STUDY OF THERMAL-MAGNETIC DRIVING FOR NEXT-GENERATION INKJET

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***Abstract:** In this paper, the authors proposed a novel type of inkjet where the ink is driving by maxwell stress employing the characteristic of thermalmagnetic. Different with the traditional inkjet technology like the piezo-vibration driving type or bubble driving type, in the proposed approach the moving elements or high temperature is absolutely unnecessary and having simple structure, so that high durability and reliability is promising with small size and strong pumping force. The working mechanism of the proposed method was explained and demonstrated by analysis and experiment.*

Index terms: inkjet, thermalmagnetic, magnetic fluid, functional ink, direct drawing, wiring, micro pattern, coating film, environment, energy saving.

1. INTRODUCTION

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 overwhelmingly 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]. According to the UN survey report available in Mar. 2004 conveyed by Kyodo News Service, it was known that to fabricate a single set of personal computer, 1.8- tons of resources are being consumed [1]. For example to fabricate a circuit board by traditional method, sets of photo-mask are required for the circuit patterns on the every layer. In this fabrication process, metallic layer was formed on the whole surface of the substrate first including the unnecessary areas, and then to be etched out except a scantling of needful patterns. In this way, the resources are consumed unavailingly and at the same time the emissions of harmful effluents are increased to aggravate the environmental problem further.

In place of the traditional method, recently researches applying the characteristic of inkjet technology to the fabrication of electronic circuit wiring have been getting big attention [2-4] . Inkjet printer could make several picoliters of ink droplet landing accurately on to the target paper by contact-free. 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 will be promising. In electronic circuit, comparing to the traditional method of Cu-covered substrate pattern etching, if to 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 used in offices or at home, the functional ink generally shows higher of viscosity and specific gravity. Further, in the expected applications, the surrounding operating condition for direct drawing by inkjet is generally not so simple but have nonplanar surface. The application of follow-on wiring after electronic packaging, generally have high bumps at the surrounding, so that a strong pumping force is absolutely necessary to make the ink droplet reach higher of motional energy to guarantee a long distance flying and accurate drawing of micro patterns.

2. TRADITIONAL INKJET TECHNOLOGY

The existing inkjet technology can be classified mainly into bubble/thermal-type and piezo-type in principle.

2.1 BUBBLE/THERMAL-TYPE INKJET [8-10]

Most consumer inkjet printers, from companies including Canon, Hewlett-Packard, and Lexmark (but not Epson), use print cartridges with a series of tiny chambers each containing a heater, all of which are constructed by photolithography. To eject a droplet from each chamber, a pulse of current is passed through the heating element causing a rapid vaporization ($300-500°C$ temperature rise during several μs of time) of the ink in the chamber to form a bubble, which causes a large pressure increase, propelling a droplet of ink onto the paper (hence Canon's trade-name of Bubble Jet for its technology). The ink's surface tension as well as the condensation and thus contraction of the vapor bubble, pulls a further charge of ink into the chamber through a narrow channel attached to an ink reservoir. The schematic illustration of the bubble-type inkjet structure was shown in figure 1.

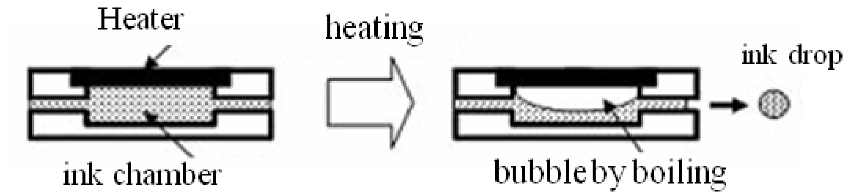

Figure 1. Thermal type inkjet printer [11]

The inks used are usually water-based (aqueous) and use either pigments or dyes as the colorant. The inks used must have a volatile component to form the vapour bubble, otherwise droplet ejection cannot occur. As no special materials are required, the print head is generally cheaper to produce than in other inkjet technologies. The thermal inkjet principle was discovered by Canon engineer Ichiro Endo in August 1977.

2.2 PIEZOELECTRIC-TYPE INKJET [2, 5-7, 10]

Most commercial and industrial inkjet printers and some consumer printers (those produced by Epson) use a piezoelectric material in an ink-filled chamber behind each nozzle instead of a heating element. When a voltage is applied, the piezoelectric material changes shape, which generates a pressure pulse in the fluid forcing a droplet of ink from the nozzle. Piezoelectric (also called Piezo) inkjet allows a wider variety of inks than thermal inkjet as there is no requirement for a volatile component, and no issue with kogation, but the print heads are more expensive to manufacture due to the use of the specialist piezoelectric material (usually PZT, lead zirconium titanate). Piezo inkjet technology is often used on production lines to mark products - for instance the use-before date is often applied to products with this technique; in this application the head is stationary and the product moves past. Requirements of this application are a long service life, a relatively large gap between the print head and the substrate, and low operating costs. The schematic illustration of bubble type inkjet structure was shown in figure 2.

