

A New Diamond Micro Heater for Inkjet Printheads

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Abstract

Thermal inkjet printheads play a dominating role in drop-on-demand printhead technology. Improvements of efficiency and lifetime are an ongoing challenge for research and development in this field. Commonly used micro heaters are based on refractory metal alloys. Therefore, a complex stack of various materials is necessary to protect the heater against oxidation and mechanical strains which limit the performance of such micro heaters.

Here, a novel thermal inkjet heater based on diamond is presented. In contrast to conventional micro actuator systems for the diamond inkjet passivation layers are not necessary. This reduces the manufacturing costs and increases the thermal efficiency of the micro heater. In addition, the excellent mechanical properties of diamond guarantee protection against cavitation damages. The new thermal inkjet heater has been tested successfully and its advantages are demonstrated by experiments using high speed cinematography.

In conclusion, the first prototype of the new thermal inkjet heater based on diamond is superior to common systems in regard to heating efficiency and resistance against mechanical strains.

Introduction

Micro heaters based on diamond can be mass produced with lower costs. The prospect of improved performance offers a good alternative to the conventional and well established micro heaters used in common thermal inkjets [1]. Recent improvements in diamond nucleation enable large area deposition of diamond on silicon [2]. A cooperation between the Department of Measurement, Control and Microtechnology and the Department of Electron Devices and Circuits at the University of Ulm has turned the idea of a novel thermal actuator based on diamond into reality and a prototype of a diamond inkjet has been designed, developed, and manufactured. In contrast to conventional actuator systems for the new diamond inkjet no passivation layers are necessary. We have developed a complete thin film and micro structure including heaters, chambers and nozzles. This new device is refilled from the back through a hole in the substrate. The prototype printhead is designed for several micro actuators with different geometries to study the influence of the actuator dimensions on the dynamic behavior of single actuators.

In this paper, first, the relevant technology of thermal micro actuators based on chemical-vapor-deposition (CVD) diamond films will be described. Second, we present experimental investigations demonstrating the functionality and the dynamic behavior of our prototype. The results of the studies indicate that our approach based on diamond allows a significant reduction of lifetime limitations and increases efficiency in comparison to common systems.

New Inkjet Based on Diamond

The extreme thermal properties of diamond require a precise thermal design and a precise heat management of the new micro heater. Therefore, the development and manufacturing processes of thermal actuators based on diamond have included both the performance of thermal simulations and the realization of prototypes [3].

The starting point of the development process was a micro heater on a 15µm thick highly oriented diamond (HOD) film [2]. The HOD film was grown in a microwave plasma CVD-system. After outgrowth the insulating diamond film has a surface roughness of less than 200nm enabling micro lithography and patterning of high resolution. The key process steps are: (i) selective growth, (ii) solid boron source doping, and (iii) silicon based contact metallization. The fabrication is described in detail in the following: The activation energy of the boron acceptor is extremely dependent on doping concentration and compensation and varies in the range of approximately 380meV to 0meV. This is directly correlated to the activation in the conductivity. A low doping concentration results in a large temperature dependence of the conductivity and enables the fabrication of temperature sensors with high characteristic temperatures. On the other hand, high doping concentrations result in low activation energies. Doping above $10^{20}cm^{-3}$ enables a negligible activation energy. The implementation in the diamond heaters and the contact layers for electrical contacts made use of this fact. The micro heater were grown and doped above $10^{20}cm^{-3}$ to obtain a specific resistance of 10mΩcm independent of temperature. In this case the diamond film also serves as contact layer for the electrical contact metallization. For the heater a thickness of 1µm was chosen to obtain a heater sheet resistance of 100Ω/square resulting in a heater resistance of 108Ω. The diamond top side patterning terminates with a final mesa etching step in an argon/oxygen RF-plasma. Si-based contacts were deposited by ion beam sputtering and patterned by standard lithography.

The final diamond inkjet consists of an optimized micro heater based on diamond on a silicon substrate, an ink supply, cavities, and a nozzle plate fabricated in polyimide technique. The design of the fluidic elements are those of common inkjet side-shooters.

