Realistic Performance Tests of a Diamond Printhead by High Speed Visualization

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Abstract

New developments in the design of drop-on-demand printheads make it necessary to apply suitable testing techniques. The evaluation of the lifetime and the performance of prototypes is especially important for the case that advanced materials are incorporated.

Here, our new thermal printhead based on diamond technology is evaluated. The outstanding thermal, mechanical and chemical properties of diamond allow the fabrication of more efficient devices, which offer a reduced complexity at the same time. The prospect of higher speed, cost reduction and longer lifetime are the reasons for an ongoing development based on this technology.

This paper presents the results of lifetime tests of diamond thermal printheads together with the evaluation of their workability visualized by real time cinematography. Such a visualization by a high speed camera system coupled to an optical microscope reveals the system's performance since nonreproducible processes can be studied as well. This is important when one wants to search for reasons of device failures.

Introduction

Thermal inkjet printheads play a prominent role in drop-on-demand printing technology. Further improvements for a device that well introduced in the market may come with the application of new materials allowing higher efficiency, longer lifetime and an increased cost effectiveness. Replacing the complex stack of materials forming a conventional micro heater by a single diamond film with no additional passivation layers, one takes profit of its outstanding physical and chemical properties.[1] Diamond consists of light atoms held together by strong forces. This results in an unsurpassed thermal conductivity, hardness and fracture strength. Though this values are reduced for thin films deposited by chemical vapor deposition (CVD), it still shows tempting material qualities. Furthermore diamond is highly chemically inert and its electrical properties can be adjusted from isolating to metal-like depending on the doping concentration. This holds the prospect to extend the application range of this printhead to harsh environments and aggressive substances.

The diamond printheads investigated here are improved versions based on our diamond micro heaters first presented by Hofer et al. in [2]. We have incorporated several new developments. First, a modification of the diamond films themselves, since we apply now diamond polycrystalline diamond. These can be grown on a more extended variety of substrates in comparison to the highly oriented diamond films used before. From this material the heating elements are fabricated. Together with a backside fluid connection, the polyimid channel system and a chemically inert nozzle plate, we present a fully functioning printhead.

When developing a new device, suitable testing methods are a major concern. They are prerequisites to gain understanding of the system, which in turn is essential for the reengineering process. Moreover, using new materials, quality assurance is very important, especially since we have to gain market acceptance. Seeking for a visualization of the system's dynamics, it is necessary to apply high speed measurement systems to overcome the difficulties imposed by the miniaturization and the fast processes of interest.

All of the workability tests presented here relay on the use of a specially developed real-time visualization setup. Visual information is a powerful tool to analyze systems failures and the realistic performance of different prototypes. This might for a future work include effects of different driving pulses, nozzle shapes or air drag and acceleration forces on the droplet ejection and the resulting flight trajectories.

Printhead Technology

The diamond film for the heater elements was grown by MWPECVD (Microwave Plasma Enhanced Chemical Vapor Deposition) on a silicon substrate, which is covered by an amorphous thermal insulation layer. This layer is inserted in order to prevent temperature losses from the heater element to the Si-substrate acting as a heat sink. The diamond deposition includes nucleation by seeding and results in a 5 μm thick polycrystalline diamond film after

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outgrowth.[3] To obtain a low specific resistance, and thus a low electrical resistance of the heater elements, doping has been performed in-situ using boron. This technology results in a doping concentration higher than 10^{20} cm^{-3}, a specific resistance smaller than 6 mΩcm with a negligible temperature dependence and thus metal-like behavior of the heater resistor. The diamond heater elements have been patterned by standard lithography and dry etching.[1] A selective etch stop at the thermal insulation layer can be obtained, resulting in well defined diamond heater areas and consequently in high lateral thermal insulation properties. For the electrical contacts, a silicon based multilayer metallization scheme was used. This metallization shows excellent high temperature stability up to approx. 700°C.[4]

For the liquid supply the technology for backside feeding was developed. The silicon substrate and the thermal insulation layer have therefore been removed locally by wet etching. For liquid distribution and supply to the heaters on the device surface, a capillary wall system, consisting of photosensitive polyimide was fabricated. The liquid supply system was capped by a chemically inert nozzle plate, which has been bonded onto the polyimide capillary wall system.

