New Thermal Ink Jet Printhead with Improved Energy Efficiency Using Silicon Reactive Ion Etching

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In thermal ink jet (TIJ) printhead design, in order to satisfy various market demands, it is important to consider how effectively the printhead transfers input energy to ejected drop performance. First, we defined energy efficiency as a ratio of ejected ink drop energy (the sum of kinetic and surface energy) to consuming electric energy in the heater of thermal ink jet printhead. We examined a method for increasing the energy efficiency in terms of printhead design, and we found that it relates with an inertance ratio of the rear fluid pass to the front. We proposed a new side shooter thermal ink jet printhead for improvement of the inertance ratio, and we tried to fabricate channels on silicon wafers by a reactive ion etching (RIE). The printhead achieved higher energy efficiency when compared with the conventional design and it has been proved that high energy efficiency enables low consuming energy or high drop energy, and other good characteristics have been also obtained by the printhead.

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Introduction

Since personal computers have been spread widely and Internet environments have been prepared rapidly, people can get various fine images that they want from all over the world. In addition, because digital cameras have become cheaper and the pixel number of CCD has increased (already exceeding 'Mega-Pixel'), we can see high quality images on our computers at home easily. As a natural desire, we want to print these images on paper and see them in our hands.

Recently, most office documents have been colored to appeal to readers. So, the demand for producing many high quality color documents at high speeds has been increased today.

In these situations, small, inexpensive, high image quality, high speed and highly reliable color printers have become more desirable. We believe, and it is recognized in the market, that thermal ink jet (TIJ) printing has a high potential to satisfy these demands in both home and office environments because ink drop ejection and the printing mechanism in thermal ink jet are very simple.

In order to respond to the above market demands, it is important to consider how little energy TIJ printhead consumes and the high performance it offers. Namely, we must consider such a printhead design that can effectively transfer input electric energy to a desired drop performance. We call this transformation efficiency *energy efficiency* of TIJ printhead. If we can get high efficiency, we will be able to achieve low energy consumption to get a desired performance (drop volume), or get a high performance (drop velocity) at the same consuming energy. The former case makes the printer size smaller and decreases its cost. The latter can widen the variety of inks and decrease maintenance work load, and consequently achieve high image quality and high reliability.

Energy Loss in Thermal Ink Jet and Definition of Energy Efficiency

Figure 1 shows the schematic diagram of a typical side shooter TIJ printhead. After an electric pulse of several microseconds is applied to the heater, the temperature on the heater surface increases rapidly and reaches to a superheat temperature. Homogeneous nucleation occurs, and a vapor bubble is generated with high pressure. The high pressure bubble pushes ink both forward (to the nozzle) and backward (to the reservoir). The pushed ink overcomes surface tension of the meniscus and forms an ink drop.

In this process, when electric energy supplied from the power source is changed to ink drop energy, a great amount of energy loss occurs. The energy losses can be classified by physical phenomena or locations where they occur:

1. Electric loss in electrode and driver (IR drop):
   electric energy changes only partially into heat due to the resistance of electrode and driver.
2. Thermal transfer around the heater:
   heat generated at the heater layer is transferred not only to the upper, but also to the lower and side directions.
3. Bubble generation:
   not all of the energy transferred to the interface of heater surface and ink contributes to bubble generations and growth.

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High-Resolution Long-Array Thermal Ink Jet Printhead Fabricated by Anisotropic Wet Etching and Deep Si RIE

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***Abstract*—This paper describes the fabrication and characterization of a thermal ink jet (TIJ) printhead suitable for high speed and high-quality printing. The printhead has been fabricated by dicing the bonded wafer, which consists of a bubble generating heater plate and a Si channel plate. The Si channel plate consists of an ink chamber and an ink inlet formed by KOH etching, and a nozzle formed by inductively couple plasma reactive ion etching (ICP RIE). The nozzle formed by RIE has squeezed structures, which contribute to high-energy efficiency of drop ejector and, therefore, successful ejection of small ink drop. The nozzle also has a dome-like structure called channel pit, which contributes to high jetting frequency and high-energy efficiency. These two wafers are directly bonded using electrostatic bonding of full-cured polyimide to Si. The adhesive-less bonding provided an ideal shaped small nozzle orifice. Use of the same material (Si substrate) in heater plate and channel plate enables the fabrication of high precision long printhead because no displacement and delamination occur, which are caused by the difference in thermal expansion coefficient between the plates. With these technologies, we have fabricated a 1" long printhead with 832 nozzles having 800 dots per inch (dpi) resolution and a 4 pl. ink drop volume. [1085]**

