Progress in Micro Joule-Thomson Cooling at Twente University

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ABSTRACT

At the University of Twente, research on the development of a sorption-based micro cooler is in progress. Because of the absence of moving parts, such a cooler is virtually vibration free and highly durable, which potentially results in a long lifetime. A miniature cryogenic cooler with these properties would be appealing in a wide variety of applications including the cooling of vibration-sensitive detectors in space missions, low-noise amplifiers and semi- and superconducting circuitry.

The objective of the present project is to scale down a Joule-Thomson (JT) cold stage to a total volume of a few hundredths of a cm^3. This size reduction introduces many problems. The proposed cold stage volume results in a restriction cross-sectional area of about a thousandth of a mm^2 which may cause clogging problems. Flow channels with a cross-sectional area of a few hundredths of a mm^2 will produce high pressure drops influencing the JT cycle. Furthermore, the micro channels must be capable of withstanding high pressures and maintaining a large temperature gradient over a relatively short length.

The project aim is to develop a reliable micro JT cold stage that is fabricated out of one material with a relatively simple and reproducible fabrication method. The length of the cold stage is calculated at about 20 mm with a width of 1.7 mm and height of about 0.3 mm. The mass flow is in the order of one mg per second to create a net cooling power of 10 mW at 96 K. The final objective of the project is to integrate the cold stage, vacuum chamber and device into one compact design. This paper discusses possible solutions to the problems mentioned and presents a concept design of such a miniature JT cold stage.

INTRODUCTION

Cooling of low-noise amplifiers, infrared detectors, and other electronic circuitry to cryogenic temperatures can be advantageous. It improves the signal-to-noise ratio and bandwidth of the system. For superconducting devices it is crucial that they are cooled below their critical temperature in order to operate properly. In many cases the system, which is to be cooled, is very small so an accompanying small cryocooler would be obvious. Several attempts have been made to construct such a miniature refrigerator.[1]

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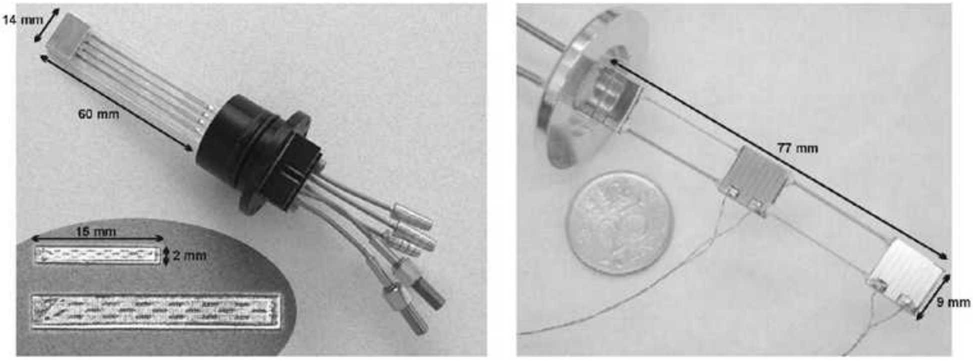

Figure 1. On the left: a two stage nitrogen/neon refrigerator made by MMR technologies, Inc.[4] and a prototype of a micro miniature N_2 refrigerator made by Little et al.[2] On the right: a micro machined ethylene cold stage fabricated by Burger et al.[5]

Much pioneering work on micro coolers was done by Little et al, who made different miniature cold stages [2,3]. The smallest had a size of 15x2x0.5 mm (0.015 cm^3). This cooler was used in an open-loop cycle with N_2 gas at a high pressure gas of 165 bar and a flow rate of 3 mg/s. It had a cooling power of 25 mW at a temperature of 101 K and with no heat load the cold stage temperature reached 95 K. It was constructed through an abrasive etching process. Unfortunately, this achievement was not reproduced or turned into an industrial product. However, larger coolers of this design are nowadays commercially available from MMR Technologies, Inc. [4]. The smallest has a size of about 60 x 14 x 2 mm (1.68 cm^3) (Fig. 1). It can cool down to 35 K with a cooling power of 50 mW using a two-stage nitrogen/neon Linde-Hampson configuration.

