Micromachined Cryogenic Coolers for Cooling Low-Temperature Detectors and Electronics

H.J.M. ter Brake, J.F. Burger, H.J. Holland,
J.H. Derking, H.Rogalla
University of Twente, Fac. Science and Technology
IMPACT Research Institute
Enschede, The Netherlands
h.j.m.terbrake@utwente.nl

P.P.P.M. Lerou
Kryoz Technologies
Enschede, The Netherlands
info@kryoz.com

Abstract—**Vibration-free miniature cryogenic coolers are relevant to a wide variety of applications, including cooling of detectors in space missions, low-noise amplifiers and superconducting electronics. For these applications, the cryogenic system (cooler plus interface) should be small, low-cost, low-interference and above all very reliable (long-life). A cold stage based on micro-electro-mechanical systems technology was designed and prototypes were realized and tested. This cooler operates on basis of the Joule-Thomson effect. A design aiming at a net cooling power of 10 mW at 96 K and operating with nitrogen as the working fluid was optimized and measures 28 mm x 2.2 mm x 0.8 mm. It operates with a nitrogen flow of 1 mg/s at a high pressure of 80 bar and a low pressure of 6 bar. The design and fabrication of the coolers is discussed along with experimental results.**

I. INTRODUCTION

Vibration-free miniature cryogenic coolers are relevant to a wide variety of applications, including cooling of detectors in space missions, low-noise amplifiers and superconducting electronics. In these applications, the operating temperature of electronic devices is lowered to reduce thermal noise and/or increase speed. In order to fully exploit low-temperature electronic devices, the cryogenic system (cooler plus interface) should be 'invisible' to the user. It should be small, low-cost, low-interference, and above all very reliable (long-life). Although different groups around the world have tried to build small cryogenic refrigerators, such small microcoolers are not yet available.

Within the Cooling and Instrumentation group at the University of Twente a MEMS-based cold stage was designed and prototypes were realized and tested (MEMS: Micro-Electro-Mechanical Systems). These coolers operate on basis of the Joule-Thomson effect and have cooling powers of typically 10 to 20 mW at about 100 K. The next section describes the design of these microcooler tips, whereas the fabrication is considered in section III. The measurement setup in which the coolers are characterized as well as the experimental results are presented in section IV. The paper is closed with a discussion in section V.

II. COLD-STAGE OPERATION

In the micro cooler, cooling is obtained by using the so-called Joule-Thomson effect [1]. Nitrogen is expanded from a high pressure of 80 bar to a low pressure of 6 bar over a flow restriction that is only 300 nm high, see Fig. 1. Through this restriction, the gas undergoes isenthalpic expansion and changes its phase to a liquid. At the low pressure of 6 bar, the boiling temperature of nitrogen is 96 K which determines the temperature of the cold tip. The evaporated working fluid returns to the low-pressure side of the system via a counter-flow heat exchanger (CFHX). In passing this heat exchanger, it takes up heat from the incoming high-pressure gas that thus is precooled on its way to the restriction [2].

The cooling power at the cold tip equals the mass-flow rate ($\dot{m}$) times the specific heat of evaporation. Since the Joule-Thomson expansion is an isenthalpic process and furthermore, the enthalpy is maintained in the CFHX, the cooling power can also be expressed as $P_{cool} = \dot{m} \times dh$. Here, *dh* is the difference in specific enthalpy of the gas between the high and low pressures at the warm end of the CFHX [2]. At a flow of 1 mg/s, the gross cooling power is about 15 mW.