***Index Terms*—Drop ejector, electrostatic bonding, micromachining, reactive ion etching, thermal ink jet.**

I. Introduction

THE market of ink jet printers is growing rapidly because of its advantages, e.g., high-quality color image, low machine cost, small size, and low printing noise. There are different kinds of ink jet printers according to their actuation method. These include thermal type [1]–[5], piezoelectric type [6], acoustic wave type [7], and electrostatically driven type [8]. Among them, thermal type and piezoelectric type are the most commonly used actuation methods in commercial ink jet printers. Three important factors for ink jet printers are print speed, print quality, and machine cost. For high-speed printing, high-density nozzle and long array printhead are the important factors. The thermal ink jet (TIJ) is suitable because it is easy to array the heater (actuator) and nozzle in high density. However, the piezoelectric type needs a large actuator, therefore, a high-density nozzle array is difficult to achieve. For high-quality printing, small ink droplets that deliver high-image quality printing can be achieved using high-precision small nozzles with high ejection power. For cost reduction and smaller size, an integration of LSI into the printhead chip is the most suitable. The cost per jet in TIJ is low because the number of components is small, by which the logic circuit is easy to integrate in the head chip. Therefore, the TIJ printer fulfills these three important factors.

Use of integration technologies of LSI process and Si micromachining process enable fabrication and operation of a high speed, high-image quality, and low cost TIJ printhead.

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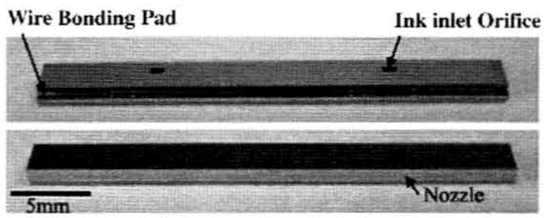

Fig. 1. Image of printhead chip.

II. Fabrication Process

The printhead chip shown in Fig. 1 is fabricated by dicing the bonded wafer, which consists of a heater plate wafer, and a Si channel plate wafer. The structures of TIJ printhead chip are shown in Fig. 2, [4]. Nozzle orifice appears at the dicing plane. Because the heater plate and the channel plate are both Si crystalline substrates, there is no difference in the thermal expansion coefficient between both plates thus, chip warp does not occur. This printhead is, therefore, suitable for long chip concept. In the following sections, the primary process technologies for the printhead chip are presented.

A. Heater Plate

The heater plate consists of logic MOS LSI, embedded high voltage (HV) MOS transistor, Poly Si heating resistor and polyimide film, which protects the device from ink attack. The polyimide film is patterned by O_2 plasma RIE. The process steps are (a) The polyimide is coated and cured at temperature (350 °C) above the glass-transition temperature (285 °C) to enhance the durability against ink. (b) The polyimide film is planarized by chemical mechanical polishing (CMP). (c) The polyimide film is patterned by O_2 plasma RIE by using a mask of Si-containing resist. The polyimide used was Durimide 7520 polyimide from Arch Chemicals Inc. having a final thickness of 10 μm.

PAPER *Special Issue on Integrated Systems with New Concepts*

High Resolution Long Array Thermal Ink Jet Printhead with On-Chip LSI Heater Plate and Micromachined Si Channel Plate

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SUMMARY This paper presents a high resolution long array thermal ink jet (TIJ) printhead which has been developed and demonstrated to operate successfully by combining two functional Si wafers, a bubble generating heater plate fabricated using LSI process and a channel plate fabricated using Si bulk micromachining technology. The heater plate consists of logic LSIs, high voltage MOS transistor, polycrystalline Si (Poly Si) heating resistor and polyimide protective layer. The polymide layer is patterned by O_2 plasma reactive ion etching (RIE) and is applicable to high resolution heater array. The Si channel plate consists of an ink chamber and an ink inlet formed by KOH etching, and a nozzle formed by inductively coupled plasma RIE (ICP RIE). The nozzle formed by RIE has squeezed structures which contribute to high energy efficiency of drop ejector and therefore successful ejection of small ink drop. These two wafers are directly bonded by using a novel electrostatic bonding of full-cured polyimide to Si. The adhesive-less bonding provided an ideal shaped small nozzle orifice. And also, the bonding method enabled to use an on-chip LSI wafer because of the contamination free material and the suitable processing conditions (low temperature). The bonded wafer is diced to form printhead chip. No delamination or displacement of the chip was observed even though the chip was subjected to thermal stress during assembly process. This is because of no difference in thermal expansion coefficient between both chips (Si and Si). And therefore it is suitable for long chip concept. With the above technologies, we have fabricated a 1.3″ long printhead with 1024 nozzles having a 800 dots per inch (dpi) resolution, a 2.7 pl. ink drop volume, 14 m/sec. ink drop velocity and 18 kHz jetting frequency. And we have confirmed high speed printing and high quality printing.
key words: *thermal ink jet, micromachining, drop ejector, reactive ion etching, electrostatic bonding*