Dynamic Behavior of Single Shooting

For an ideal operation of a thermal micro actuator an explosive vaporization over the whole area of the heater is necessary. The nucleation behavior of our first version of a thermal insulated heating element is shown by high speed visualization in Fig. 1. The experiment has been performed using pseudocinematographic visualization based on the stroboscopic technique [4]. An exposure time of 250ns and an interframe time of 500ns has been used for this visualization. The starting point of the time scale is the beginning of the heating pulse.

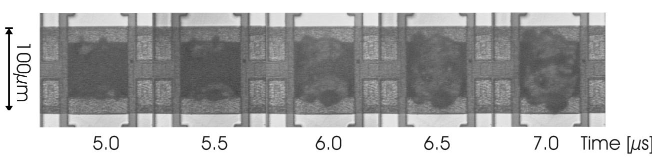

Figure 1. Nucleation on a Diamond Heater with Narrow Electrical Contact Pads

The visualization clearly demonstrates that the nucleation begins at the electrical contact pads. The reason for this undesirable effect is the high contact resistance of the semiconductor contact pads realized with highly doped p+-silicon and p+-diamond on the heating element. This arrangement leads to a similar behavior like metal semiconductor Schottky contacts.

The problem just outlined has been abolished with extended contact pads which lead to a decreasing contact resistance. The influence of the extended contact area on the nucleation behavior is demonstrated in the pseudo-cinematographic image sequence in Fig. 2. In this case the nucleation is extended over the whole heating area in an explosive manner.

A power of approximately 4.5W has been applied to generate the bubble and the visualization was performed with an interframe time of 300ns. The time scale of the image sequence in Fig. 2 starts at the beginning of the heating pulse.

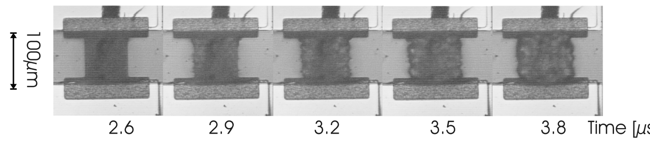

Figure 2. Nucleation on a Diamond Heater with Extended Electrical Contact Pads

The variation of the nucleation time in dependence of the heating power is demonstrated in Fig. 3. The results obtained by numerical simulations are in good agreement with the experimental data.

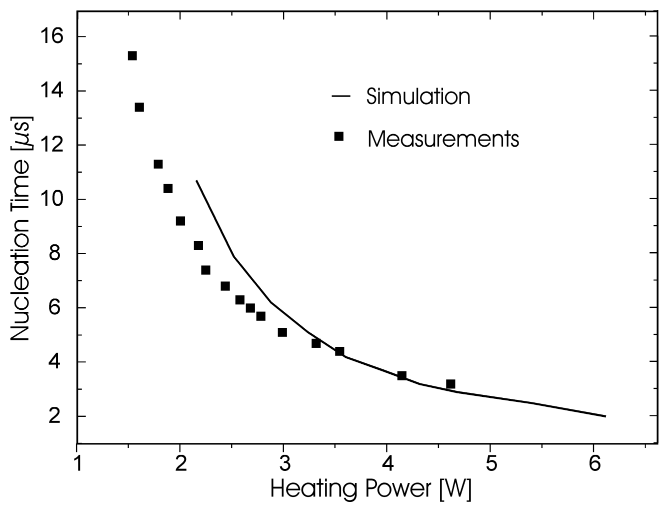

Figure 3. Variation of the Nucleation Time in Dependence of the Heating Power

The simulations are performed with the finite-volume-program PHOENICS [5]. The spinodalian temperature of 320°C serves as the nucleation criterion [6]. The simulation model contains the temperature dependence of the thermal properties of the various materials of the micro heater and the ink. Proof of an explosive vaporization over the whole area of the micro heater has been furnished for heating powers higher than 2W. As a result the functionality of our device can be guaranteed for heating powers as low as 2W.