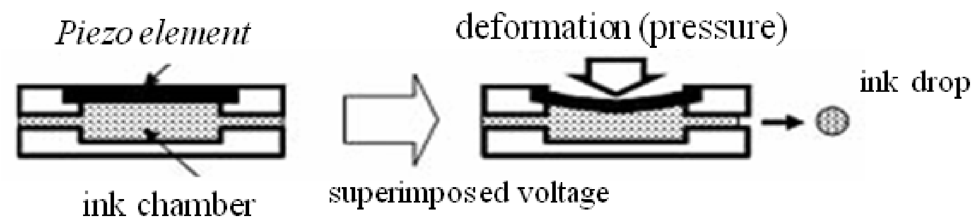

Figure 2. Piezo type inkjet printer [11]

2.3 LIMITATION AND PROBLEMS IN TRODITIONAL INKJET TECHNOLOGY

In the traditional inkjet technology, the main attention had been for the application of planar target print with higher printing speed, higher-resolution, higher durability and lower cost etc. The utilizable ink was limited in a low-viscosity type (below tens of mPa・s [5-7]) like the dye-based or pigment-based ink having nanometers of fine particles, and assured ink drop reaching distance was only several millimeters long. To realize electronic circuit wiring by means of the existing inkjet technology, it is necessary to be able to eject the ink droplet with enough pumping power in which the functional particles like metallic and magnetic as well as dielectric particles were dispersed in the binder. In this case, in order to enhance the functionality of the ink, it is required to make the dispersed particles maintain the characteristics of bulk material, so that need to employ several hundred nanometers of particles (much bigger than in the general printing ink). In existing inkjet technology, the pumping power is not enough for the functional ink application. In order to buildup higher of pumping force in the existing 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 consume, but also affect the miniaturization, reliability and durability of the inkjet device as well as the pattern refinement.

3. WORKING PRINCIPLE OF PROPOSED INKJET TECHNOLOGY

As mentioned above, the existing inkjet technology has principally inevitable problems for the functional ink application, mainly in structure and size enlargement (Piezo-type) as well as ink sort limitation due to the high temperature rise (bubble-type). In recent years, the authors have been working on the basic and applicable research of thermal magnetic driving to construct a novel type of pumping mechanism employing Curie temperature of magnetic material [12-13]. Utilizing magnetic fluid ink, the bursting phenomenon of the ink-drop will be alleviated due to the magnetic flocculation in the outside of the nozzle (free space), and also to be insusceptible to scattering in the air space due to the higher of specific gravity of the ink, profitable for the longer of ink flying distance. In the proposed ejection mechanism of thermal magnetic driving, the pumping stress is realized by the precipitous magnetic gradient of magnetic fluid at the forefront of the nozzle. Different from the traditional inkjet technology, in the proposed approach the moving element is not necessary, so that simple structure, high reliability and durability is promising.

Working principle of thermal magnetic driving: The schematic illustration of thermal magnetic driving was shown in figure 3. In the magnetic circuit composed from N-S poles of the magnet, the magnetizing field through temperature-sensitive magnetic fluid inside the circuit will show no-gradient uniform vector field as shown in figure 3-a. When the temperature-sensitive magnetic fluid inside the circuit get rapid temperature rise locally, its magnetization will disappear locally, so that results in a precipitous magnetic gradient and pumping force (Maxwell stress) as shown in figure 3-b. There, moving elements like piezo plates are absolutely unnecessary, and several hundred of high temperature rise ($300-500°C/\mu s$) like in bubble-type inkjet is also not necessary. By employing low Curie-temperature magnetic fluid (Ferrite or FeNiCr nanoparticle), it is possible to generate enough of ejecting power at $50-120°C$. Energy-saving and high durability as well as high reliability of new-type inkjet is promising. Figure 4 shows the actuation model of proposed thermal magnetic driving inkjet.

