All-Micromachined Joule-Thomson Cold Stage

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ABSTRACT

A micro Joule-Thomson cold stage was designed, built and tested, as part of the micro cooling research project at the University of Twente. The cold stage consists of a stack of three glass wafers. In the top wafer, the high-pressure line is etched as a rectangular channel with supporting pillars. The high-pressure line ends in a flow restriction and an evaporator volume that crosses the center wafer into the bottom wafer. The bottom wafer contains the low-pressure line, again etched as a rectangular channel containing supporting pillars, thus forming a counter-flow heat exchanger. A design aimed at a net cooling power of 10 mW at 96 K and operating with nitrogen as the working fluid was optimized based on the minimization of entropy production. The optimum cold finger measures 28 mm x 2.2 mm x 0.8 mm (max. dimensions). It should be able to generate a net cooling power of 10 mW at 96 K at a nitrogen flow of 1 mg/s at a high pressure of 80 bar and a low pressure of 6 bar. A batch of 14 prototype coolers were made for 8 different designs, including a design of the theoretical optimum. Liquid nitrogen is collected in the evaporator, and since the low pressure is 6 bar, the temperature should be 96 K. However, due to some thermal resistance in the thermocouple attached to the cold tip, a temperature of 105 K was achieved. A net cooling power of 5 mW was measured. In the paper, the design of the coolers will be discussed along with experimental results.

INTRODUCTION

Cooling of electronic circuitry to very low temperatures can improve the signal-to-noise ratio and bandwidth of a system. For superconducting devices, it is crucial that they are cooled below their critical temperature to operate properly. In many cases the device, which is to be cooled, is very small. The need for an accompanying small cryocooler is obvious. Several attempts have been made to construct such a miniature refrigerator.[1]

At the University of Twente, research on miniaturization of cryocoolers is continued. The goal of the present study is to design and fabricate a micro cooler with a net cooling power of about 10 mW @ 96 K using Micro Electro-Mechanical (MEMS) technology. The fact that the presented cold stage is optimized for a maximum cooling power in combination with a minimum pressure drop makes the design distinct from that of former attempts to make a micro cold stage (e.g. Burger et al.[4], and Little et al.[5]). The next section will discuss the optimization of the cooler design. Afterward, the cooler production process and measurements are presented.

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OPTIMIZATION OF THE COOLER DESIGN

The chosen parameters for the design optimization is as follows: eighty (80) bar, a low pressure of p_{low} = 6 bar and a mass flow of 1 mg s^{-1}. The temperature of the cold tip which is 96 K, is determined by the evaporation temperature of the working gas (N_2) at the chosen low pressure. Clarification of the chosen parameters and further explanation of the cycle can be found in the paper by Leroux, et al.[2].

The most criticial part of a cryocooler based on the Joule-Thomson (J-T) principle is the counter flow heat exchanger (CFHX). The CFHX maintains the temperature gradient between the warm and cold ends of the cooler and greatly improves the efficiency of the cooler cycle by exchanging heat between the high and the low-pressure gas flows. Because the amount of energy that is exchanged in the CFHX is typically two orders of magnitude larger than the cooling power, a small reduction in the effectiveness results in a large decrease in available cooling power.

To maximize the effectiveness of the CFHX, a geometry that results in an optimal heat exchange between the high and low-pressure lines is needed. In general, this means that the heat exchange surface area between the lines has to be maximized. Two rectangular channels on top of each other form a convenient configuration. A very thin layer separates the channels (see Fig. 1).

In a CFHX, two important loss mechanisms can be distinguished. The first is the loss due to pressure drop in the flow channels and the second is the loss due to conductive heat flow. To reduce the heat flow from the hot side to the cold tip of the cooler, the entire device is fabricated in glass. Glass has a relatively low thermal conductivity ($\lambda \approx$ 1 $Wm^{-1}K^{-1}$, in comparison silicon: $\lambda \approx$ 1000 $Wm^{-1}K^{-1}$ which is the most commonly used MEMS material). To minimize the losses, and to optimize the effectiveness of the CFHX, a study was performed based on minimizing the total entropy production in the CFHX. This study was published elsewhere.[2]

The optimal dimensions of the flow channels were used in the final design. However, due to fabrication constraints, the thicknesses of the wafers differ slightly from the assumed wafer thicknesses in the optimization study. Also pillars inside the flow channels were added later to the design to reduce mechanical stresses inside the glass. The relevant dimensions of the optimal design[2] are

