A Review on Cooling Technologies for Micro and Miniature Devices and Systems

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ABSTRACT: As electric and mechanical devices have been miniaturized and highly integrated, heat generation per unit volume has been greatly increased. Therefore, effective cooling methods for micro and miniature systems have emerged as critical issues nowadays and a lot of studies have been carried out to find an optimum cooling strategy. This paper reviews recent researches on the cooling technologies which are mainly based on microfabrication processes. Design, development, experiments and numerical analysis of various cooling devices are discussed and their characteristics, problems and advantages are compared.

1. Introduction

Microfabrication techniques of the last decade have led to development of various compact and multi-functional devices. These miniature devices have many advantages such as energy-saving operation, cost-effective mass production, as well as compactness and mobility. The micro electro mechanical system (MEMS) is one of the most successful methods for miniaturization. The applicable fields of MEMS are still expanding not only in the mechanical or electric devices, but also to the biological or chemical applications, such as the micro total analysis system (μ-TAS) and the lab-on-a-chip devices. But behind the challenges for miniaturization and high-integration, there are a lot of problems also. Among the problems, the high heat density within the device is a major one. As a device or system gets smaller and more highly integrated, the heat generation per unit volume will increase as well, which may increase the operating temperature of the device. Therefore, cooling method and thermal management should be investigated before designing a micro device or a system.

Since most of the cooling targets are made by the microfabrication processes, a new cooing strategy is required rather than conventional cooling techniques. There have been many attempts to cool down the micro devices, such as micro heat pipes, microchannel heat sinks, fin-fan coolers, micro miniature refrigeration system, and so on. The fin-fan coolers are widely used for the chip cooling application because of its simple principle and low production cost. However, fin-fan coolers are based on forced convection of ambient air, which is difficult to control. Moreover, large flow rate is required because the cooling capacity of air is not so large. That is why the fan speed should be kept high in spite of the mechanical vibration and noise. Contrarily, the working principle of the micro heat pipe and microchannel heat sinks is based on the latent heat of working fluid, that is, the cooling effect of two phase

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flow on evaporation. Since the cooling capacity of the phase changing fluid is much larger than that of the single phase fluid, these methods are suitable for the small devices with high heat flux. Moreover, the heat pipes and microchannel heat sinks have no moving parts, which have outstanding advantage for miniaturization. The microchannel heat sinks need additional pumping devices to circulate the fluid. As for the heat pipes, the working fluid is driven by the capillary force. So these devices are known as the passive cooling devices. The major disadvantage of the passive cooling devices is that it is hard to control the working conditions when thermal load changes. The micro miniature refrigeration (MMR) system is an active cooling system, which means that the working fluid is driven by an actuator. A promising principle for the micro miniature refrigeration system is the vapor compression refrigeration cycle. This system is also based on the phase change phenomena of the working fluids, namely, refrigerants. The refrigerants are driven by a vapor compressor, which means that this system can work as an active cooling device. The compressor needs to have large stroke volume, but most of the micro actuators do not produce large displacement. That is because the materials for the microfabrication are mainly silicon and glass substrates, which have less elasticity than conventional mechanical materials. Therefore, the vapor compressor is a bottle neck to development of micro refrigeration system.

2. Microchannel heat sinks

From the beginning of 1980s, microchannel heat sink has been studied and tested as a high performance and compact cooling scheme for microelectronics. A lot of tests have shown that high heat generation of electronic devices can be effectively removed but large pumping power is required due to pressure drop in the microchannel.

