論 文 の 内 容 の 要 旨

論文題目　On-chip LSI Cooling Device Using Electroosmotic Flow Micropump Integrated with High-Voltage Generator
(高電圧生成回路集積電気浸透流マイクロポンプによるオンチップLSI冷却機構)

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Within the past decade, there has been rapid advancement of three-dimensional stacked integrated circuits (3DIC). The technology has not only improved the interconnection performance and power dissipation but also increased the number of I/Os. Although the 3DIC technology has still developed by increasing the number of stacked chips and thinning the chips, these developments decrease thermal conductance and degrade the thermal dissipation leading to increase heat density in a device. It degrades the performance of chips and causes a shorter lifetime of the chips. As a result, the cooling of 3DICs is an essential issue to be solved to develop integrated circuits.

For cooling of 3DICs, forced liquid cooling and liquid-vapor convection in micro-channels have gotten attention. While the other cooling components such as heat-pipes and vapor chambers require a large volume of a bulk heat sink on the backside of the chip, the required volume on the backside is low in the micro-channel cooling. Due to the advantage, the micro-channel cooling device can be integrated into 3DICs. However, conventional micro-channel cooling methods require extensive bulky liquid circulating systems such as a pump, condenser, and chiller. These components not only occupy lots of space but also have low reliability of cooling. Therefore, to decrease the size of the cooling components and failure rate, integrating active fluid components in cooling devices is essential.

As an active fluid component, micropumps is one of the significant parts. Electroosmotic flow (EOF) micropumps are one type of electrokinetic micropumps, and it is based on the free ion movement in conductive fluids. The attractive feature of the EOF micropump is that it does not require mechanical moving structures and air gaps and that it can output high pressure in micro-channels. However, some issues still exist to use EOF micropumps. One of the most significant issues is the driving voltages of the micropumps. Compared to mechanical micropumps, which conventionally require at most 200 V, the EOF micropumps require higher voltages than at least 40 V (in some cases over 800 V). This has prevented the integration of micropumps into 3DICs since these high voltages are higher than maximum voltages of commonly-used through-silicon-vias (TSVs) connecting stacked chips. Another issue of EOF micropumps is a measurement method of surface parameters. The performance of EOF micropump depends on the surface charges of EDL, which is changed by the surface condition. However, as the conventional method cannot measure the surface charge without breaking the device, the prediction of fabricated EOF micropumps was difficult.

This dissertation presents the design, fabrication, and testing of a novel cooling device having an on-chip micropump integrated with an on-chip high-voltage generator to drive the micropump. The high-voltage generator is realized by standard CMOS technology and MEMS post-processes called post-processed deep-trench-isolation (or mesa isolation). Due to the isolation, the breakdown voltages of the standard 5 V transistors can be extended up to 800 V.

Firstly, the process optimization of MEMS post-process deep trench-isolation to form the complete isolation of transistors has been discussed. The process optimization is performed using novel test structures that do not require breaking the measurement samples, and two different etching modes are found. By using the optimized process, a high-voltage switch is presented to demonstrate the use of the post-processed high-voltage transistors, and also a high-voltage generator using the post-processed high-voltage transistors is presented. Then, the design, fabrication, and analysis of the on-chip integrated EOF micropump using the high-voltage generator are discussed. Besides, to predict the performance of an EOF micropump, a novel on-chip zeta potential measurement sensor is discussed. Finally, the cooling efficiency of micro-channel devices is investigated. By the experimental results, we have found two cooling modes of the micro-channels depending on the flow rate. Besides, the suitable placement of micro-channels and a micropump in each cooling mode is presented.

In summary, this dissertation reports an integrated micro-channel cooling device. The integrated on-chip EOF micropump is driven by a high-voltage generator using post-processed deep-trench-isolated transistors. Having high reliability and high-voltage output of the integrated high-voltage generators in microfluidic devices also enhances the other applications such as point-of-care devices and one-chip micro total analysis systems. The cooling demonstration using micro-channel devices indicates the future integration of these devices into power-consuming circuit chips, including a processor and 3DICs.