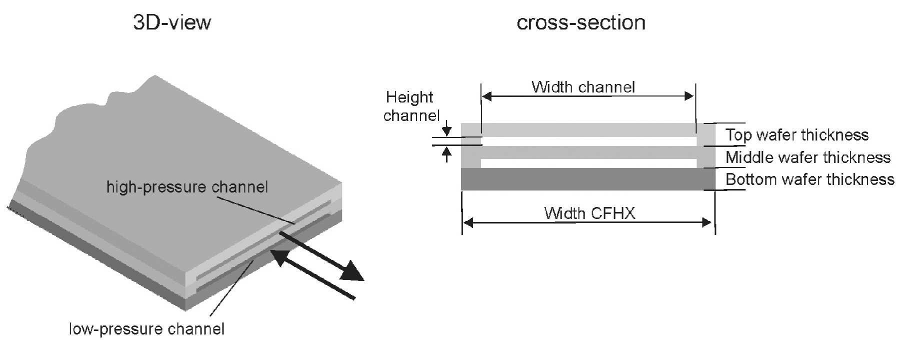

Figure 1. 3D-view of a part of the CFHX and a cross-section of the CFHX.

Table 1. Optimum design dimensions. First three dimensions apply to both the high- and the low-pressure channel.

CFHX channel width:	2.0 mm	Total cooler length:	30 mm
CFHX channel height:	50 μm	P_{gross}:	14.7 mW
CFHX channel length:	25 mm	P_{net}:	10 mW
Top wafer thickness:	175 μm	dp_{high}	0.002 bar
Middle wafer thickness:	145 μm	dp_{low}	0.03 bar
Bottom wafer thickness:	400 μm	COP:	0.05

given in Table 1. Besides this optimal design, seven other designs, all based on the optimal design, are fabricated. This is done to verify the optimization model used and to investigate the influence of different design parameters like the dimensions of the CFHX and the value of the mass flow.

MICRO COOLER FABRICATION

The cold stage is manufactured by means of micro machining, more specifically by wet etching and fusion bonding techniques. This technology provides high fabrication accuracy, the possibility to integrate the system with the electronic circuitry and the use of batch processing, which can result in relatively low cost per unit. The fabrication is described in more detail elsewhere.[3,6]

The cooler consists of a stack of three fusion bonded glass wafers (see Fig. 2). Nitrogen gas flows inside the stack through etched micro channels. The main part of the cold stage serves as a CFHX. The high-pressure channel connects to the low-pressure side via an etched shallow flow restriction that has a length of 140 μm, a width of 1 mm and a height of only 300 nm. A batch of 14 prototype coolers was made in 8 different designs, among them, the theoretical optimum. Some examples are depicted in Fig. 3.

MEASUREMENTS

Fig. 4 shows the results of a measurement which was performed on a cooler designed to have a mass flow of 2 mg s^{-1} at 96 K and a net cooling power of about 20 mW at that temperature. The graph on the left shows the cold-tip temperature versus time. The right graph shows the mass flow through the restriction as a function of the measured cold-tip temperature. This graph also gives the theoretical curve of the mass flow versus temperature for a flow restriction with the actual depth of 300 nm as well as that for a restriction depth of 280 nm. The variation of the flow with temperature is caused by the temperature dependence of the gas density and viscosity. The experimental mass-flow curve coincides with the theoretical 300 nm curve for temperatures above about 190 K. At that temperature, the mass flow curve shows a small decrease in slope. This is an indication that the restriction is getting partly clogged (probably due to condensation of water inside the N_2 gas). The curve now "follows" another theoretical line somewhere between a restriction depth of 300 and 280 nm.

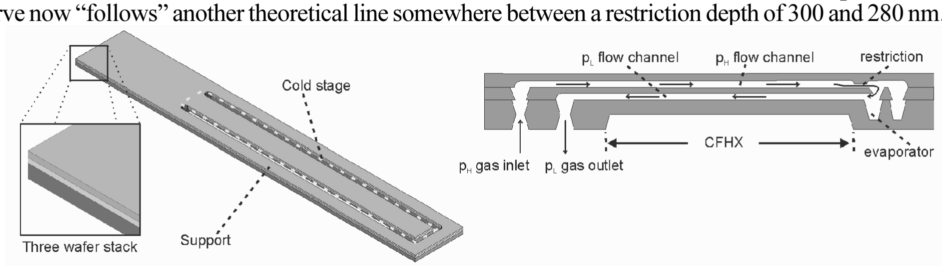

Figure 2. Left: three dimensional schematic of the recuperative micro cooler prototype. Right: schematic of a cross-section of the cold stage.