1. Introduction

In recent years, the market of ink jet printer is expanding rapidly because of its advantages, e.g., high quality color image, low machine cost, small size and low printing noise. One of the important components of ink jet printer is a printhead which ejects ink drops. There are some kinds of ink jet printer according to the actuator which generates pressure and ejects an ink drop, e.g., the piezoelectric type which uses the displacement of a piezoelectric material [1], the electrostastically driven type which uses the displacement of a Si pressure plate caused by the electrostatic force [2] and thermal type which uses a bubble caused by the heating of an ink [3], [4]. The performance of ink jet printhead is influenced by the kind of actuator and its fabrication process. For example, ①the density of nozzle array depends on the size of actuator necessary to eject an ink drop in desired volume and velocity, ②the jetting characteristics (energy efficiency, ink supply response, etc.) of drop ejector is influenced by the shape of the nozzle (design flexibility), ③the flexibility of an ink selection is poor in TIJ method, which uses high temperature heating of heater element, because an ink kogation phenomenon occurs on the heater [5], ④the change of an ink drop volume due to the rise in head temperature is large in TIJ method and in which the chip temperature is easy to rise in printing operation [6]. Every ink jet method has at least one disadvantage, but each problems are solved and thus it is commercially available. In that situation, TIJ method has some advantages, such as ①it is suitable for high speed printing because it is easy to array the heater (actuator) and nozzle in high density, ②the cost per jet is low due to the decrease of the number of components because the logic circuit is easy to integrate in the head chip. Furthermore, to perform high speed printing, the number of nozzle may be increased by increasing the printhead length. On the other hand, in the view point of fabrication process, the chip warps at elevated temperature during the fabrication process steps or printing operation when the materials with different thermal expansion coefficient are used as a the substrate. If the chip is long, the bonded chips delaminate due to the large warp. So it is desirable to use the same material for long chip concept.

In this study, to achieve high speed and high quality printing, high resolution, small ink drop, and long array TIJ printhead is developed by using Si LSI process and Si micromachining technology.

2. Advanced TIJ Printhead

The structure of advanced TIJ printhead is shown in Fig. 1. The chip is fabricated by dicing the bonded

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論　文

インクジェットプリントヘッドから吐出された微小インク滴の挙動解析

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Analysis on Behavior of Small Ink Drops Ejected from Ink Jet Printhead

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A trajectory of ink drop ejected from printhead is affected by airflow generated by media moving in parallel with printhead, and dots are formed at undesirable position on a paper. Ink drop becomes smaller for high image quality, or relative moving velocity of paper and printhead becomes higher for high speed printing, this problem will be serious.

In this paper, the trajectory of flying ink drops was analyzed by computational fluid dynamics under the model where paper moves, and the change of orbit was accounted by investigating airflow conditions. In the simple case where single drop was ejected from a nozzle, dot position error dependencies on drop initial velocity, drop volume or paper moving velocity were examined. Relative displacement among dots formed by various volumes of drops was also studied. In the case where ink drops were ejected from multi-nozzles continuously, the effect of print pattern to dot displacement was examined. It also became clear that the effect of print pattern depends on nozzle position. The explanation of this dependency on print pattern or nozzle position was attempted by analyzing the airflow change caused by colliding against continuous ink drop flux.

Keywords: ink jet, line printhead, small ink drop, airflow, ink drop trajectory, dot displacement

インクジェットプリントヘッドから吐出された微小インク滴の飛翔軌道は，用紙の移動によって生じる気流の影響を受け，用紙上で着弾位置ずれを生じさせる．高画質化のためにインク滴を微小化し，高速化のためにプリントヘッドと用紙の相対速度を早くするとこの問題はより大きくなる．

本報では，計算機シミュレーションにより用紙が移動している系でのインク滴飛翔挙動（着弾位置ずれ）を計算するとともに，生じている気流の解析からこの挙動を説明した．特に単独ノズルからインク滴が吐出される単純な場合においては，インク滴の初速，滴量，用紙移動速度が位置ずれ量に及ぼす影響や，異なる大きさのインク滴が形成するドット間の相対的な位置ずれを検討した．またマルチノズルから連続的にインク滴が吐出される場合において，プリントパターンが軌道ずれに及ぼす影響を検討し，この影響がノズル位置によっても異なることを明らかにした．さらに連続的に吐出されるインク滴群が形成する流束と気流との衝突などによって生じる気流変化を解析することにより，軌道ずれのプリントパターンやノズル位置依存を考察した．

キーワード：インクジェット，ラインヘッド，微小インク滴，気流，インク滴飛翔軌道，ドット位置ずれ

1. 序　論

インクジェットにおける高画質化のアプローチの１つとして，吐出インク滴量の微小化が進んでいる[1,2]．またインクジェットの生産技術への展開（デジタルファブリケーション）においても，より微細なパターン描画の要求に応えるため，一層の液滴の微小化が検討されている[3,4]．オンデマンド型のインクジェットでは，ある初速でプリントヘッドから吐出されたインク滴は，静電場により加速される静電吸引方式などを除き，空気による慣性抵抗，および粘性抵抗による速度低下が起き，その影響はインク滴が小さくなるほど大きな問題となる．また

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