure 7. Photographic imagery of the flying ink drop when the ink is in the charge-free state

From figure 7, it is predictable that in the electric field the charge on the flying ink drop will be distributed intensively on the apical part of the ink drop. For the purpose of a long reach flying by means of the electrostatically accelerated ink droplet, it is the key issue how to increase the amount of built electric charge as higher as possible in the limited period of time during which the long tail ink droplet does not completely break away from the nozzle yet. Experimental result on the electrostatic acceleration was shown in figure 8. From figure 8 it was clear that according with the increment of applied voltage the amount of built electric charge on the ink drop will be maintained an upward trend, and the flying speed of the ink droplet was increasing. Simulation by FEM analysis was also performed employing software ANSYS. The flying velocity differences in the ink droplet between the experimental result and that of analysis might be due to the used flying condition difference. In the experiment, the ink drop was electrically charged in a limited time, while, in simulation, the analysis was performed in an infinite steady state because of the ability limitation of used software.

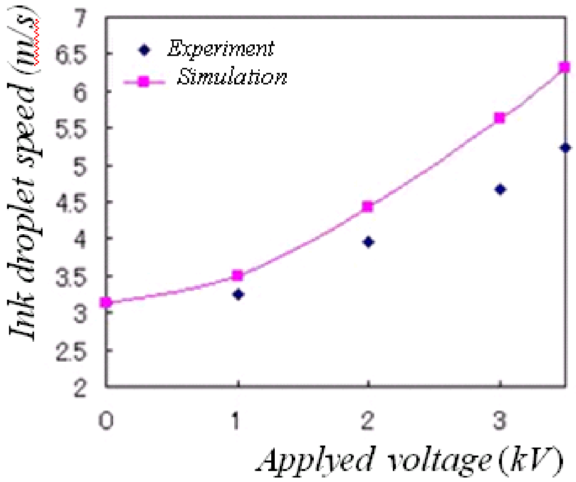

Figure 8. Relationship between the applied voltage and increased ink droplet flying speed.

In our experiment, it was also understood that although the increment of applied voltage can make a contribution to the acceleration and longer of flying distance for the ink droplet, there exists a limited maximum value in the increment of applicable voltage over which the ink drop will be burst out before pumping. When the distance between the nozzle and the correspondent electrode was 5-mm long, in our experiment the applicable maximum voltage was 3.5kV, and the increased droplet flying velocity was about 67% up (1.67 times) from the initial speed of no applied voltage. Figure 9 shows the photograph of bursting ink droplet after it was over charged. As shown in figure 9, when the applied voltage was over 3.5kV the charged ink drop was burst out in the forefront of the droplet before pumping. This result is due mainly to the electrostatic attraction generated from the Coulomb force which was stronger than ink drop surface tension.

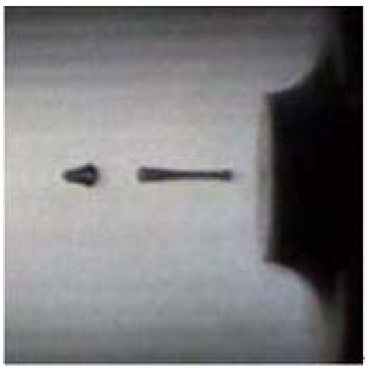

Figure 9. Bursting of ink-drop at a high voltage over 3.5kV.

6. ANALIZED RESULTS

In the experiment it was known that when too big amount of the charge is built up in the ink liquid, forefront of the ink droplet will be deformed, burst and diffused like a spray. The realizable maximum charge amount Q on ink drop could be calculated by the following Rayleigh's formula [17].

$$\frac{Q^2}{64\pi^2\sigma\varepsilon_0 R^3} \leq 1 \quad .... (1)$$

Where, Q is maximum charge amount, ε_0 is space permeability, σ is surface tension on droplet, and R is dimension of the droplet radii.