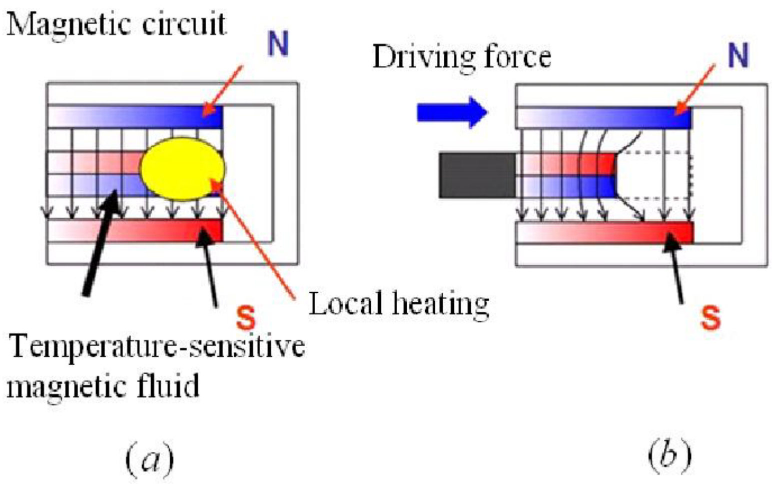

Figure 3. Thermal magnetic driving principle

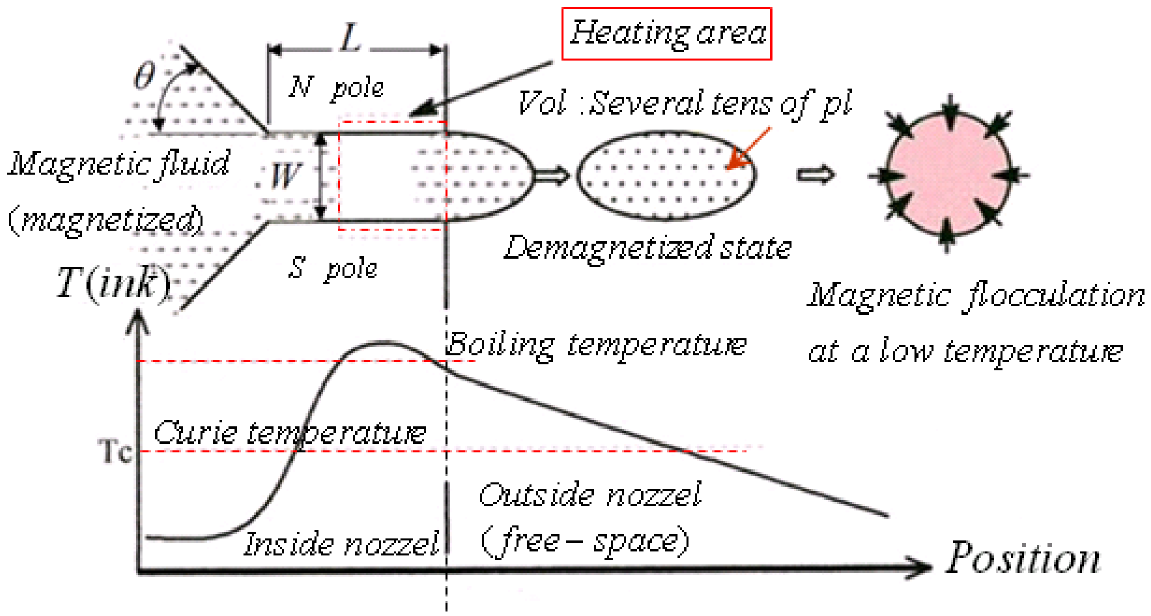

Figure 4. Thermal magnetic driving inkjet model

4. ANAYSIS AND EXPERIMENTAL RESULTS OF PROPOSED INKJET

4.1 ANALYZED RESULTS

Proposed inkjet structure: In the proposed approach, it is important to be able to generate a high gradient magnetic field routinely at the channel. Figure 5 shows the schematic illustration of the proposed inkjet structure. As shown in figure 5, in the proposed inkjet structure, the ink channel was formed by etching arrayed trench which perpendicular to the direction of the uniform magnetization generated from the permanent magnet. When the trench width of the channel is W, the generated ejecting force will be changing depending on the heating position, and by heating forefront area of the channel locally, the ejecting force could be reached much efficient level. Micro-heater elements were formed on an excellent insulation substrate by a thin resistant film at the opposite position of the forefront in channel to realize higher of pumping force.