Burger et al. developed a Joule-Thomson (JT) cold stage with a total volume of 0.76 cm^3 (77 x 9 x 1.1 mm) combined with a sorption compressor, thus realizing a closed-cycle micro cooler.[5] This miniature cooler had a cooling power of 200 mW at 170 K (Fig. 1). Burger used Micro Electro Mechanical System (MEMS) technology to construct different components of the cold stage. Wet KOH etching and wafer bonding techniques were used for the fabrication of a condenser, restriction and evaporator in silicon. Counter flow heat exchangers were made out of tiny glass capillaries. After fabrication the different cold stage parts were glued together.

As a continuation of this previous research we present an approach for the development of a miniature cold stage with a total volume of about 0.010 cm^3. Compared to the previous work, the present project will only use MEMS technology to fabricate the cold stage. By using a sorption compressor the gas cycle will be closed in combination with a total exclusion of any mechanical moving parts. The cold stage temperature will be about 96 K with a net cooling power of about 10 mW. In addition, the cold stage will be highly reproducible by applying a relatively simple production process. As a final goal we are aiming at the integration of cold stage, vacuum chamber and device into one compact easy-to-use device.

CHOOSING WORKING GAS AND PRESSURES

In a Linde-Hampson cycle, gas is pressurized using a compressor (Fig. 2, 1→2). After compression the gas flows from the compressor through a counter flow heat exchanger (CFHX) to a flow restriction (2→3). Through this restriction, the gas undergoes isenthalpic expansion to the low-pressure side and usually changes its phase to a liquid (3→4). By absorbing heat from its surroundings the liquid evaporates (4→5) and the produced vapor flows back through the CFHX absorbing heat from the warm high-pressure side (5→1). Once the gas has reached the compressor it can be compressed again, closing the cycle.

In certain applications the device to be cooled has a very low dissipation or no dissipation at all. In these cases the required cooling power is determined by the total parasitic heat load from the

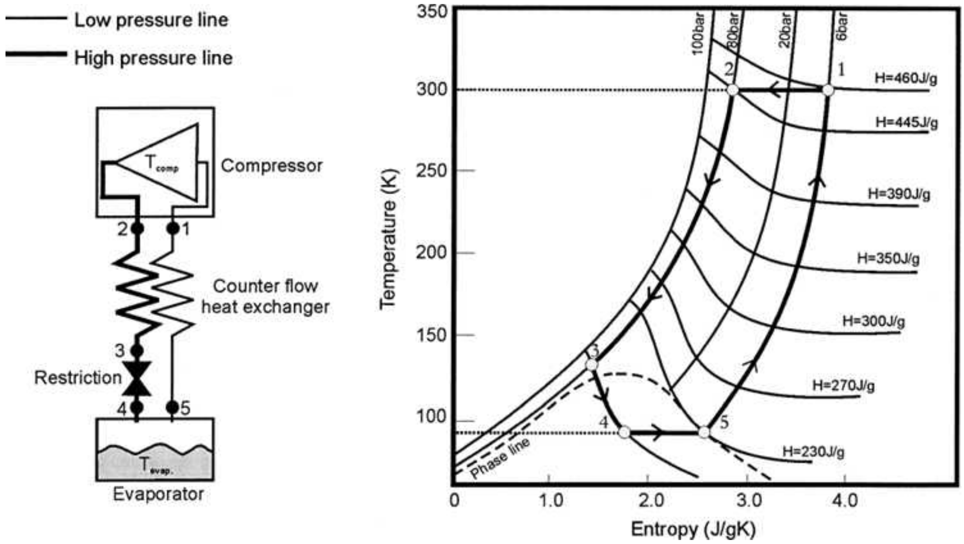

Figure 2. On the left side, a schematic scheme of the Linde-Hampson cycle. On the right side, the T-S diagram of nitrogen with isobars and isenthalps. The bold line with numbers represents the cycle.

environment. By a clever design of the cryogenic enclosure of such a small device, the required cooling power can be limited to a few mW only.

The gas used in a Linde-Hampson cycle in combination with the chosen low pressure will determine the temperature of the cold stage. In the search for a cheap, non toxic and nonflammable gas which can create a cryogenic temperature (roughly T<120 K), nitrogen is an obvious choice. The boiling temperature of nitrogen at 1 bar is about 77 K.

With the change in pressure during compression, the gas undergoes a change in enthalpy. Theoretically this change in enthalpy will determine the available gross cooling power of the cold stage. To create sufficient cooling power with nitrogen, a relatively high pressure (80 bar) is chosen at the high-pressure side of the cycle (Fig. 2). It is our intention in the future to combine the cold stage with a sorption compressor.[6] Based on first calculations of a two-stage nitrogen sorption compressor the low-pressure side is chosen at 6 bar. At this pressure the sorption material of the compressor has considerably more sorption capacity than at lower pressures. This way a cooler with acceptable efficiency can be designed.

