Thermal Bubble Jet Printhead with Integrated Nozzle Plate

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Abstract

This paper reports on a new 1/3 inch thermal bubble jet printhead with integrated nozzle plate. This new kind of printhead consists of a standard printhead substrate and a three-dimensional structured polyimide nozzle plate containing the fluidic channels and the nozzle. Furthermore the use of an adequate design of the fluidic supply is of outstanding importance to achieve high print frequencies.[1] The integrated nozzle plate with two precise aligned structural layers is made by an advanced laser ablation process which uses both a stepping and a full-scale scanning mode. The nozzle plate is assembled with the substrate using an adhesive layer of only 3 μm thickness. The required adhesive layer thickness can be achieved by an adhesive transfer technology. In this case the alignment can be done with an accuracy of 3 μm over 1/3 inch length. Thus it is not mandatory to have a three layer system like in other commercial printheads. A further improvement concerning printing speed will be the anticipated size of one inch of the final printhead prototype.

In order to assess the tolerances in assembling and aligning the nozzle plate simulations have been performed to predict the effect of misalignments or additional adhesive layers on the characteristic inkjet parameters droplet quality, volume, velocity and print frequency. Therefore a fully three-dimensional model was set up using the Volume of Fluid (VOF) method. The differences in ejected droplet volume and droplet velocity between simulation and experiment are below 5%.

Introduction

High quality colour image, low machine cost and low printing noise are basically the main advantages of ink jet printers. This has led to a rapid expansion of this technology in the recent years. The two competing actuation principles of these, so-called drop-on-demand printers are the piezoelectric driven printhead as reported in Ref. [2] and the thermally actuated bubble jet printhead developed in the 1980's.[3] Currently the bubble jet printer outstands with low manufacturing costs at comparable print quality. The aim of manufacturers and many research establishments is the further optimization concerning maximum print frequency, active area of the printhead, resolution and quality of ejected droplets.[4-8] This requires a further miniaturization and optimization of the printhead geometry including fluid channels, heaters and nozzles to achieve an ideal printhead performance. Furthermore the number of nozzles and the printhead size should be increased to gain printing speed. An important tool for the optimization is the simulation of the complete device which is very cost- and time-effective compared to experimental hardware optimization. With computational fluid dynamics (CFD) simulations a variety of relevant parameters like geometrical dimensions and ink properties can be investigated.

Integrated Nozzle Plate

Aim of the reported work is to develop an integrated nozzle plate avoiding a three layer design where the first layer includes the electronics and the heaters, the second layer contains the fluidic parts like channels or nozzle chambers and finally the nozzle plate with generally laser drilled nozzles.[9] Advantage of an integrated nozzle plate is to have only two layers, an electrical and a fluidic layer whereas the integrated nozzle plate made of polyimide forms the entire fluidic part. Further advantages are the reduction of processing steps and having only one alignment procedure. Due to this, smaller fluidic structures can be realized leading to a better control of the printhead geometry and therefore optimization opportunities for the ejection process.

To meet the demands of high print speed the approach is to have a much wider printhead in order to print a larger area in the same time. A one inch integrated nozzle plate promises a realistic and cost effective solution. This is very challenging because of the high requirements concerning the alignment of nozzle plate and substrate, the fabrication technology and assembly of the printhead. The recent R&D

results reported here provided suitable fabrication technologies for this purpose.

Laser Machining

An excimer laser with a wavelength of 248 nm was used by STEAG microParts[10] to structure different variations of integrated nozzle plates: A 1/3 inch nozzle plate with different channel and nozzle dimensions, respectively.

The 1/3 inch nozzle plate can be processed by using a commercial excimer laser system. But the structure area of a one inch nozzle plate exceeds the exposure area of a usual optical system for excimer laser ablation. The optical system (especially the projection lens) can not be made much larger without extremely high cost to meet the requirement in the one inch case because of the necessary high precision and the high energy throughput.

It is obvious that the whole structured area of a one inch nozzle plate must be firstly divided into several parts and then the laser has to be stepped sequentially. This can easily be realized for the nozzle layer. The channel layer however, is a whole area without any break. A stepping process would produce overlaps between the sub-areas. To avoid this, a full-scale scanning process was applied for lasering the channel layer. With this process the nozzle plate was structured "on the fly".