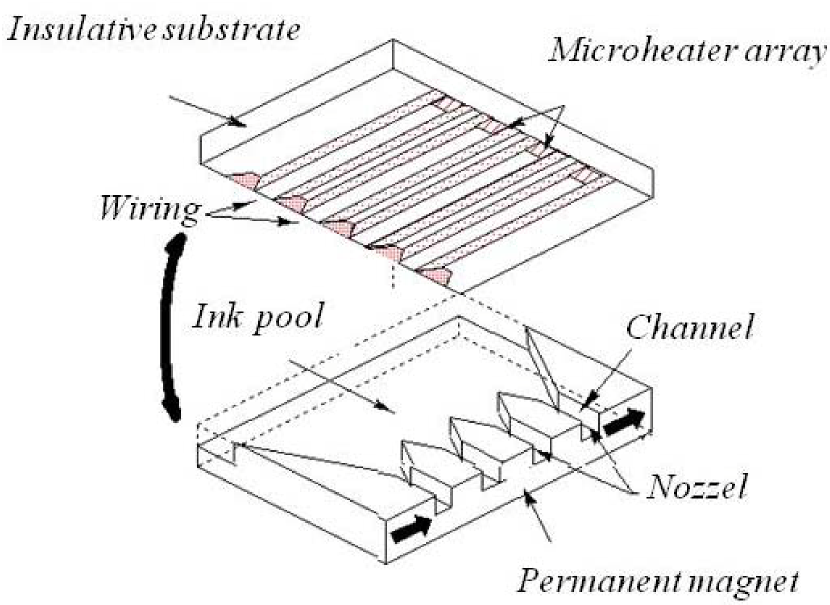

Figure 5. Proposed thermal magnetic driving inkjet structure

Figure 6 shows the simpified model of a single channel structure employed in the analysis. The magnetic field H in channel can be described as $H = \Phi / W$. Where, Φ shows the magnetic potential differences generated between opposite walls of the channel. When the length of the channel L is long enough comparing to the width W, the magnetic potential differences Φ can be shown with the remanent magnetization Mr, and $\Phi \approx Mr$. A narrower width of the channel W, will result in a higher of magnetic field H. From the results mentioned above, it is clear that in order to get a higher of ejecting power, a finer of ink droplet will be profitable, and fine ink droplet is well fitting to the requirements of micro patterns too.

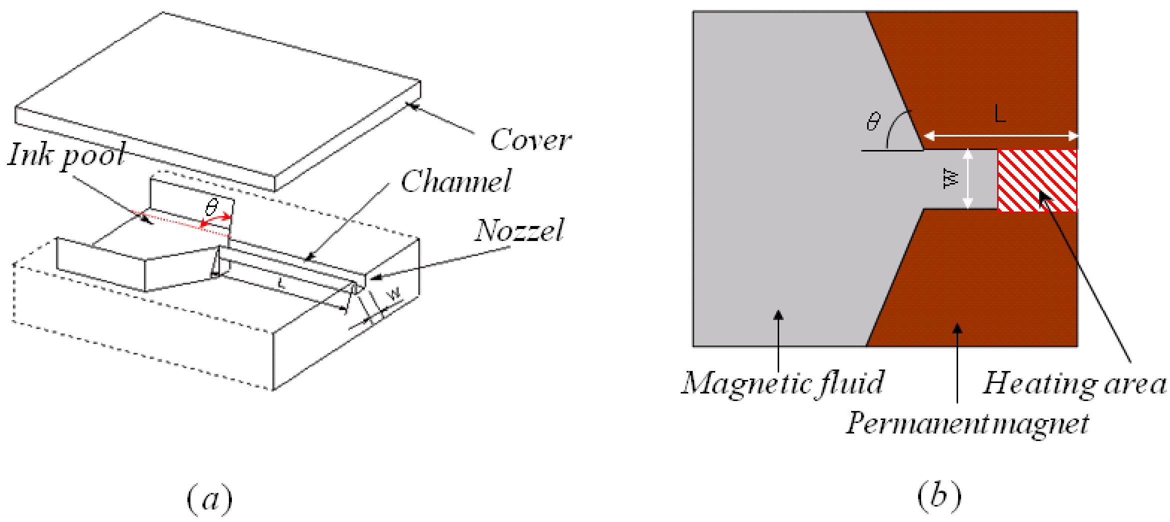

Figure 6. Simplified model : (a) Single channel structure ; (b) Simplified model used in analysis

Analysis results: By using the model as shown in figure 6, analysis was performed with the parameters of structural dimension $L, W \ and\ \theta$ etc. for the ejecting force in the proposed inkjet mechanism. The material properties employed in this analysis are shown in table 1.