High Speed Visualization

The standard visualization technique used for characterization of ink jets is based on the stroboscopic principle.[5] The so called pseudocinematographic visualization can be applied to reproducible phenomena. During the measurement the investigated process is repeated several times and is visualized at different points in time, respectively. In opposition to this method the realcinematographic visualization technique, which allows registration of several frames of one single process offers the possibility to investigate nonreproducible phenomena. Especially nonreproducible phenomena are very critical regarding lifetime and performance of ink jet printheads. Therefore, the tests presented in this paper have been performed with real high speed cinematography using a microscopic ultra high speed motion analyzer developed by us.[6] As main part of the newly developed realcinematographic test rig shown in figure 1 the commercial ultra high speed camera *Imacon 468* from *DRS Hadland Ltd.*[7] has been optically coupled with a standard microscope Zeiss Axioplan via a fiber optic plate.[6]

Inside the camera, relay optics channel the light onto a special beam splitter consisting of eight lenses and an eight-sided mirror pyramid from where it passes to at eight intensified CCD units. The CCD sensors which are arranged in a circle around the beamsplitter are amplified by micro channel plate (MCP) units mounted in front of the CCD camera sensors. These intensified CCD (ICCD) units act as high speed shutters to determine the ultra short exposure time of 10ns of the camera. A special and self-designed pulsed light source fitted inside the lamp housing of the microscope ensures optimum illumination. The discharge of an artificial transmission line provides the current for the light pulse of 50Mcd generated in a Xenon flash lamp.

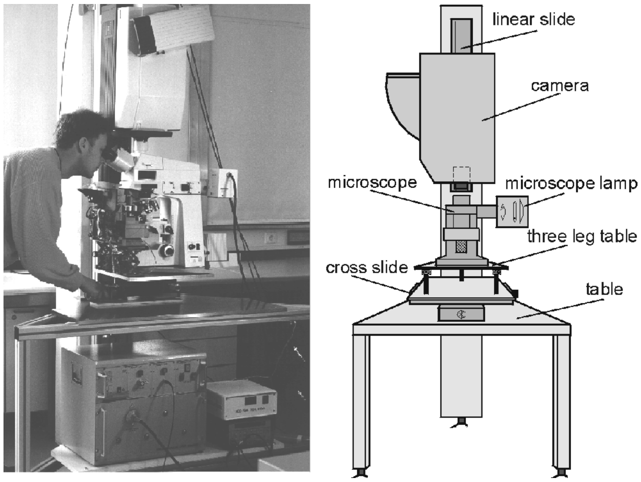

Figure 1. Ultra high speed motion analyzer.

Reliability Tests

Lifetime tests have shown that the diamond printheads function for more than 100 million cycles. The limiting factors in our long-term tests have not been the breakdown of the devices themselves but the appearance of ink residuals or the thermal exhaustion of the external bond wires.

In order to determine the operational limits of the diamond devices high power driving pulses well beyond the typical operational range were applied to open pool structures. High speed visualization is used in this case to observe a possible instant breakdown of the electrical contacts or the heater elements. As an advantage of recording this process in real time, one can locate the origin of the breakdowns and therefore determine weak points of the heater design.

Figure 2 presents driving pulses adjusted in length in order to reach the nucleation on a 60µm x 60µm heater. Up to the highest power densities provided by our specially designed power source of 30 GW/m^2 the heater elements rest undamaged as long as the maximum pulse duration is carefully chosen. In this high power regime the nucleation time is with 0.5µs extremely short, which can be seen in figure 3. As shown in figures 4 and 5, the destruction of the diamond heaters appears only if the heating pulses are deliberately extended beyond the nucleation limit. Exposed to air diamond films oxidize for temperatures higher than 600°C.[10] It is also visible that the heater elements' impedance shows a temperature dependence which could be used to sense their temperature.