The charged amount Q on ink drop can be calculated by employing the following formula 2 associated with the principle of conservation of energy. Where, the required ink drop flying initial velocity v_0 and the accelerated terminal velocity v was got from experiment. In formula 2, the air resistance was ignored.

$$\frac{1}{2}mv^2 = QV + \frac{1}{2}m{v_0}^2 \quad ...... (2)$$

In a uniform electrical field E, the received Coulomb force F_q on the charge Q can be described as formula 3. Where, d means the distance between the electrode plates, and V is applied voltage.

$$F_q = QE = Q\frac{V}{d} \quad ...... (3)$$

In practical, the charged ink droplet will receive not only Coulomb force but also air resistance R_f , when flying in the air. Air resistance R_f can be calculated by formula 4.

$$R_f = \frac{1}{2} C \rho S \left[\frac{d}{dt} x(t) \right]^2 \text{ ...... } (4)$$

Where, ρ is air density $(= 1.2 kg / m^3)$, C is coefficient of air resistance, S is projected area in the forefront of the ink drop, and $\frac{d}{dt} x(t)$ is the ink drop velocity relative to air.

When the charged ink drop is flying in the electrical field of air medium, its motion equation can be described as formula 5. Where, M means the quality of the ink droplet.

$$M \frac{d^2}{dt^2} x(t) = QE - \frac{1}{2} C \rho S \left[\frac{d}{dt} x(t) \right]^2 \text{ ...... } (5)$$

The coefficient of air resistance C can be calculated by using Reynolds number from formula 6. Where, D is the droplet diameter, and μ is the coefficient of air viscosity $(= 1.8 \times 10^{-5} Pa \cdot s)$.

$$\mathrm{Re} = \frac{D\rho}{\mu} \frac{d}{dt} x(t) \text{ ...... } (6)$$

In inkjet, the Reynolds number of droplet is generally in the range of $2 < R_e \le 500$, so that the relationship between Reynolds number R_e and the coefficient of air resistance C can be described as formula 7:

$$C = 10\,\mathrm{Re}^{-\frac{1}{2}} = 10\left[\frac{D\rho}{\mu}\frac{d}{dt}x(t)\right]^{-\frac{1}{2}} \quad \ldots\ldots \; (7)$$

By substituting formula 7 to the 5, the flying velocity of the droplet could be calculated. Figure 14 shows the evaluated results from formula 1 and 5 associated with the relationship among the droplet diameter, applied voltage as well as the droplet flying velocity

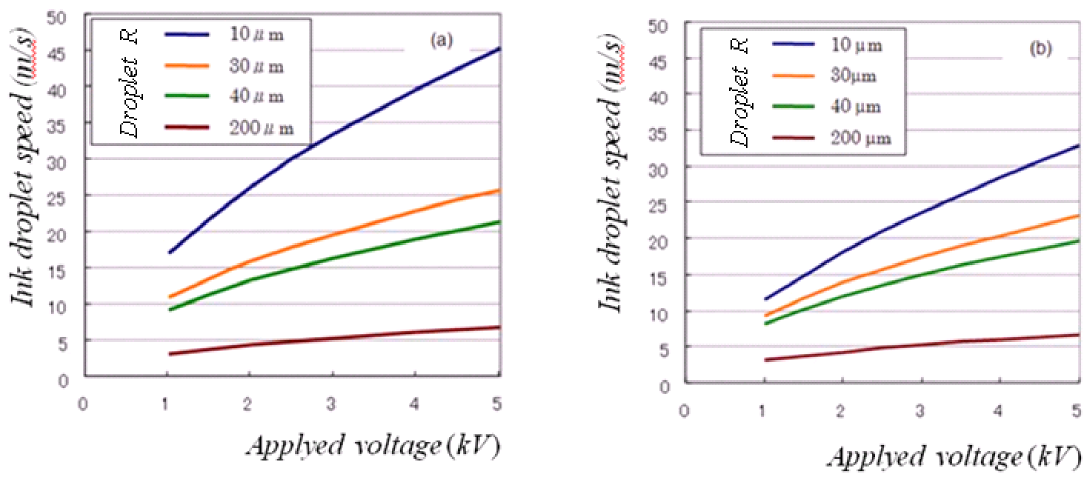

Figure 11. Relatoinship among droplet diameter and applied voltage as well as droplet flying velocity: (a) When the distance between nozzle and charging electrode is 5-cm; (b) When the distance between nozzle and charging electrode is 10-cm