The 50 µm and 75 µm thick polyimide foils were structured successfully in two precisely aligned structural layers with the full-scale scanning laser process in combination with the sequential nozzle stepping. The two necessary masks contain the nozzle chamber and the ink channels and the nozzle, respectively. The misalignment of the both laser processes is less than 1 µm. A SEM picture of one nozzle chamber of the nozzle plate is depicted in figure 1 a) and the corresponding nozzle outlet is displayed in figure 1 b). An excellent sharpness of the edges and planar surfaces can be observed. The laser machining of a one inch nozzle plate is still in progress at the moment and will result in printheads with integrated nozzle plate of one inch size in the near future.

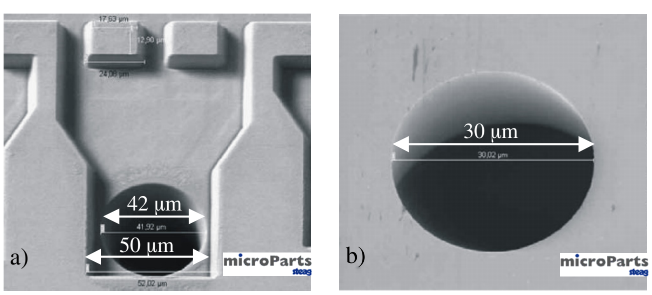

Figure 1. Full-scale lasered nozzle plate consisting of two precise aligned structural layers. The nozzle chamber, ink channel and the nozzle. View from the inlet a) and outlet b), respectively.

To fulfill the specifications of different nozzle and chamber designs the draft angle of the lasered structures can be varied between 7° and 28° by varying the energy density of the laser pulse in a certain range and in addition by using of other techniques such as a wobble plate in the laser optics. The draft angle also depends on the material of the nozzle plate and the ablation depth. In figure 2 a vertical cut through a nozzle and a chamber filled with a filler with a typical draft angle of about 8° in the nozzle layer is displayed. In addition to the draft angle also the two structural layers with different heights can be seen clearly.

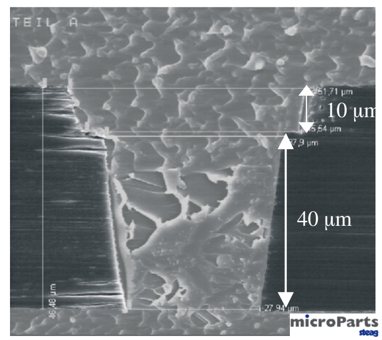

Figure 2. Vertical cut through the two structural layers with a nozzle chamber and nozzle filled with a filler.

Surface Treatment

After the laser machining of the nozzle plates various treatments of the surfaces are required. On the one hand a cleaning of the laser entry side is necessary to remove the hangover of the laser process, not only for the performance but also for the liquid-tight assembly of the nozzle plate with the substrate. Therefore different kinds of cleaning processes such as cleaning with organic/inorganic solvent, ultrasonic cleaning and plasma cleaning using oxygen (O_2), oxygen-argon (O_2-Ar) or oxygen-tetrafluoromethane (O_2-CF_4) and combinations of those processes were tested to prove the best purification. As well known, for a plasma cleaning process the parameter-set (pressure, temperature, gas flow rate, process duration field density and frequency) plays an important role. Process optimization for the nozzle plate cleaning has been made successfully with a commercial system. The best result was obtained using the oxygen plasma in combination with a suitable pre-cleaning like it is depicted in figure 3 before a) and after the cleaning b), respectively.

On the other hand a surface treatment of the front side of the nozzle plate is necessary to provide an adequate hydrophobicity. Using a chemical treatment leads to an increase of the contact angel of up to 95° and shows a better long-term stability compared to conventional plasma treatments.

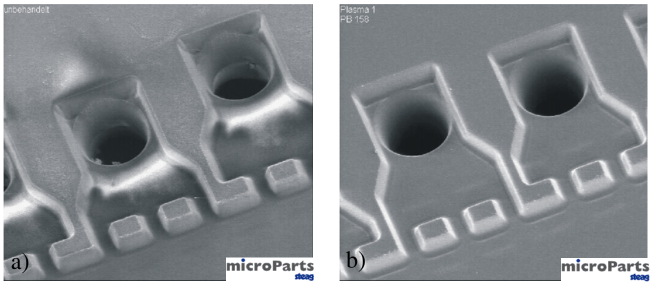

Figure 3. Laser structured nozzle plate before a) and after b) the cleaning in an oxygen plasma.