A pressure change from 80 to 6 bar results for nitrogen in a cooling enthalpy of about 15 J/g. The cold stage temperature at 6 bar is about 96 K. Since the gross cooling power is given by $\dot{m}dh_{45}$, where $\dot{m}$ is the mass flow and dh_{45} the cooling enthalpy, the mass flow will have to be in the order of 1 mg/s to create a net cooling power of 10 mW.

FABRICATION OF MICROSTRUCTURES

The abrasive etching technique used by Little et al. is based on powder blasting.[2] This is a micromachining technique where a high pressure mixture of air and powder particles is accelerated towards a substrate[7]. The powder consists of Al_2O_3 particles and is accelerated through a nozzle (Fig. 3). Once the particles hit the target they erode surface particles. A mask protects parts of the target to create different structures. Wensink et al. found a removal rate for glass and silicon of approximately 25 µm/min.[7] The smallest feature size attainable is about 30 µm with an aspect ratio of 2.5.

The main disadvantage of powder blasting is the relatively high roughness of the blasted surface which goes hand in hand with the process. Small imperfections at the sides of the channels are likely to be the starting point of a rupture when a micro channel is pressurized to a high pressure.

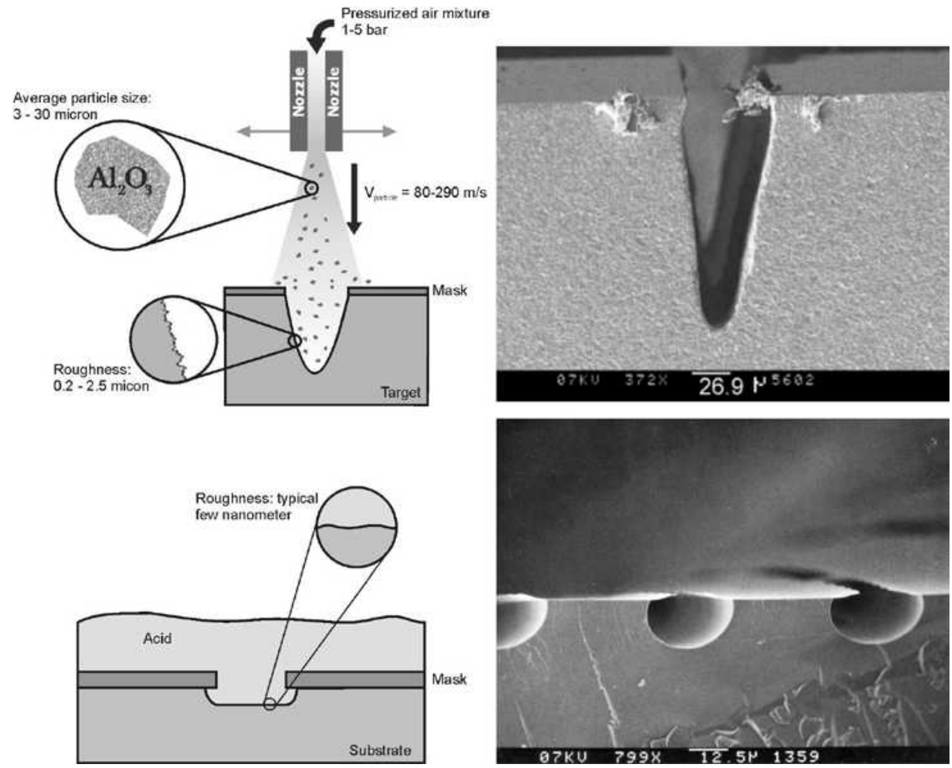

Figure 3. The top two figures show a schematic impression of the powder blast process and a 50 μm wide channel in Pyrex with an aspect ratio of 2.5 (blasted with 9 μm alumina particles at 290 m/s).[7] The lower two figures show a schematic impression of the isotropic wet etch process and three etched channels with a width of approximately 30 μm.[9]

Also the flow behaviour through the micro channels is influenced. Higher roughness results in a higher flow resistance and associated pressure drop. The rough surface can also be more sensitive to clogging. This is why we prefer to use a wet etching process for fabricating a miniature cold stage.