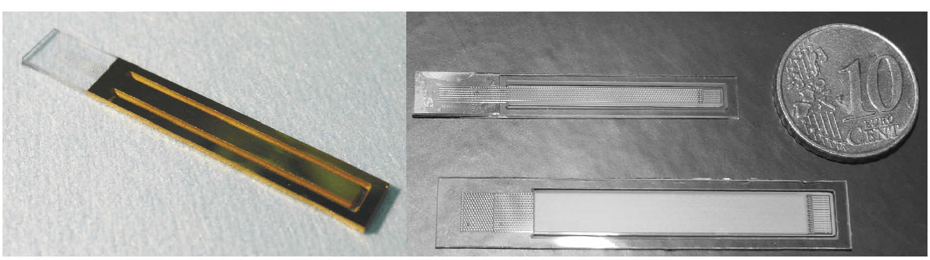

Figure 3. Left: micro cooler prototype with thin gold layer to reduce radiation losses. Dimensions are 28 mm x 2.2 mm x 0.8 mm Right: 2 different micro coolers.

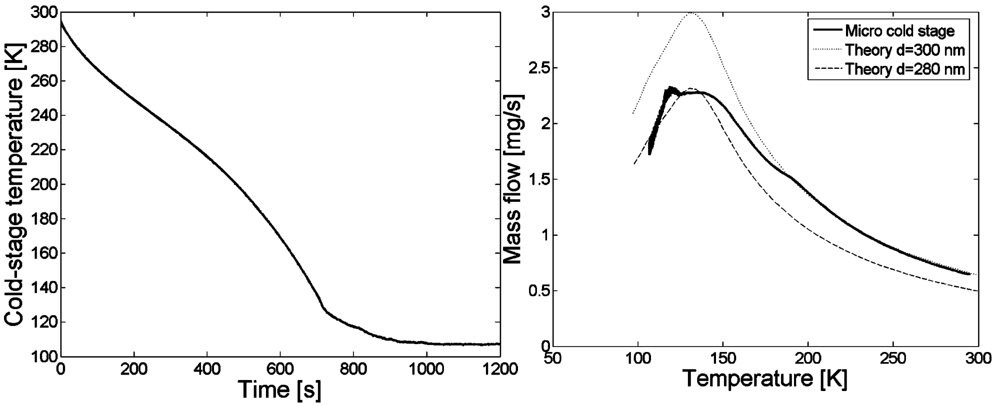

Figure 4. Measurement data of a cool-down. Left: the temperature of the cold tip vs. time. Right: the temperature vs. the mass flow through the restriction. The graph also shows two theoretical curves with different restriction depths.

A layer of less than 10 nm height on the surface of the restriction already accounts for the measured effect. It results in a decrease of the mass flow and thus of cooling power. Nevertheless, the cool down continues and below a temperature of about 130 K, the mass flow fluctuates. This indicates that liquid nitrogen is formed inside the evaporator. It also means that there is a relatively large temperature gradient from the evaporator to the flow restriction since at a low pressure of 6 bar the evaporator should be at the boiling point of 96 K. The liquid nitrogen in the evaporator further cools the restriction, thus affecting the flow as depicted in Fig. 4. It can be seen that the temperature does not reach the predicted 96 K. The cold tip temperature is measured with a thermocouple that is connected to the outside of the evaporator. It is calculated that the thermal resistance of the thin layer of glass and the connection between the thermocouple and the cold stage can easily give a ΔT of about 10 K. Because this specific design is developed to have a mass flow 2 mg s^{-1}, its theoretical net cooling power will be about 20 mW. Through measurement and calculation of additional losses, the estimated net cooling power which is about 20 mW, agrees with this value. Also, for the optimal design tested, the net cooling power agrees with the predicted value of 10 mW.

CONCLUSION AND DISCUSSION

A set of micro cryogenic coolers, consisting of a stack of three fusion bonded glass wafers, is fabricated using MEMS technology. An optimization study has been done to minimize the cooler dimensions in combination with an optimal performance. A cool-down curve of one of the fabricated cold stages, with dimensions of 30 x 2.2 x 0.5 mm is presented. The micro cooler has a net cooling power of 20 mW at about 100 K. The measurements show that the cold stage (partly) probably clogs due to condensation of water inside the flow restriction. In the future, the micro cold stage will be combined with a sorption compressor creating a closed-loop cycle. In this way the gas is recycled, minimizing the amount of water contamination inside the nitrogen gas which should prevent clogging. Also, measurements of a multi stage micro cooler with a theoretical tip temperature of 27 K are planned.

ACKNOWLEDGMENT

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