Table 1. Material properties used in analysis

Magnetic fluid	Ferrite:Water: Neutral detergent =1:1:1 (volume ratio)		Saturated magnetization : 0.15-T
Ferrite	Relative permeability (μr): 212.78	Curie temperature : 47-°C	Saturated magnetization : 0.45-T
Magnet	Magnetic field intensity (Neodymium magnet) : 800kA/m		

The analyzed result was shown in figure 7. From the analysis it was known that at the condition of $L = 2W$ and $\theta = 60 - 90°$, higher of pumping power is promising. But, by enlarging the length of the channel L further, no payback can be expected for the increased pumping power, due to the increased viscosity resistance which in proportion to the channel length. By enlarging the channel length L over $2-3W$, only unbenefited results are obtained due to the increased viscosity resistance.

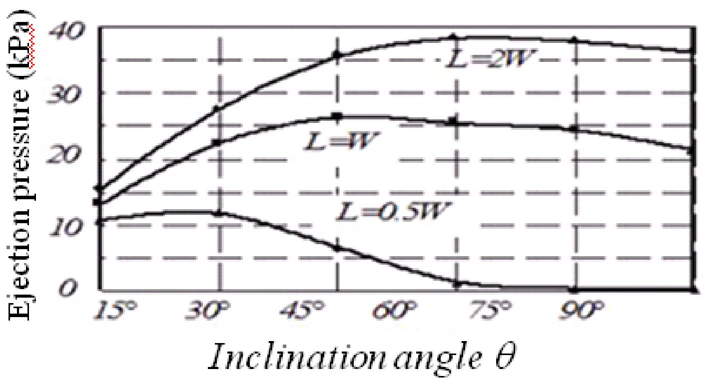

Figure 7. Analyzed results using the model of figure 5-6

From the analysis it was known that, at the condition of the same magnetic field distribution with that of figure 5, if shift the heating area much more forward to outlet side of the permanent magnet, there must exist a position having the highest pumping power. Necessary new structure having nonmagnetic material (NM) is shown in figure 8. The compared results of analysis between the model of figure 5 and 8 are shown in figure 9. From figure 9, it is known that at the condition of $W = 100\mu m$, by adding a nonmagnetic material with the thickness of $W/2$ (structure to see

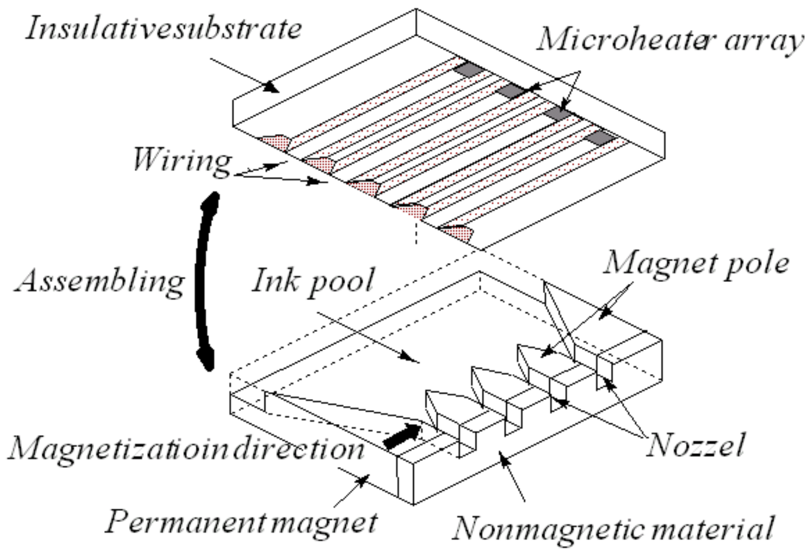

Figure 8. Proposed thermal magnetic driving inkjet structure having nonmagnetic material