As an alternative, photolithography can be used, which is a widely used technique in MEMS technology.[5,8] A wafer is coated with a photo resist layer and exposed through a mask to ultraviolet light. Using positive resist the exposed areas are removed with a development solution. Now the wafer can be etched using an acid, usually hydrogen fluoride (HF) (Fig. 3). After etching the resist layers are stripped from the wafer and the wafer is cleaned. These processing steps can be repeated to create different structures and depths in the wafer. To create closed channels the processed wafer is closed with another wafer through an anodic or fusion bonding process. Miniaturizing cold stage parts using MEMS technology

One of the most crucial parts in a Linde-Hampson cycle is the counter flow heat exchanger (CFHX). The CFHX maintains the temperature gradient between the warm and cold ends of the cooler. The CFHX also improves the efficiency of the cooler by exchanging enthalpy between the high and low-pressure side. In an ideal cycle we presume that the counter flow heat exchanger works with an efficiency of 100%, theoretically corresponding to an infinite length. Inefficiency of a CFHX results in a loss of the cold stage's gross cooling power.

To maximize the efficiency of the CFHX we are looking for a geometry that results in an optimal enthalpy exchange between the high and low-pressure lines. In general, this means that the heat-exchange surface between these lines has to be maximized. Two rectangular channels on top of each other seem to be a convenient configuration. A very thin layer separates the channels (Figs. 4 and 5).

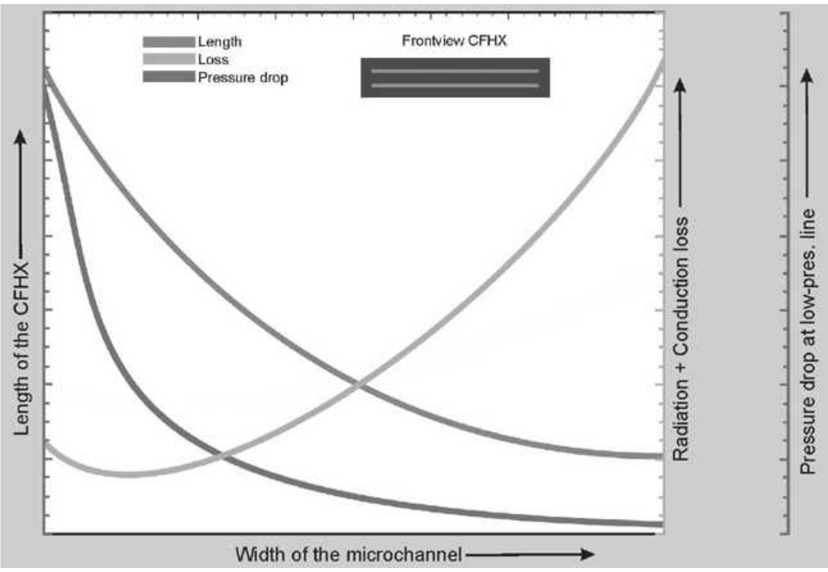

Figure 4. Width of a microchannel versus CFHX length, total loss and pressure drop at the low-pressure line. The graph is calculated for two symmetrical channels with constant high and low pressure, CFHX efficiency, wall thickness, channel height and mass flow.

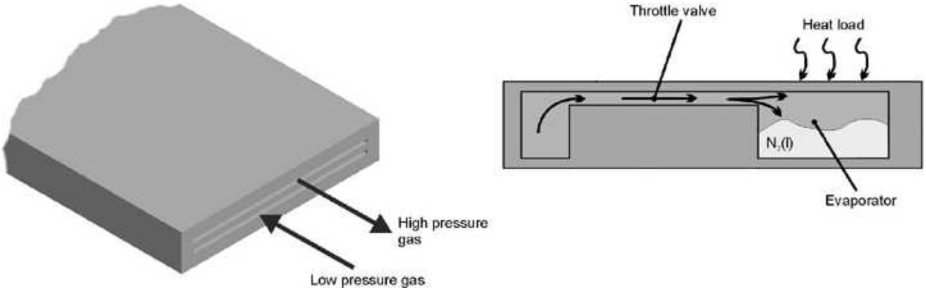

Figure 5. On the left: cross-section of a CFHX. On the right: crosscut of a restriction and evaporator. The throttle valve and evaporator will be etched into the glass.