Assembling

The assembly of the structured nozzle plate done by HSG-IMIT[11] is a major challenge for completing the printhead. Especially in view of handling a one inch nozzle plate as foreseen for the final prototype, the integration process becomes critical. A further challenging requirement is the minimum height of the adhesive to guaranty the maximum printhead performance.

Especially when depositing adhesive layers with a thickness of less than 10 micrometers, one has to face two major challenges. The one considers the depositing process itself, the other the characteristics of the resulting thin layer of adhesive, that can significantly differ from the characteristics of layers of adhesive bulk material. Reasons for this behavior can be found in the domination of surface effects towards structural properties of the bulk material, inhibition of oxygen from the surrounding atmosphere as well as possible evaporation of solvents or hardeners.

Different approaches were analyzed to coat the substrate provided by Olivetti I-Jet[12] with a homogenous thin adhesive layer. Applying different well known procedures of coating like spraying, spinning, capillary transport and transfer techniques, different types of epoxy based adhesives were studied. Epoxy was chosen because of the suitable media properties and good adhesion abilities. Main challenges could be identified to be the prevention of bubble embedding, desiderative bond strength or plugging of the fluid channels.

Finally, best performance was achieved using a procedure derived from the one illustrated in figure 4. Cavities measuring few micrometers in depth were fabricated by reactive ion etching (RIE) in silicon and were subsequently used to provide the adhesive in a predefined layer thickness. Using an especially adapted handling unit, the structured nozzle plate itself served as a stamp to pick up adhesive from the silicon cavities. The coated nozzle plate was then aligned onto the printhead substrate applying a FinePlacer of FineTech GmbH[13] to seal the individual channel structures against each other with a very good reproducibility without clogging of the fine structures (cf. figure 5). The adhesive Epotek 353ND by Polytec[14] showed adequate performance to create a layer thickness of approximately 3 µm. The achieved alignment accuracy was measured to be 3 µm. After an adequate curing process, satisfactory bond forces were obtained.

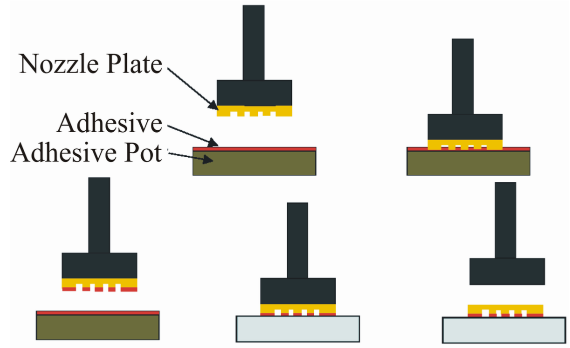

Figure 4. Schematic illustration of the adhesive transfer process.

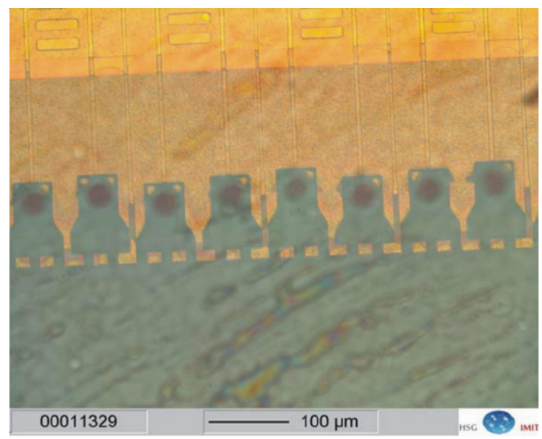

Figure 5. Assembled nozzle plate on printhead substrate. The dark areas are ink filled cavities, whereas the light areas represent leak-proof joined areas.