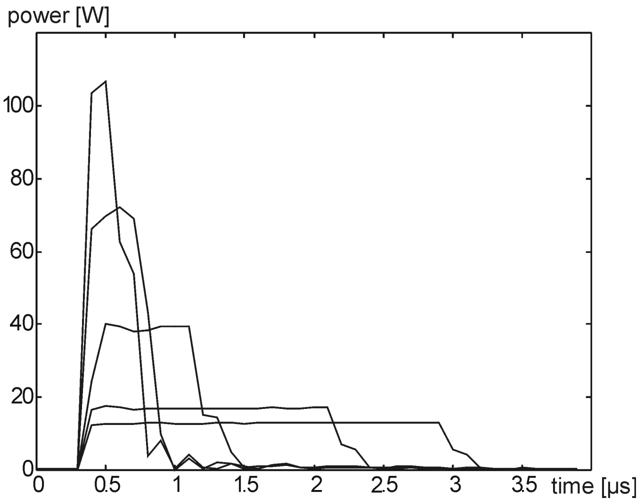

Figure 2. High power pluses for ordinary nucleation on 60µm x 60µm heaters without breakdown

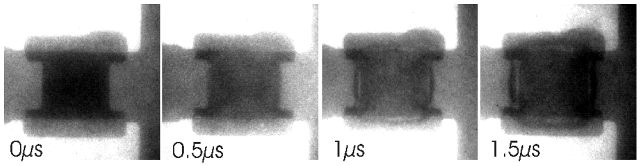

Figure 3. Nucleation for 30 GW/m^2 heating pulse

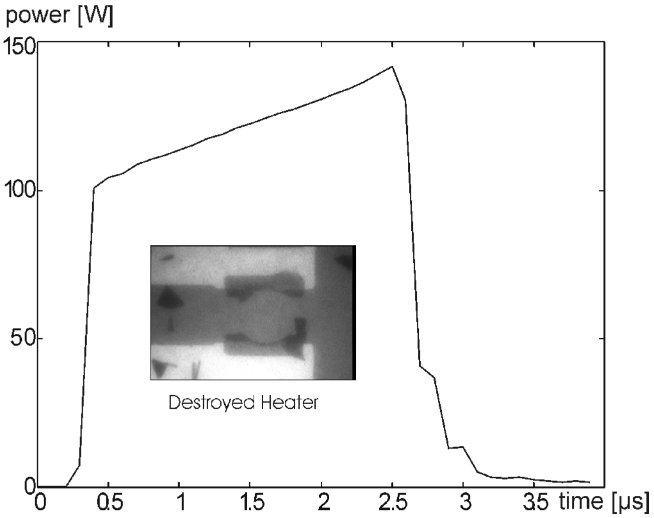

Figure 4. Destruction limit for the 60µmx60µm heaters

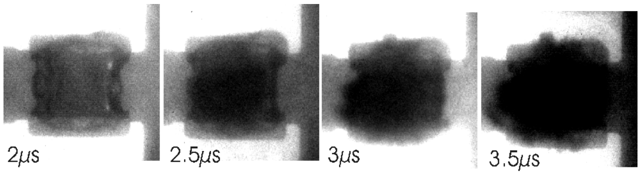

Figure 5. Exploding diamond heater

Thermal Simulations

We have used thermal simulations exhaustively in the reengineering process as described in detail by Hofer et al..[11] They contain a full three-dimensional model of the actuator on the substrate and the fluidic elements, i.e. chamber and nozzle geometry, with temperature-dependent thermodynamic properties of the materials and the ink. The calculations are performed on a standard PC with the commercial finite-volume code PHOENICS. One of the results shows that the diamond heater provides a larger effective heater surface in comparison to common micro heaters. It is possible to achieve this large area of superheating due to the large heat conductivity of diamond.