In figure 11 it was shown that when the droplet diameter is tens of μm, its velocity can reach over several ten meters per second easily by employing electric acceleration. Received electrostatic force in droplet is proportional to its surface area, and when its volume become smaller, received electrostatic force per unit volume will become higher. In this way, the smaller the diameter the higher of flying speed could be realized due to the increased electric accelerate effect as shown in figure 11. Further, it was also known that the shorter the distance between nozzle and electrode the stronger the generated electrical field, so that result in a stronger of electrostatic force on droplet. It is clear that by 2 or 3-steps of accelerating, further of speed increment and longer of flying distances in droplet are promising.

As mentioned above, when there is only one charging electrode in the accelerating system, further of acceleration effect is not expected due to the limitation of applicable voltage. In order to accelerate the flying ink droplet further without droplet bursting, it is an approach to arrange the electrode for charging and that of accelerating respectively as shown in figure 10. In this approach, by arranging the charging electrode in the front of the nozzle, it is possible to make the ink inside of the nozzle to be electrically charged. The charged droplet which ejected from the nozzle will be accelerated by the charging electrode first, and then when the droplet pass through the charging electrode, by switching off or inverting the polarity of the charging electrode and switching on the accelerating electrode, can make the charged ink droplet to be accelerated further. In the same way, at the moment when the ink droplet pass through the accelerating electrode, by switching off or inverting the polarity of the accelerating electrode, the accelerated flying ink droplet will be accelerated further more and flying repulsively to the target with a 2-steply accelerated velocity.   .

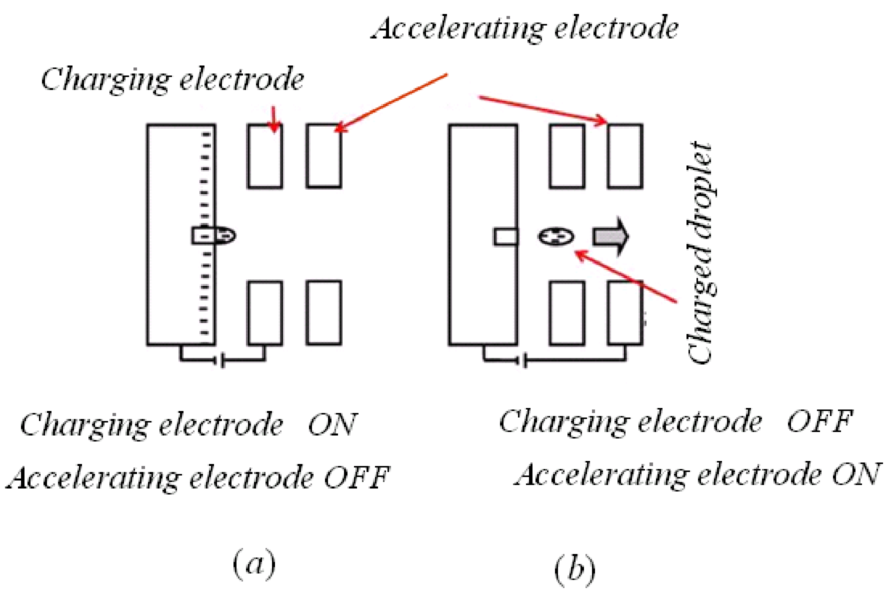

Figure 10. 2steps of accelerating mechanism by means of charging and accelerating electrodes: (a) By switching on the charging electrode and turn off the accelerating electrode at the same time, make the ink to be charged till it separated from the nozzle; (b) After pumping out and separated from the nozzle, the charged ink droplet is accelerated by the charging electrode first and then by the accelerating electrode further.