To optimize the geometry we study the effect of different parameters on the operation of a CFHX. Next to a high efficiency in exchanging enthalpy per unit length of the CFHX, only a small pressure drop over the high and low-pressure lines can be accepted. A large pressure drop at the high-pressure side will increase power loss and a drop at the low-pressure side will result in an increase of the cold-stage temperature. For a constant shape of the channel, the cross-sectional area will mainly determine the pressure drop per unit length of the CFHX. The smaller the area the higher the pressure drop. However, a smaller cross-sectional area will improve heat-exchange properties. Another very important parameter influenced by the geometry of the CFHX is the loss in the gross cooling power due to conduction from the warm side of the CFHX to the cold side.

The objective is to make a very small, highly efficient heat exchanger. However small, or in other words short, goes hand in hand with a high conduction loss. The task is to optimize the heat exchanger's geometry for minimal pressure drop and heat losses (conduction and radiation) in combination with very small dimensions. Figure 4 shows the general behavior of all parameters for a constant height and changing width of the CFHX-channels.

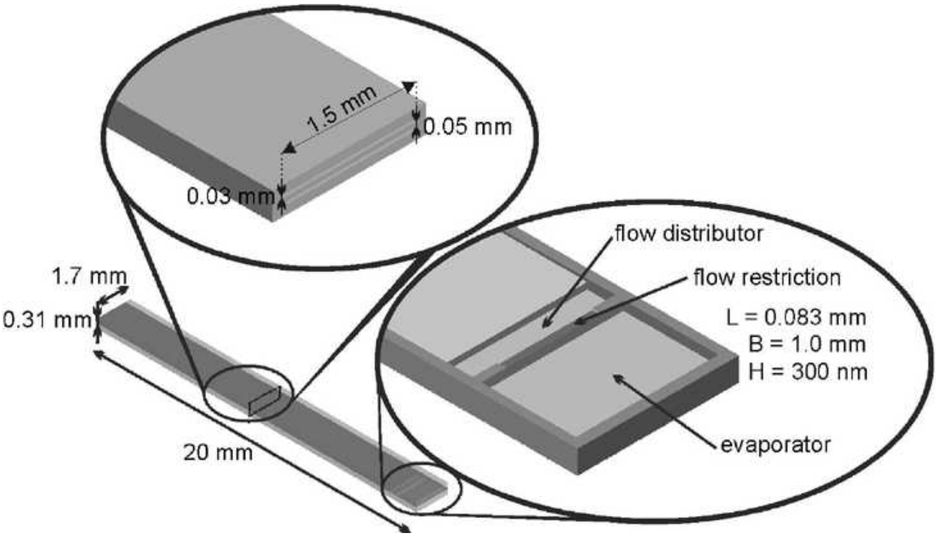

Figure 6. Concept design for a N_2 miniature cryocooler with a net cooling power of about 10 mW at 96 K.

Similar calculations can be made for different geometries. In this way an optimal configuration can be found. Aiming at a net cooling power of about 10 mW, an optimal channel geometry of (L x W x H) = (18.9 x 1.5 x 0.03) mm was found. The thickness of the wall between the two channels is calculated at 50 µm. The mass flow is 1 mg/s and the total parasitic heat loss is about 4.57 mW. The pressure drop over the low-pressure line is about 0.15 bar resulting in a cold-stage temperature of 97 K.

A wide and shallow channel will be etched in the glass wafer to serve as the restriction establishing a flow of 1 mg/s at a pressure drop of 80 to 6 bar. The dimensions of this channel are calculated at (L x W x H) = (0.083 x 1.0 x $0.3 \cdot 10^{-3}$) mm. An etched reservoir in the wafer will serve as the evaporator (figure 5). Combining all the different designed parts a concept design for a miniature N_2 cooler is made (Fig. 6).

Since the miniature coolers will be etched in glass wafers it is possible to fabricate a high number of coolers at the same time. Some test structures are etched in glass to test the technology and some properties of micro channels and restrictions (Fig. 7). Micro channels with varying widths and lengths and different flow restrictions are fabricated.

TOTAL INTEGRATED COMPACT DEVICE

One of the final objectives is to integrate the miniature cold stage with the device that is to be cooled and a vacuum chamber into one compact design. Since the construction material of the cold stage is glass (Pyrex) it is expected that it is possible to connect the cooler to devices made out of silicon (e.g. integrated circuits or MEMS devices).

