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Two-dimension full array high-speed ink-jet print head

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An ink-jet print head in a structure, similar to a liquid crystal display, is suggested. It is based on a segment, containing a microink reservoir, feeding one or a few nozzles. The segment is autonomous and unlimitedly duplicable to form a large ink-jet print head. The microreservoirs are open to the atmospheric pressure, and pressure regulation in the nozzle is accomplished by capillary action. The microreservoirs are replenished by slow wiper smearing action. Experiments with a 57600 nozzle matrix print head showed good results for the design. Printing speed of ~1000 pagesmin, and even more, is achievable. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2337107]

An ink-jet printer can be compared to liquid crystal display (LCD), as both devices eject contrasting colored elements to build a pixel accumulated picture. While a printer ejects pixels of ink, a LCD ejects light. An unavoidable question rises from this comparison: Why is the printer slower than the LCD? A closer look into the technology history even sharpens the question. The early ink-jet developments were inspired by the cathode ray tube (CRT) concept and were actually an adaptation of the CRT display concept to the printer. In 1951, Elmqvist[1] of Siemens patented the first practical Rayleigh[2] break-up ink-jet device. Charged ink drops were electrically deflected to form a picture, similar to the electrons in the CRT. In 1965, Dr. Sweet of Stanford University used electrically deflected charged ink to form fast oscillograms.[3] Already in this pioneering letter, the author states: "Extensions of the technique should be applicable for high speed printing…." Through the years, display and printing technologies have continued to be developed in similar directions and, instead of one ejector, multiple ejectors were developed.[4] In the display technology, a LCD was obtained and in the printing technology, a multiple nozzle drop-on-demand (DOD) method was developed. Still, the image construction time in DOD is incomparably slower than that of the LCD. Is this a necessity? What are the obstacles to creating a DOD ink-jet printer, which can operate in a manner closer to the LCD in terms of size and speed? This letter tries to answer this question. The size limiting factors of a DOD print head are addressed and a modification enabling unlimited enlargement is suggested. A model is built to examine the concept and results are given.

Commercial progress in the DOD nozzle-per head number[5] is shown in Fig. 1. This progress was accompanied by higher printing speed and quality. Still the overall nozzles' number in a single print head is limited to ~1000 in commercial products. The reason seems to be related to inherent physical limitations of the technology. The first limitation is related to the ink supply process. In order to eject the ink drops, channels supply ink to the nozzles from a main reservoir. The pressure of the ink inside the nozzle has to be well regulated in order to achieve a constant drop volume. The ink pressure in the print heads used today is slightly lower than the atmospheric pressure. These pressure conditions are crucial for drop ejection. The negative pressure is obtained by regulating it inside the main reservoir, using various methods, such as pressure pumps, placing the ink level below the print head, or by capillary foam.[6] Traditionally, a manifold is used to connect the ink reservoir to the nozzles. As the nozzles' number increases, the manifold becomes complicated, stable conditions become more difficult to maintain, and shock waves in the liquid tend to create undesired cross-talk problems between the nozzles. Efforts to overcome these limiting physical problems are described in Ref. 7.

A second physical limitation is related to the drop ejection rate, and, more specifically, to the time constants of the ejection: drop formation time, meniscus reformation, and postejection relaxation time. A drop ejection rate of ~20 kHz seems to be a practical limit.[8] These parameters limit the time between two sequent drops and therefore introduce a limitation to the whole print head. Moreover, in order to improve control and stabilize the drop formation, longer periods are required and the printing speed is further reduced, when a high quality printing mode is selected. Scientific works present various arrays in order to increase speed and resolution,[9,10] but it seems that the current theology has come close to its limits regarding the above points of view, and improvements in the ink-jet printing speeds, based on the existing concepts, can be expected only in small steps.

This letter suggests a nozzle structure, which is not limited by size and can be enlarged to sheet size. Therefore the

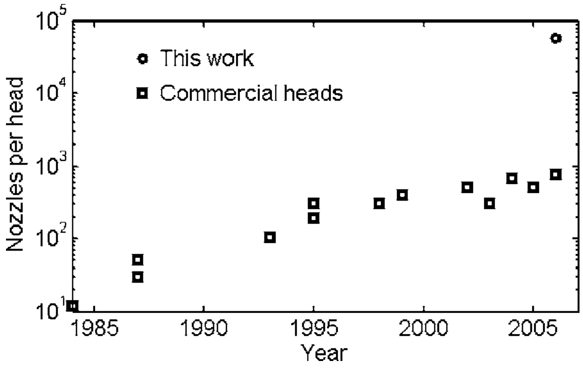

FIG. 1. Development of nozzles per head number of commercial ink-jet print heads through the years, and the number of nozzles in the built 2D full array print head.