Peng and Petterson[1] investigated the single phase forced convective heat transfer and flow characteristics of water in microchannel structures experimentally. Results indicate that the geometric configuration had a significant effect on the heat transfer and flow characteristics. In recent years, the pressure drop and heat transfer characteristics of a single phase microchannel heat sink have been investigated both experimentally and numerically. Qu and Mudawar[2] have shown that their experimental data of measured pressure drop and temperature distribution showed good agreement with the corresponding numerical predictions. However, there is unavoidable large pressure drop in single phase flows to remove high heat dissipations of the micro devices. Therefore, two phase microchannel heat sinks have been investigated by many researchers with various fluids. Peng and Wang[3] tested the boiling characteristics of subcooled water through 600 by 700 μm^2 microchannels. Their results indicated that nucleate boiling quickly became fully developed. Bowers and Mudawar[4] showed that the high heat flux could be removed with low flow rate and low pressure drop in microchannel heat sinks using R113. Critical heat flux (CHF) in microchannel heat sinks was investigated and results showed that the thermal performance was much better that that of the single phase flows. Zhang et al.[5] studied boiling of water in rectangular microchannels with hydraulic diameters from 25 to 60 μm and aspect ratios from 1.0 to 3.5, and nearly constant heat flux conditions. Nucleation and small bubble growth were observed inside the microchannels. Higher heat fluxes resulted in annular two phase flow. Hetsroni et al.[6] investigated flow boiling of water in the silicon triangular microchannels having hydraulic diameters of 103 and 129 μm respectively. Their experiments were carried out at a heat flux of $8 \sim 36\ W/cm^2$ and at a Reynolds number from 20 to 75. They mentioned that two types of periodic flow patterns were observed: the periodic annular flow and the periodic dry steam flow. However, no fluctuation data of pressure or temperature were reported in their paper. Qu and Mudawar[7] studied the transport phenomena in the following aspects of microchannels: hydrodynamic instability, two phase flow patterns, pressure drop, and convective boiling heat transfer. High speed photographic methods were used to determine dominant flow patterns and characterize the hydrodynamic instabilities. Wu and Cheng[8] carried out a simultaneous visualization and measurement on flow boiling of water in parallel silicon microchannels of trapezoidal cross-section (Di = 158.8 μm, 82.8 μm). Fluctuations with large amplitude long period have been measured in wall temperature, fluid temperature, fluid pressures and fluid mass flux during flow boiling in the microchannels. They found that the fluctuation periods depend on channel size, heat flux, and mass flux. With the aid of a microscope and high speed video recording system, bubbly flow, slug flow, churn flow, and other peculiar flow patterns are observed. Hetsroni et al.[9] studied two phase flow patterns in parallel microchannels. Experiments were performed for air-water and steam-water flow in parallel triangular microchannels. In air-water flow, different flow patterns were observed simultaneously in the various microchannels at a fixed flow rate. In steam-water flow, instability in uniformly heated microchannels was observed. A simple one dimensional model of boiling two-phase flow and heat transfer in a single triangular microchannel has been proposed.[10] It has been shown that the dry-out length increases with the hydraulic diameter and decreased with the heat flux. They used water as a working fluid. Thome et al.[11] suggested three-zone flow boiling model to describe evaporation of elongated bubbles in microchannels. This model shows the importance of the strong cyclic variation in the heat transfer coefficient and the strong dependence of heat transfer on the bubble frequency, the minimum liquid film thickness at dry out and the liquid film thickness.

In the heat sinks of multiple channels, the thermal performance depends on the mass flow distribution also. Therefore, a lot of studies have been carried out to obtain an optimum design of header or manifold for a uniform mass distribution.[12-15]

3. Micro heat pipe

Heat pipe, or thermosiphon is a promising principle for the micro cooling device because it does not need any moving part such as vapor compressor and valves. Khrustalev and Faghri[16] introduced a miniature heat pipe in the size of $2 \times 7 \times 12\ mm^3$ with the cooling capacity of $100\ W/cm^2$. The heat pipe has enhanced heat transfer coefficient with the use of porous plate. Maziuk et al.[17] conducted numerical calculation on thermal performance of a miniature heat pipe (50~250 mm length, 8~11 mm width). They focused on the relation between the heat transfer coefficients in the evaporators and condensers and the thermal conductivity of the wick. Lin et al.[18] developed a miniature heat pipe for the cooling of high heat flux electronics with a newly designed copper sheet fin. The device was fabricated with conventional machining job, and its cooling capacity was higher than $140\ W/cm^2$. Berre et al.[19] fabricated and tested a micro heat pipe based on silicon substrate. The evaporator, condenser and channels were etched by anisotropic etching process and a polysilicon heater was also fabricated on silicon wafer. Except the sensors such as thermo couples, they realized most of the components by microfabrication process. This device worked for the cooling capacity between 0.5 and 4 W.

A major advantage of the micro heat pipe on silicon wafer is that the silicon has a higher thermal conductivity compared to conventional materials, i.e. iron and steel. On the contrary, this also means that the micro heat pipe may have small effectiveness. Peterson et al.[20] had found that the conduction heat transfer in silicon wafer is so large that the improvement due to the micro-heat pipe is not so large (25 ~80 % enhanced heat transfer). Launay et al.[21] introduced another micro heat pipe fabricated by microfabrication process and this device had 22 % enhanced heat transfer compared to an empty silicon structure. They investigated the effectiveness of the micro heat pipe quantitatively by measuring the temperature distribution along the micro heat pipe. A transient response of a micro heat pipe was also tested and numerically analyzed.[22] This analysis includes the variation of wall temperature, pressure and mass flow rate at a sudden change of cooling load. Berre et al.[23] fabricated thermistors on an oxidized surface of the micro heat pipe. They measured temperatures of all channels in a heat pipe array (27 channels) with thermistors so that the optimum working condition was obtained.