To prove the successful assembling of the integrated nozzle plate different tests have been performed. First the capillary filling of the printhead was studied using an optical observation like it is displayed in figure 5. Afterwards the functionality of the printhead was analyzed by operating single nozzles at different frequencies and making stroboscopic pictures which are illustrated in figure 6. After operation and cleaning with acetone in an ultrasonic basin the printhead demonstrates a good and reproducible functionality which argues for the robustness of the assembling process.

In order to estimate the effect of the inevitable adjustment tolerances on the printhead performance simulations of the inkjet have been performed which are presented in the next section.

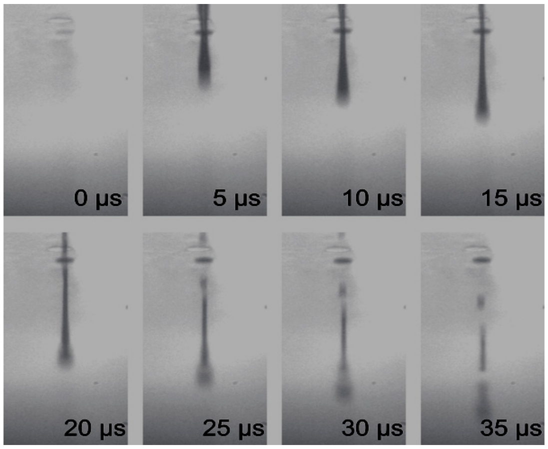

Figure 6. Ejection cycle of one of the first prototypes.

Simulation

To simulate an entire ejection process of a thermally actuated bubble jet printer it is state of the are to apply an appropriate pressure boundary condition to substitute the complicated bubble nucleation, expansion and collapse. Using this as input for the simulation package ACE+ of CFDRC[15] a CFD simulation has been set up and the droplet ejection process has been studied by the IMTEK.[16,17] Using a complete three-dimensional model, instead of a simplified two-dimensional one, provides the opportunity to examine the influences occurring in the real device.

Pressure Boundary Condition

A given current pulse through a micro-heater of a conventional bubble jet printer can be converted into an equivalent exponential decreasing pressure function following the approach of Asai et al.[18,19] The initial pressure of this pressure pulse can be determined using the Clausius-Clapeyron equation.

$$P_v[T_v] = P_{atm}\exp\left[\frac{w\cdot Q_{vap}}{\mathrm{R}}\left(\frac{1}{T_b}-\frac{1}{T_v}\right)\right] \qquad (1)$$

Where P_v and T_v are the approximately uniform pressure and temperature in the vapour bubble, P_{atm} is the atmospheric pressure (= 100 kPa), R is the gas constant (= 8.3148 J mol^{-1} K^{-1}), T_b is the boiling point of the ink, and w and Q_{vap} are molecular weight and heat of vaporization, respectively. Adding a time-dependent heating pulse leads to the following exponentially decreasing pressure function $P_v[t]$ which is displayed in figure 7.

$$P_v[t] = P_t(T_t)\exp\left[-\left(\frac{t}{t_0}\right)^{0.5}\right] + P_s(T_{amb}) \qquad (2)$$

where $P_t(T_t)$ is the initial bubble pressure depending on the maximum heating temperature T_t. In this case the initial bubble pressure is 9 MPa. P_s is the bubble pressure in the later stage depending on the ambient temperature T_{amb}. The parameter t_0 is a time constant, which has been estimated to be 0.055 µs by calibrating a series of simulations with corresponding experimental results starting from the value of 0.17 µs reported in the literature.[18,20]

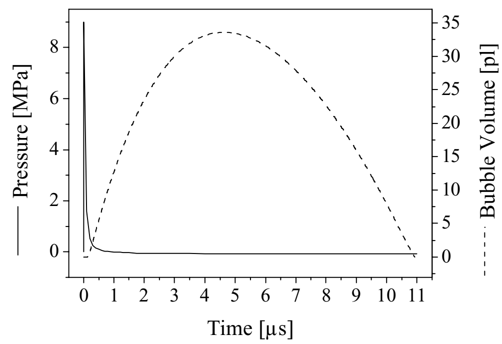

Figure 7. Pressure pulse used as pressure boundary condition calculated by applying the Clausius-Clapeyron equation and the resulting bubble volume.