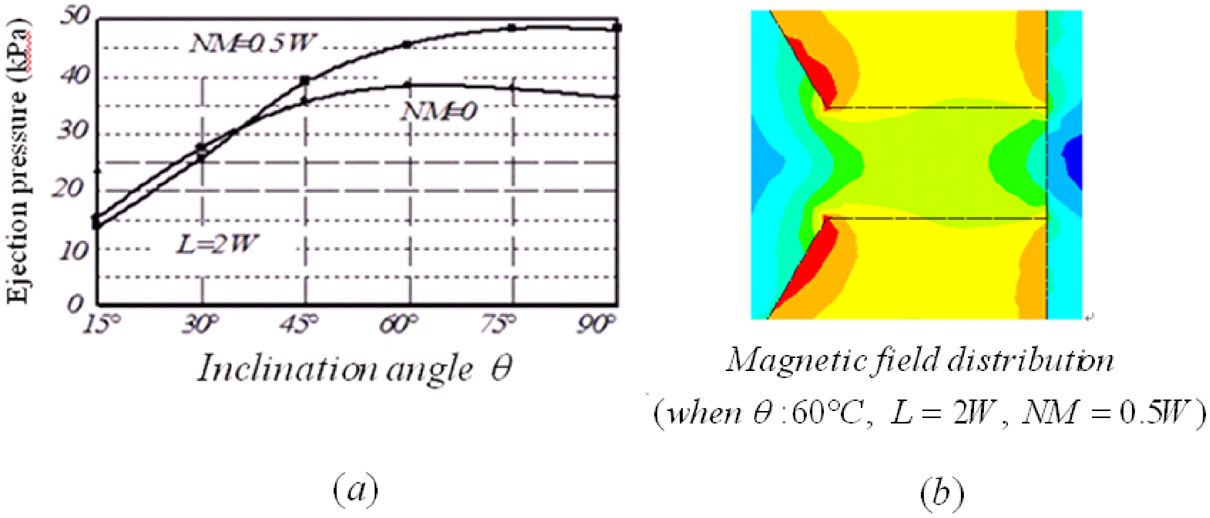

Figure 9. Comparing of analyzed results between the model of figure 5 and 8 (having nonmagnetic material): (a) Analyzed results by the model of structure as figure 5 and 8; (b) Magnetic field distribution at the condition of $\theta = 60°C, L = 2W, NM = 0.5W$

figure 8 for reference) and make the position of heating area shift to outlet side of the permanent magnetic with $W/2$, over 20% of increased pumping power could be realized. However, if enlarge the thickness of nonmagnetic material and make the heating area apart from outlet side of the permanent magnetic further, the acquired pumping power will be decreasing due to the enlarged length of the channel and the increased viscosity resistance. In the structure of figure 8, it is advisable to employ such a nonmagnetic material having low viscosity resistance and less of thermal conductivity like Teflon or SiO_2.

In the proposed inkjet, the pumping power will be increased in proportional to the amount of included magnetic nano-particles. Although by increasing the included particles, the viscosity and specific gravity of the ink will be increased, but because of the proportionally increased pumping power, it is still profitable for the enrichment of ink functionality.

By employing thermal magnetic driving mechanism, it is possible to eject high content of magnetic particle fluid which has been traditionally considered impossible by inkjet. In the proposed inkjet the contents of the ink are magnetic nano-particles and by depositing different kind of materials on to the magnetic nano-particle surfaces, for instance by depositing copper, the interfacial surfaces of the particles will be connected by copper so that make it possible to printout low resistance copper wiring directly by inkjet method with low cost and quick delivery.

4.2 FABRICATION PROCESS AND EXPERIMENTAL RESULTS

In order to fabricate a prototype for the experiment, fabrication process was performed as shown in figure 10. (a) A positive photo-resist was coated on the nonmagnetic copper substrate first and then patterned; (b) Using the patterned photo-resist layer as the etching mask to etch the copper substrate; (c) After electrical Ni-Fe plating on the patterned copper substrate the photo-resist was removed; (d) Photo-resist was coated again and then patterned; (e) Using the patterned photo-resist layer as the etching mask to etch the copper substrate first and then to remove the photo-resist, and the required prototype structure was formed; (f) Assembling with glass cover and permanent magnet: A permanent magnet (Neodymium magnet) was used to realize magnetic circuit and a glass plate was used as the cover to seal-up the ink-pool. Fabricated prototype was shown in figure 11-(b). Figure 11-(a) shows the experimental setup used in the demonstration. Figure 12 shows the schematic illustration of the experimental concept for to demonstrate proposed inkjet mechanism. In the state of figure 12-(a), the magnetic fluid is filled in the channel which means no heating was added to the magnetic fluid and the magnetic field in channel is uniform. Here, the hydrostatic fluid pressure could be measured by means of the experimental setup as shown in figure 11-(a). In the state of figure 12-(b), by increasing the hydrostatic fluid pressure the water in micro-tube was drifted into the inside of the nozzle about $100\mu ms$ long, and the hydrostatic fluid pressure was measured again. In this case, the magnetic field gradient will be generated inside of the inkjet channel, just like the situation of locally heated magnetic fluid in the forefront of the nozzle and lost magnetic properties due to the Curie temperature.