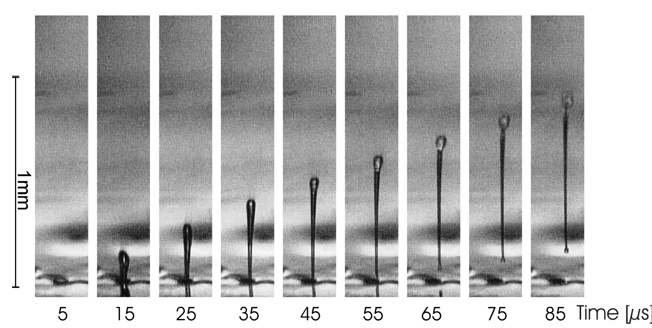

Figure 4. Droplet Ejection of the New Diamond Inkjet

The photo reproductions in Fig. 4 demonstrate that our new diamond micro heater is applicable as actuator in a thermal inkjet printhead. A polyimid channel and a nozzle structure with a geometry comparable to common systems have been chosen to realize an ink jet ejected with the diamond heater. Therefore, the low cost diamond actuator is an attractive alternative for common heating elements with a complex stack of heater and passivation layers.

Dynamic Behavior at High Driving Frequencies

Several experiments without a polyimide nozzle plate have been performed to evaluate the dynamic behavior of the new heater at high driving frequencies.

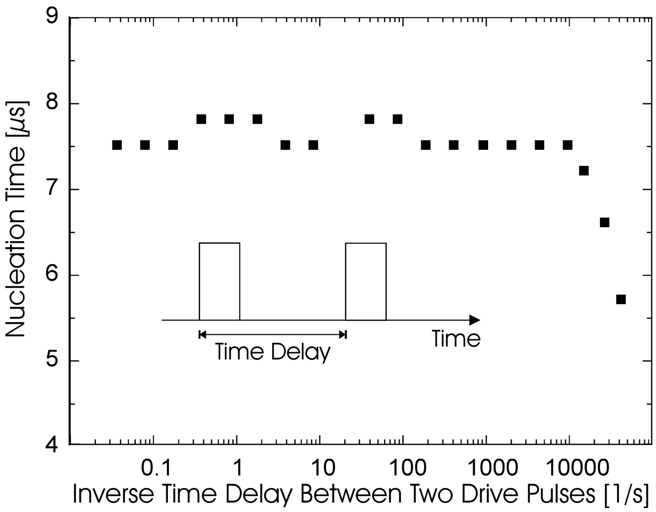

Figure 5. Nucleation Time for the Second Pulse in the Double Pulse Experiment

In a series of several drive pulses the heater temperature raises with each additional pulse. Therefore, the first experiment is performed with two pulses only. Observing the second one of the two pulses we determined the variation of the nucleation time with respect to different delay times between the two consecutive pulses. The result displayed in Fig. 5 shows that the nucleation time shifts in a significant manner only for time delays smaller than 100µs. In the case of a 17µs time delay a decrease in the time duration between the beginning of heating and the nucleation is observed down to 4.5µs. In addition, this is the limit for the explosive vaporization.

The simulation of the thermal behavior of the micro heater for a double pulse shown in Fig. 6 illustrates that the time delay of 20µs is not sufficient for a complete relaxation of the temperature after the first pulse. Therefore, the second nucleation begins 2µs earlier. This result agrees well with the experimental facts (Fig. 5).