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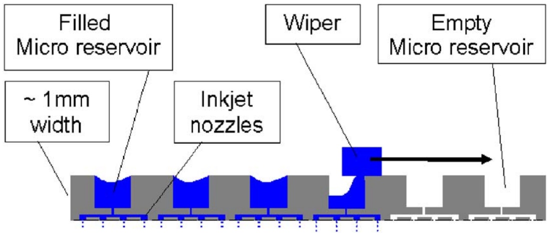

FIG. 2. (Color online) Schematic of the ink-jet print head. A local microreservoir is used for feeding ink to four nozzles by capillary action, and it is open to environmental pressure. A wiper fills ink into the reservoirs by capillary action.

ratio of pixel to nozzle can be 1:1 and a two-dimensional (2D) full array is accomplished. Moreover, using such a print head allows static printing in which there is no movement between the media and the print head during the printing. This is in contrast to the existing systems, where printing is done during the head movements for scanning. Such a static printing reduces significantly difficulties related to the movements such as satellite drops. Also, the high number of nozzles enables lowering of the ejection rate and, therefore, a high printing quality is obtained together with a high printing speed. Since the print head can be in the size of the media, all printing is done almost simultaneously. The printing time limiting factors are not related to the ink-jet process anymore, but to the mechanical paper feed and electronic data-transfer time.

The innovations presented in this letter are related to the ink supply method and the liquid pressure regulation. A schematic of the print head is presented in Fig. 2. The print head is comprised of local microreservoirs, each one of which is associated with one or a few nozzles (Fig. 2). Each reservoir has a liquid connection only to these few nozzles and has no connection with the other reservoirs. The reservoirs are open to the atmospheric pressure on the upper side. This is in contrast to the conventional closed systems, where a negative pressure is regulated in the main reservoir. The ink is supplied to the local reservoirs by a smearing method. A wiper (previously wetted with ink) is used to smear a layer of ink over the open upper side of the reservoirs. The reservoirs then fill up with ink, due to the capillary properties of the ink. Avoiding pressure regulation is accomplished by the high surface/volume ratio, physical structure of the ink. This high ratio, together with an open system, could result in dry ink clogging the nozzles. In order to avoid ink solvent evaporation and drying of the ink, the print head is open, on its upper side, to a chamber that is saturated with ink solvent vapors. Small opening apertures allow pressure equalization and minor air flow through filters. Each local reservoir feeds ink into its associated nozzle by capillary action, and so the nozzles are filled with ink. The constant pressure is achieved by the capillary force between the ink and the microreservoir walls.

Since the microreservoir with its associated nozzles is an independent structure, enlargement of the nozzles' number is no longer limited by the ink supply method. This structure can be duplicated to increase the nozzles' number without any mutual effect. As feeding of the ink is by capillary action and is independent of pressure, the ink feed method ceases to provide an intrinsic limitation on the size of the print head.

Each reservoir supplies only one or a few nozzles and, therefore, small ink consumption is required from each reservoir. Prior to every smearing action, the wiper is refreshed with ink. Following is an estimation of the wiper smearing rate. Assuming an ~50 pl drops and a reservoir dimension of $1\times1\times0.5$ mm^3, i.e., 0.5 μl, the ink volume in the reservoir is sufficient for ~10^4 drops. Since the benefit of multidrop is applicable to obtain half toning, it is likely to have several drops on the same pixel in order to enlarge the pixel. Assuming an average of 15 drops per pixel, we obtain a total of >600 pixels that can be printed between sequent smearing actions. Dividing the four nozzles supported by the same reservoir, we obtain that over 150 fully printed pages can be printed. Statistically, not all the pages will contain all the four pixels, and therefore this number can be considered as the lower barrier for the number of pages between sequent wiper smearing actions. Assuming a printing rate of ~1000 pagesmin which is two orders above the current technology, a 10 s duration is needed between sequent wiper smearing actions. This is a slow rate that can be easily achieved.