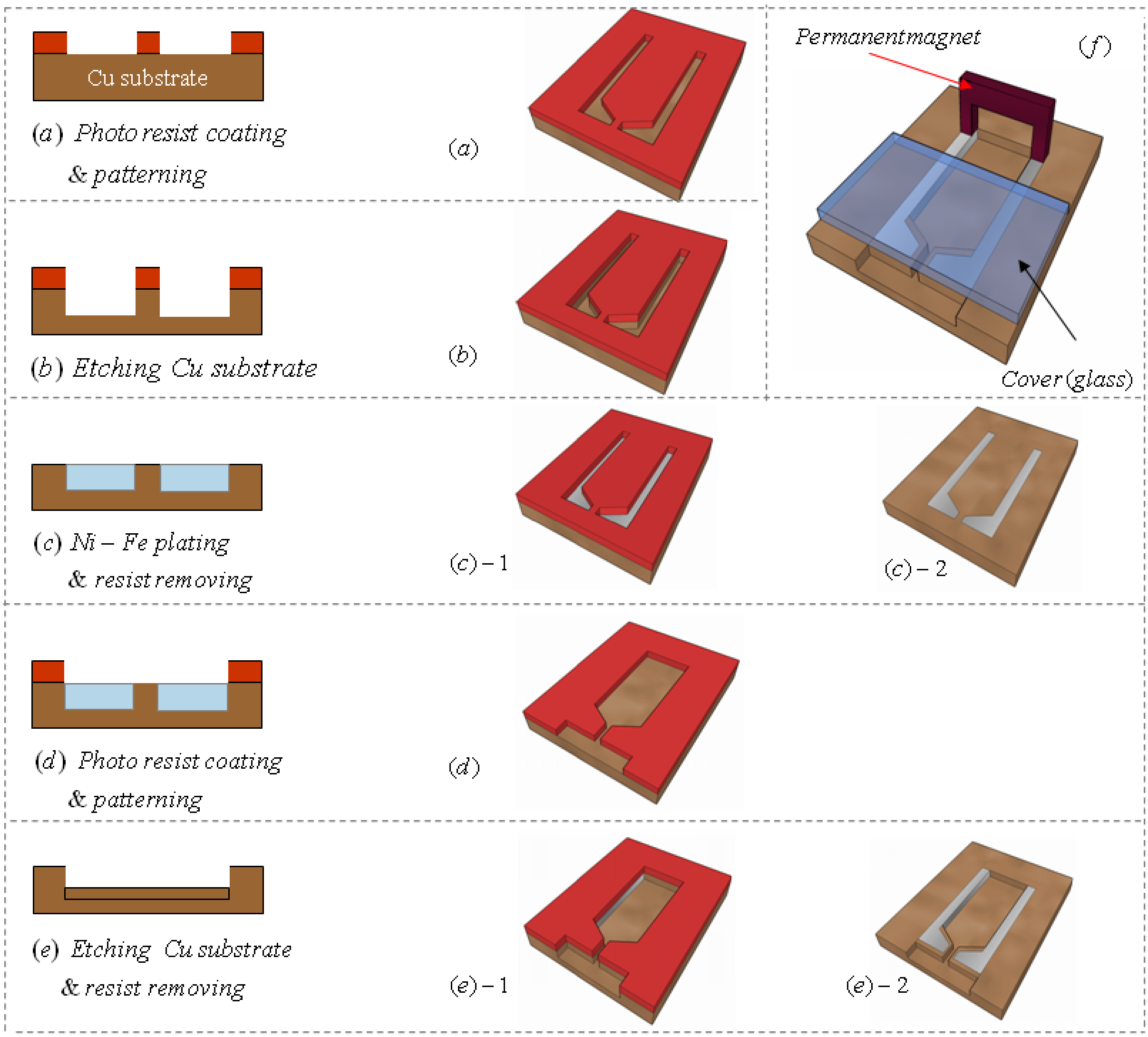

Figure 10. Fabrication process for the prototype used in experiment: (a)-(e) Process detail; (f) Assembling with glass cover and permanent magnet (Neodymium).