7. SUMMARY

A novel type of inkjet system was proposed for the purpose of a long-reach flying inkjet to realize functional ink micro pattern plotting by contact-free. The employed electrostatic acceleration principle was introduced and the proposed initial idea of inkjet mechanism was demonstrated through experiment and analysis. When the gap of electrodes was 5-mm and utilized nozzle size is $\phi 120\,\mu m$, the applicable maximum voltage on the electrode was 3.5kV without accompanying the phenomenon of ink drop bursting, and 1.67 times increment on the ink drop flying velocity was realized. By using smaller size of the nozzle and $\phi 10\,\mu m$ of droplet, over 30m/s (10-times) of flying velocity was promising and by 2~3 steps of accelerating, further of speed increment could be expected. Due to the ability of high acceleration in the proposed approach, long reach flying by variety of functional ink is promising. By employing a variety of functional-ink including conductive or insulating material it is possible to printout electronic wiring, device patterns or over-coating directly on to the non level surface. Further of detailed experiment using sorts of functional ink will be performed next and the results will be reported near future.

REFERENCES

[1] Kazuhiro MURATA, "Super Fine Patterning by Using Inkjet Technology", Japan Institute of Electronics Packing (JIEP), Vol.7, No.6, 2004, pp. 487-490.

[2] Shiri SAKAI, "The Printed circuit Board Manufacturing Using Inkjet Technology", The Institute of Electronics Information and Communication Engineers (IEICE), Vol. 90, No. 7, (2007), pp. 544-548.

[3] H.P. Le, "Progress and trends in ink-jet printing technology", J. Imaging Science of Technology, Vol. 42, No. 2, (1998), pp. 49-62.

[4] Y. Hagio, H. Kurosawa, W. Ito, and T. Shimoda, "Development of ink jet wiring technology", Proceedings of ICEP2005 (International Conference on Electronics Packaging), TA I-5, pp. 106-111, 2005.

[5] K. kitahara etc., "Latest inkjet technology - technical advantages and industrial application developments -", Technical Information Society, ISBN9784861041822, 2007, pp. 213-236,

294-302.

[6] Nakano juniti etc.,"Latest inkjet technology know-how collection – high-definition, high-resolution, high-speed, fine wiring, thin film", Technical Information Society, ISBN4861040620, 2005, pp. 28-38.

[7] Nomura Syunji, "Various types of inkjet technology and countermeasure for it's deficits", Information organization, ISBN9784901677943, 2008, pp. 2-8.

[8] Hara Endo, "Bubble jet print", Journal of IIEEJ (The Institute of Image Electronics Engineers of Japan), No. 11, (1982), pp. 66-71.

[9] A. Asai, "Bubble dynamics in boiling under high heat flux pulse heating", ASME J. Heat Transfer, Vol. 113, (1991), pp. 973-979.

[10] Nakasima, "Latest bubble jet technology", Journal of the Imaging Society of Japan, No. 140, (2002) , pp. 37-44.

[11] http://en.wikipedia.org/wiki/Inkjet_printer

[12] http://ja.wikipedia.org/wiki/

[13] Tae Coo Kang etc. "Droplet volume adjustable micro injectors using a micro-heater array", IEEE Journal of Micro-electro-mechanical Systems 16th IEEE International Conference (2003) 690-693.

[14] http://www.nasa.gov/centers/glenn/about/history/ds1.html

[15] H. Kuninaka, "Microwave Discharge Ion Engines onboard HASABUSA Asteroid Explorer", Journal of. Plasma and Fusion Research, Vol82. No.5 (2006) 300-305.

[16] http://www.jspf.or.jp/Journal/PDF_JSPF/jspf2006_05/jspf2006_05-300.pdf

[17] Oleg. V. Salata, "Tools of nanotechnology: Electrospray", Current Nanosience, (2005) 1, 25-33.