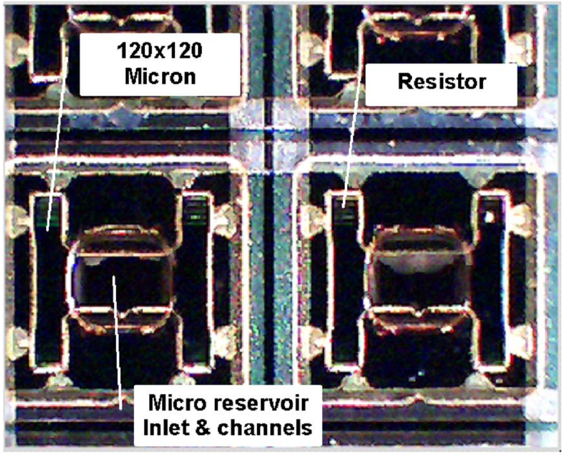

FIG. 3. (Color online) Two segments of print head matrix. Each segment is comprised of four nozzles and a central inlet hole for the ink supply. Horizontal and vertical conductors are connected to each resistor of every nozzle. The nozzles are 500 μm apart.

A 120×120 mm^2 print head of $240\times240=57\,600$ nozzles in the structure described above was made of four tiled printing areas, fabricated by microelectromechanical system technology from 4 in. silicon wafers. Two sequent segments of the structure are shown in Fig. 3. Each segment is autonomous and contains four nozzles and a microreservoir. The nozzles' cavity cross section is 120×120 μm^2 and they are distant 0.5 mm. Resistors are formed in the nozzles and each segment is surrounded by conductors, electrically feeding the resistors. The nozzle's volume is obtained from a 100 μm SU-8 layer and the microreservoir inlet hole is etched by deep reactive ion etching. A nickel foil with 50 μm diameter aperture holes, made by electroforming, is glued to close and finalize the nozzle structure.

During the experiments, the microreservoirs were filled with ink by wiper smearing action. The ink, derived by capillary, penetrated through the inlet holes to the nozzles and filled them properly. In order to verify the ink flow in the system, a dry tissue paper was attached to the nozzle plate, and as a result, the ink oozed out of the nozzles onto the paper, due to capillary wetting. This process was repeated many times. Also, after this process, the print head was totally emptied of ink and cleaned, and then refilled again. The process of delivering ink succeeded again and repeatedly. The nozzles delivered the ink to the tissue equally.

A standard nozzle structure (as described above) was used in regular convenient operating conditions (~40 V, ~6 μs at 1 kHz operating pulse), and ink drops were obtained. Since there is no innovation in the nozzle structure itself, its operation is assured. Moreover, since the discussed concept is not dependent on the nozzle structure itself, any old or modern nozzle structure can be adapted. Moreover, since the nozzles' number is significantly increased, a relatively slow operating frequency per single nozzle can be allowed without degradation in the total system's printing speed. Each nozzle can, therefore, operate in more convenient conditions with a long relaxation time between sequent drops and eject stable uniform drops. Some of the jetting characteristics were as follows: a drop size of 50 pl ± 20% was obtained during operation at a drop rate of 1–3 kHz; ~10% variations in drop size were observed among the nozzles. Other parameters were a drop velocity of ~6 ms, a viscosity of 10 cp, and a surface tension of 25 dyncm. Clearly these parameters are not the state of the art and modern commercial nozzles allow better performance.

As a conclusion, this design allows the ink supply limitations on the print head size to be alleviated. A design of a microreservoir together with one or a few nozzles is used as a basic segment, which can be repeated unlimitedly. As a result, the size of the print head can be enlarged with no degradation in the performance and stability caused by the ink supply system. The ink is supplied by a slow wiper smearing action. A sheet size print head is achievable with a 1:1 pixel-to-nozzle ratio. This is a 2D full array print head. The printing speed is increased by two orders or more. The printing quality is also affected by several factors. The printing is done statically and all the difficulties related to the print head's movement are alleviated. Multidrop is applicable due to the static printing and therefore half toning can be used. The very large number of nozzles allows a low drop rate for each nozzle, which also improves the stability and the quality of the drops. On the other hand, a two-dimensional array with very large number of nozzles introduces fabrication questions such as nozzle uniformity and inspection, especially in view of the inherent instability of the ejecting process. These issues may reflect on the engineering and production processes and on the cost of a commercial product. Relating again to the LCD, integrating the suggested print head design with the known art of nozzle design and large matrix addressing (as in the LCD), results in a 2D full array ink-jet printer that operates in a manner close to the LCD, in terms of size and speed.

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