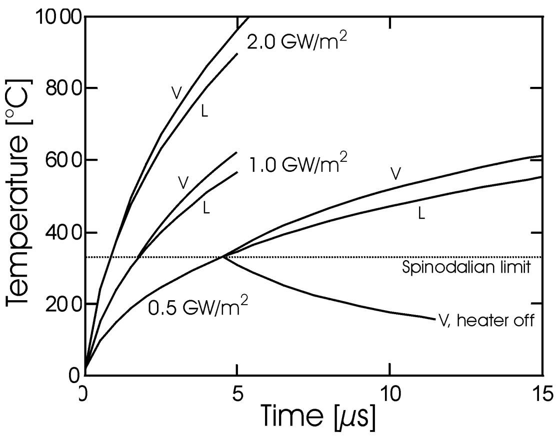

Figure 6. Temperature development of the heater.

In figure 6 for three heating power densities the simulated temperature developments as function of time are shown. The curves labeled with L corresponds to simulations with liquid ink for all times, the curves labeled with V correspond to simulations assuming a vapor layer after reaching the spinodalian limit of approximately 320°C above the micro heater and constant heating power, respectively. In addition, the temperature development for an economic heating pulse with a power density of 0.5 GW/m^2 and a heating time duration of 4.5 µs is given as well. It follows that the heating pulse should not be applied longer than reaching the nucleation temperature, i.e. reaching the spinodalian limit, because further increasing of temperature attacks the heating elements strongly.

Printing with the Diamond Ink Jet

The full workability of the ink jet based on diamond, as can be seen in figure 7, was already achieved with the first prototypes.[2] The progress in this work is the introduction of polycrystalline diamond as the heater structure. Compared to highly oriented diamond this presents an opportunity for an easier production of the devices but still keeps the same performance when it comes to lifetime and driving frequencies.

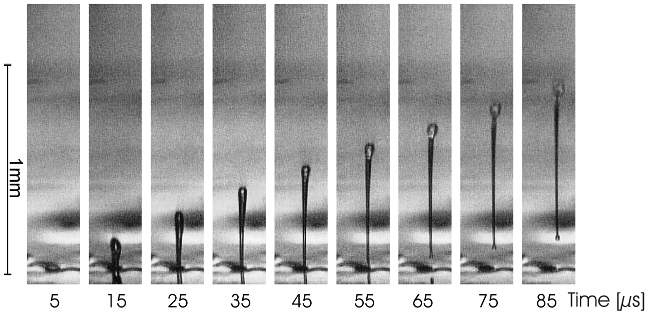

Figure 7. Droplet ejection from a diamond ink jet

Conclusion

Highly efficient, durable and cost effective thermal ink jet printheads can be fabricated using polycrystalline diamond for the heater elements. Here we tested their workability and reliability using a realcinematographic setup to visualize non-transient processes like the breakdown of the devices.

Acknowledgment

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Biography

Eberhard P. Hofer received his Diploma in Mathematics and his Doctorate in Control Engineering from University of Stuttgart, Germany. After several years with industry in Germany and the U.S. he held positions as Full Professor at the Universities of Essen and Hamburg-Harburg. Since 1989 he is Head of the Department of Measurement, Control and Microtechnology at the University of Ulm. He has been Visiting Professor at the IBM Research Laboratory, San Jose, at UC Berkeley, and at Waseda University, Tokyo. His research activities cover modeling, control, and optimization of nonlinear dynamical technical systems. Since 1982 in microtechnology he is involved in non-impact printing technologies, micro actuators for dosimetry, micro fluid dynamics and cinematography for visualization of highly dynamical processes in micromechanical structures.

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