It is our aim to combine the integrated cold stage package with a small sorption compressor. Optimization of sorption compressor configurations is ongoing at the University of Twente.[6]

CONCLUSIONS

An approach for the fabrication of a miniature N_2 cold stage using MEMS technology was presented. The total volume of the cold stage is about 0.010 cm^3. An optimal channel geometry for the counter flow heat exchanger was calculated at (L x W x H) = (18.9 x 1.5 x 0.03) mm with a wall thickness between the two channels of 50 µm. A wide and shallow channel with the dimensions (L x W x H) = (0.083 x 1.0 x $0.3 \cdot 10^{-3}$) mm will serve as flow restriction. A high pressure of 80 bar and a low pressure of 6 bar in combination with a mass flow of 1 mg/s results in a net cooling power

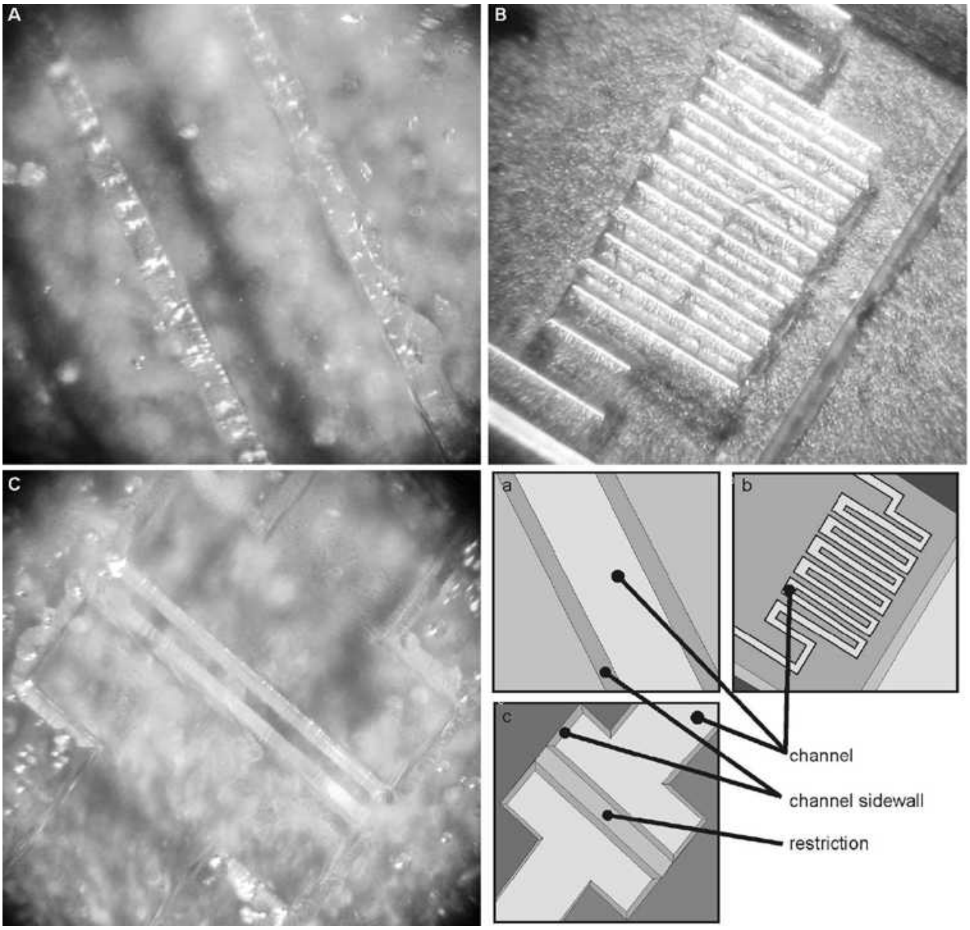

Figure 7. Micro test structures etched in glass with HF. A channel with a width of 110 μm (A), a meandering channel structure, channel width is 140 μm (B), a flow restriction with a width of 3 mm, a length of 0.253 mm and a height of 248 nm (C)

of 10 mW and a cold stage temperature of 97 K. The pressure drop over the low-pressure line is about 0.15 bar. Since a photolithography fabrication method is used it is possible to fabricate a high number of coolers at the same time. It is our aim to combine the cold stage with a small sorption compressor and to integrate the miniature cold stage and vacuum chamber with the device that is to be cooled into a totally integrated compact device.

ACKNOWLEDGMENT

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