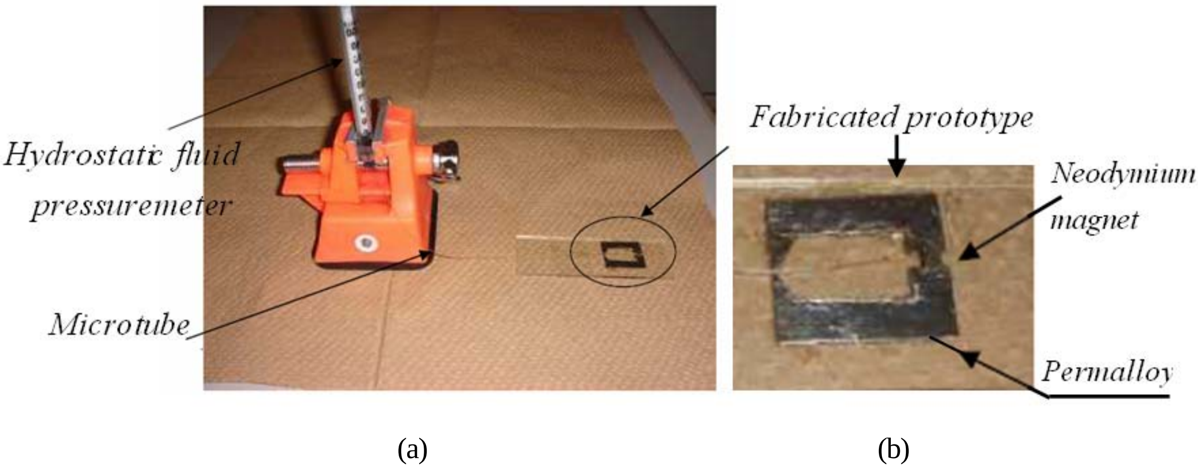

Figure 11. Experimental setup and fabricated prototype: (a) Experimental setup; (b) Prototype.

From the measured hydrostatic fluid pressure differences between the state (a) and (b), the generated force by magnetic field gradient could be evaluated. In our experiment, at the state of figure 12, the generated force from the magnetic gradient was about 250-kPa, high enough to be used in the application of an inkjet ejection. The optimal design for the inkjet head structure is necessary in order to get the most precipitous magnetic field gradient at the outlet of the nozzle, and further experiments are necessary to evaluate the responsive properties by means of pulsed laser power or thin film micro heater. The relationship among the magnet pole arrangement, magnetic field distribution and the magnetic liquid viscosity resistance in channel need to be clarified too, and these results will reported in the near future.

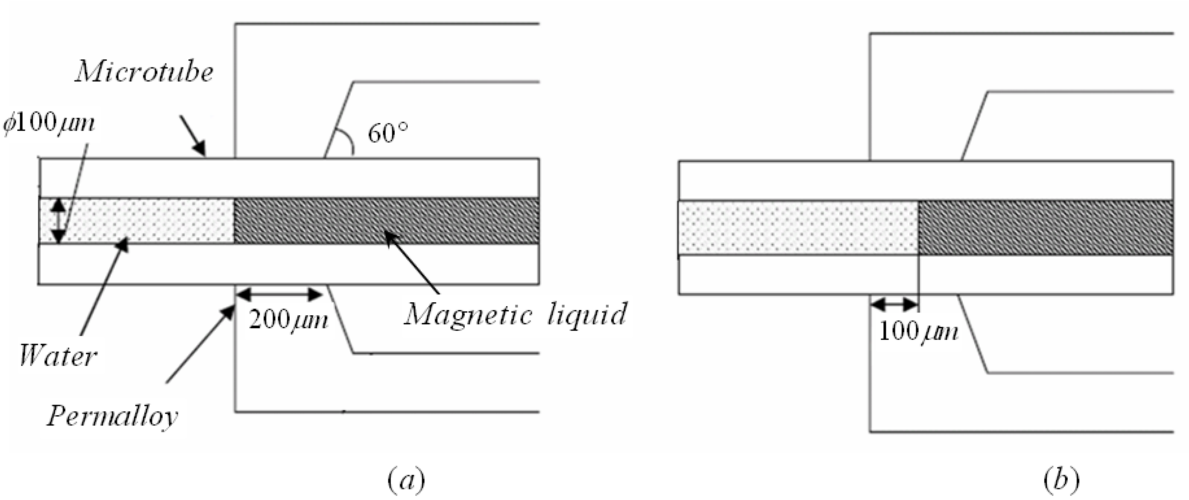

Figure 12. Measurement for the generative force: (a) Model of without heating magnetic liquid; (b) Model of heating magnetic liquid at the area of 100 μm from nozzle outlet.

5. SUMMARY

A novel type of inkjet mechanism was proposed and demonstrated with analysis and experiment. In the proposed approach, the moving elements like the piezo-vibration plate or high temperature like in the bubble driving type is absolutely unnecessary so that high durability and reliability is promising with small size and strong pumping force. Further more, by depositing different kind of functional materials like copper etc. on to the magnetic nano-particle surfaces, the interfacial surfaces of the particles will be connected by copper so that make it possible to printout low resistance copper wiring by inkjet method. Further experiments and detailed research will be performed and the results will be reported in the near future.

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