Resulting Bubble Volume

The presented pressure pulse was used as inlet pressure boundary condition for a simulation model of a printhead. Thus the pumped air, used as incoming medium forms a bubble with a parabolic time-dependency of the bubble volume as also displayed in figure 7. The maximum bubble volume and the time characteristics depend essentially on the printhead geometry and ink properties.

Using the described approach the simulation results of simple 2D devices presented in literature[5,6,21] could be reproduced easily by using the VOF module including surface tension as implemented in ACE+. Afterwards the more complicate 3D model of a Olivetti I-Jet printhead, like it is displayed in figure 8 has been set up to simulate a complete dosage cycle including first priming, printing and refilling.

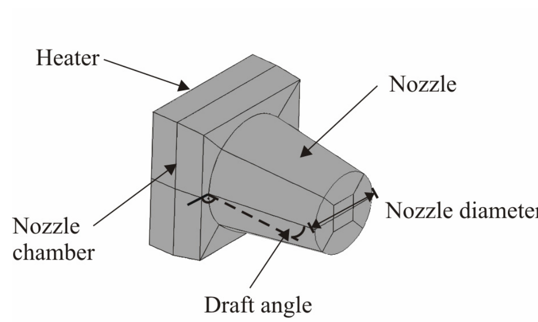

Figure 8. Simplified picture of the 3D model of one nozzle of the bubble jet printhead showing only the fluidic part (inlet channels not shown).

Simulations vs. Experiments

Comparing the simulations with experimental results like stroboscopic pictures as displayed in figure 9, good qualitative agreement has been obtained. The shape of the droplet and the tail looks very similar. There is also a good quantitative agreement between experimental findings and simulations. The gravimetrically measured droplet volume of 26.0 pl agrees well to the simulated volume of 25.6 pl.

Thus the used pressure boundary condition, presented for the first time by Asai for a 2D case, can also be applied successfully for the 3D case. The applicability of the simulation model is validated with tolerable deviations.

Simulation Results

After having validated the simulation model further simulations have been performed to optimize the printhead with fixed guidelines by varying parameters like geometry dimensions, heating pulse or ink properties.

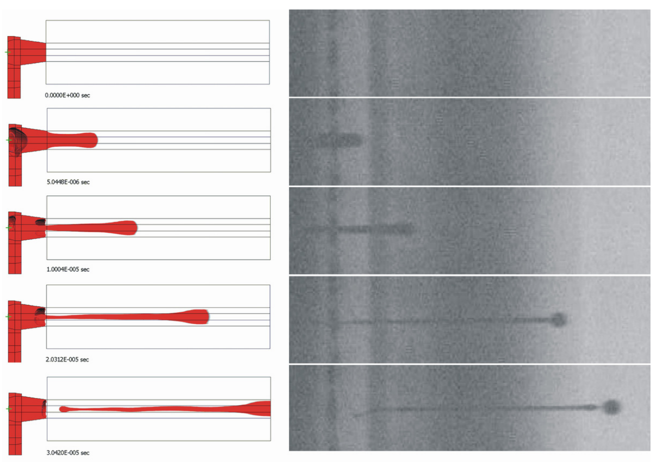

Figure 9. Comparison of the 3D simulations of the droplet ejection (only the fluidic part is shown) and the corresponding stroboscopic pictures from Olivetti I-Jet.

Laser Machining and Assembly and Packaging Tolerances

The knowledge of the allowable tolerances is very important for the laser machining and the assembly and packaging of the printhead. Especially the effect of lateral adjustment deviations or differences of chamber height are interesting for the current research project particularly for the intended assembling of the one inch printhead. The effect of a variation of the nozzle diameter or the draft angle which are both affected by the laser machining process on the droplet volume and velocity are displayed in figure 10 and figure 11, respectively.

The effect of other variations like an adjustment deviation or an additional height of an adhesive on the droplet volume and velocity is summarized in figure 12. As mentioned before these results are very useful for determination of allowable tolerances for the assembling and packaging.