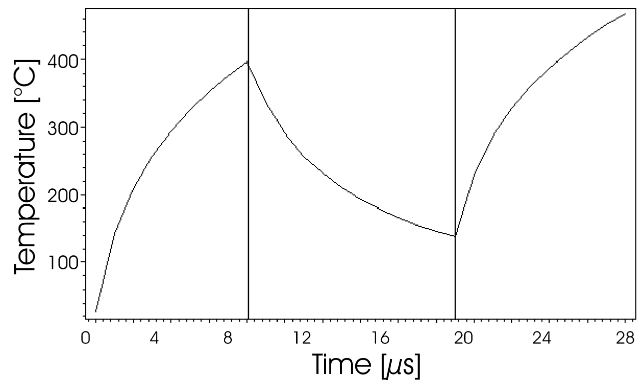

Figure 6. Simulated Effect of Heater Temperature for a Double Heating Pulse

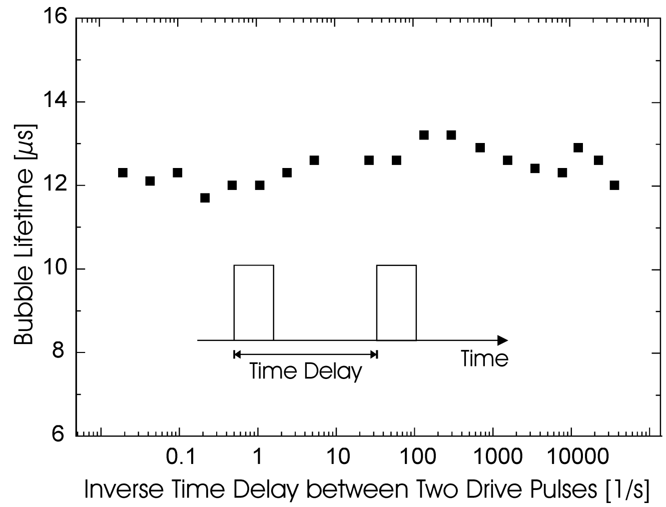

Figure 7. Lifetime of Ink Bubbles for the Second Pulse in the Double Pulse Experiment

Fig. 7 displays a fairly constant lifetime of the vapor bubbles independent of the time delay in the double pulse experiment. This behavior must be expected since the bubble dynamics is independent of the thermal heating once the nucleation has started [7].

In order to estimate the limit of the driving frequency the measurements plotted in Fig. 8 have been performed. In the train of consecutive pulses the nucleation of the last bubble has been observed pseudocinematographically. The graphics shows the minimum delay necessary for a given number of pulses in order to generate regular bubble shapes up to the last one.

As a result of the measurements displayed in Fig. 8 for bubble generation a repetition rate higher than 5kHz can be estimated under the assumption of a linear extrapolation of the plotted time delay.

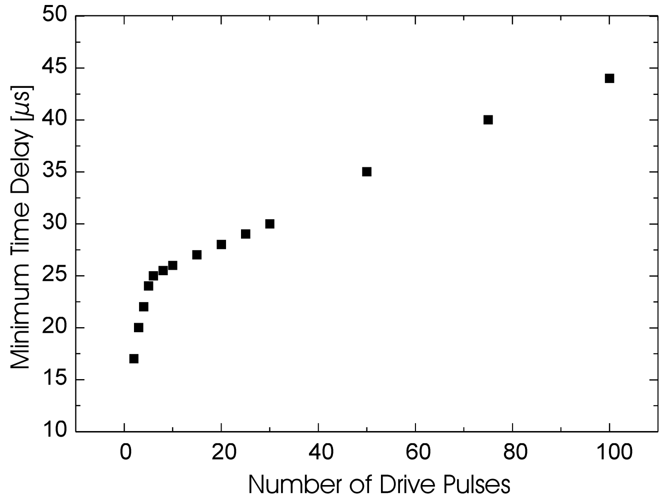

Figure 8. Minimum Time Delay Between Consecutive Drive Pulses for Bubble Generation

Conclusion

A novel thermal micro actuator concept has been realized using diamond as a multifunctional material. The new thermal inkjet heater based on diamond has successfully demonstrated its functionality. Already the first prototype of the diamond inkjet is superior to common systems in regard to heating efficiency and resistance against mechanical strains. The excellent frequency behavior of the bubble dynamics with respect to the thermal management has been demonstrated.

In contrast to conventional actuator systems, for the new diamond micro heater only 4 different materials, namely, diamond, silicon, tungsten, and gold, are required. The reduction of manufacturing steps makes the diamond inkjet attractive for the printer industry. In addition, costs can be significantly reduced which offers great possibilities and advantages for the printer market.

References

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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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