4. Micro miniature refrigeration system

There are several attractive features when the microfabrication technology is applied to refrigeration systems. First, high heat flux or mass flux can be exploited more effectively in the miniature system. Second, a distributed processing of mass and energy can be realized by the micro energy systems, rather than relying on one central system. Third, the size and weight of the systems can be greatly reduced. Finally, cost effective mass production is possible, because most components of the miniature energy system are built with the microfabrication process.[24] However, few researches have been focused on the micro refrigeration systems which are integrated with the micro components, while enormous studies have been conducted on the development of the individual components. Munkejord et al.[25] suggested various possible applications such as the microprocessor cooling, portable cooling device and even into the building as a wall element which is integrated with the micro miniature refrigerators. They also built a miniature heat pump in an open circuit, which has a condenser and an evaporator made from the microfabrication process. The refrigerant from a bottle enters the condenser in the heat pump and condenses to liquid. Then it expands through a regulating valve, and it evaporates through the microchannel evaporator, finally the refrigerant goes out to the atmosphere. Overall heat transfer coefficient and pressure drop at the heat exchangers were measured, providing quantitative information about the performance of miniature heat pump, except the compressor. Drost et al.[26] have tested a portable absorption heat pump using lithium bromide (LiBr) and water solution. This heat pump was designed for thermal load up to 350 W with the net weight of 5 kg. Choi et al.[27] have made and tested a micro sorptioin refrigerator using silica gel and water. The test results showed that the thermal load was up to about 30 W, when the cycle period of the adsorption compressor was 100 s. Selby et al.[28] have developed a flexible polymer membrane for the micro vapor compressor, which was driven by the electrostatic actuation. The deflection of the membrane was up to about 400 μm. The polymer membrane was bonded on the glass and silicon substrates by the sub-micrometer thick bondlines of all-aromatic thermosetting copolyesters (ATSP). Narayanan and Venkatarathnam[29] conducted a numerical analysis on a micro miniature refrigerator which included evaporator, condenser and capillary tube. All of the devices were designed in the form of microchannels, which enabled a simple fabrication process on a single silicon or glass substrate. Darabi and Ekula[30] introduced a chip-integrated micro cooling device. An electrohydrodynamic (EHD) micropump was used to transport the dielectric fluid. The fluid evaporated and condensed in a closed-loop system, producing cooling rates of 35 W/cm^2. Gromoll[31] presented a heat exchanger for micro cooling systems. The heat exchanger was fabricated on silicon wafer and it could be used with compressed air (15 W/cm^2) or thermosiphon (25 W/cm^2).

Since the compressor is a bottle neck for development of micro refrigeration system, there have been studies on the vapor compressors on silicon substrates. A number of experiments on micropumps have shown that vapor can be compressed by silicon-based devices.[32-34] Performance characteristics of a compressor with a silicon membrane, cantilever check valves and a piezoelectric actuator have been investigated by numerical analysis[35] and experiments.[36]

Stirling cycle is one of the thermodynamic cooling systems with a number of advantages for miniaturization. It can be built with simple devices and can operate over a wide range of temperature, sometimes below 100 K. Therefore, a number of studies have been conducted on the miniature Stirling cycle for cryogenic use. Organ[37] performed a numerical simulation on the performance of miniature Stirling cycle, including the input power of the electromagnetic drive. Bapat[38] investigated the miniature Stirling cycle with two-component and two-phase mixture. He obtained the cooling capacity of 1 W at temperature of 74.7 K when charged with helium of 20 bar.

There are still many kinds of cooling principles, such as a micromachined cooling fan using cantilever,[39] a pulse-tube based on silicon and glass substrates,[40] and a Linde-Hampson cooler with glass-tube heat exchanger.[41]

5. Conclusion

Impressive progress in the microfabrication techniques has contributed to recent development of miniature and micro devices with high integration and multi-function. However, the high heat flux from the device is a major side effect, which may cause malfunction or critical damage. Therefore, a lot of studies have been carried out in order to solve the thermal problem in the micro devices. Since the cooling target is in small size, two phase heat transfer is very effective cooling mechanism. Therefore, this paper has reviewed studies on the microchannel heat sinks, micro heat pipes, micro miniature refrigeration systems. The passive cooling devices, such as the microchannel heat sinks and micro heat pipes, have no moving parts, which have a strong advantage for miniaturization and microfabrication. But these devices are affected by the surrounding conditions and hard to control. So more studies are required to enhance robustness in operation of these devices. The active cooling device, such as the micro miniature refrigeration system, is a very attractive candidate, but the vapor compressor is hard to realize on the silicon substrates. Therefore, a lot of researches are needed for realization of vapor compression principle on the microfabrication process.

Since more vigorous miniaturization and high integration are expected in near future, more attention will be paid to effective and creative challenges for cooling technology.

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