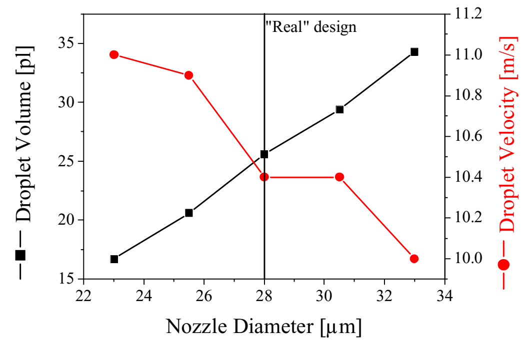

Figure 10. Simulated effect of varying the nozzle diameter on the droplet volume and velocity.

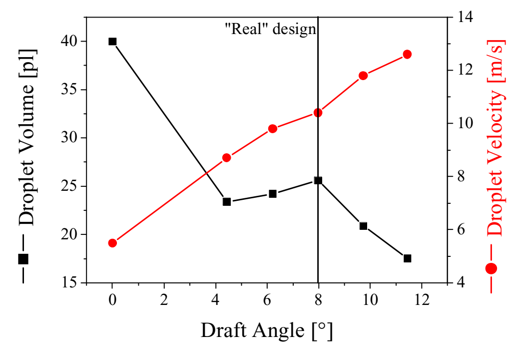

Figure 11. Simulated effect of varying the draft angle on the droplet volume and velocity.

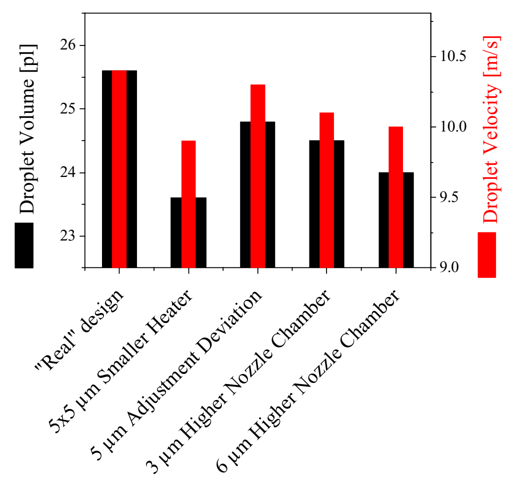

Figure 12. Comparison of simulated droplet volumes and velocities considering different geometrical tolerances.

Summarizing the figures above it can be stated that a small variation of the nozzle chamber height or a minimal deviation of the adjustment leads to a negligible change of the resulting droplet volume and velocity whereas a deviation of the nozzle diameter or its draft angle induces a more significant change of the ejected droplet volume and velocity.

Combining all this results with earlier simulation results regarding the effect of ink properties[17] the optimum interaction between print head geometry and ink parameters can be found.

Conclusion

The presented innovative laser machining of a polyimide integrated nozzle plate provides a beneficial manufacturing method for bubble jet printheads in order to meet the requirement of making a high speed and wide format inkjet printer. The integration of the channel layer and the nozzle layer in one material and one process step in contrast to standard manufacturing methods offers better accuracy and saving of one adjustment step. The anticipated fabrication of a one inch printhead will be a further improvement which is a necessary approach towards faster bubble jet printheads and therefore staying competitive compared to state-of-the-art laser printers

Furthermore an assembling method using an adhesive layer of only 3 µm thickness was presented. A 1/3 inch printhead was successfully assembled demonstrating a good impermeability, capillary filling and droplet ejection.

The presented three-dimensional simulation model of the thermal ink jet printhead provides a valuable approach to optimize thermal bubble jet printheads regarding droplet volume, droplet velocity, droplet quality and print frequency also including the consideration of 3D sensitive problems. The correctness of the used pressure boundary condition and the simulation model in the three-dimensional case was verified by comparing simulation, gravimetrical and stroboscopic results. For the optimization or the designing of a new printhead a variety of specific models may be investigated by adjusting all relevant parameters like geometry effects and ink properties.

Acknowledgement

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Biography

Timo Lindemann studied Microsystem Technology at the Institute of Microsystem Technology (IMTEK), University of Freiburg and received his diploma in 2002. In his diploma thesis he performed research on the temperature distribution in micro-hotplates. Since August 2002 he is PhD student at the IMTEK – laboratory for MEMS Applications (Prof. Zengerle). There he is working within the 'IDEAL' project developing a new kind of a one inch thermal bubble jet printhead. Therein he mainly deals with the three-dimensional CFD-simulations of free jet dosage systems.