In contrast to earlier micro cold stages [3-5], this cold tip is optimized for maximum performance in combination with minimal size. The dimensions are optimized by minimizing the entropy that is generated. In this optimization, all heat- and pressure-drop losses in the cooler are written as a production of entropy. By minimizing the total entropy production, it is possible to find an optimal cold-stage configuration, which has minimum losses and thus
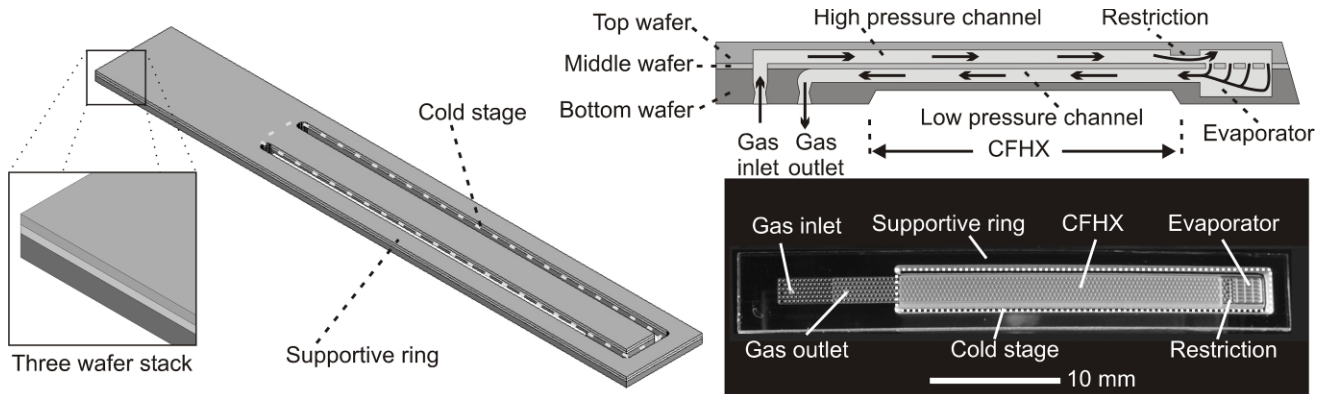
Figure 1. Left: 3D schematic of a cold stage; Right top: schematic cross section of a cold stage; Right bottom: photograph of a cold stage
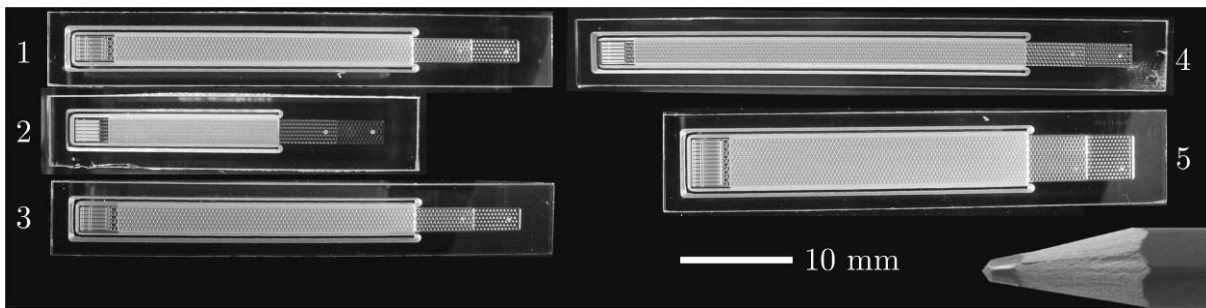

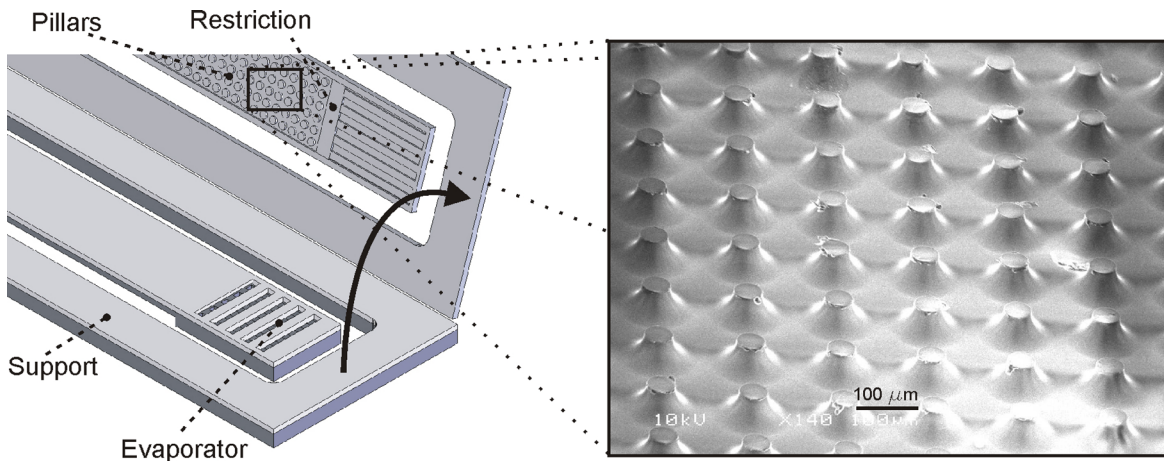
Figure 2. Photograph of five prototype microcoolers

Figure 3. Zoom of the cold tip; Right: SEM picture of a grid of 50 μm wide pillars to support the high-pressure channel construction

maximum performance [6]. A photograph of the prototypes can be found in Fig. 2.

III. FABRICATION

The micro coolers are fabricated in glass wafers using HF etching and abrasive etching (a.k.a. powder blasting). The production process has seven lithography steps and roughly 100 process steps. 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. This line ends in a flow restriction and an evaporator volume that crosses the center wafer into the bottom wafer. This bottom wafer contains the low-pressure line, again etched as a rectangular channel, thus forming a counter-flow heat exchanger (CFHX), see Fig. 1. The high- and low-pressure gas channels are fabricated by

HF etching. The channels are 50 μm deep and 2 mm wide. To create a mass flow of 1 mg/s with the pressure difference of 74 bar, the height of the restriction has to be only 0.3 μm. Since the absolute pressure inside the high-pressure channel is relatively high (80 bar) and the thickness of the wafer is only 150 μm, the channel is supported by micro pillars as is shown in Fig. 3. The cold-stage fabrication process is described in more detail in [7].

IV. CHARACTERIZATION EXPERIMENTS

A. Measurement setup

Measurements on the micro cold stages are performed in a setup in which high-purity nitrogen gas (6.0) is supplied from a gas bottle. The high pressure is regulated to 80 bar using a pressure controller. The inlet mass flow can either be controlled or measured by a mass flow controller. The gas is directed through a getter stabilized zeolite filter. In particular water is filtered out thus minimizing the change of clogging due to water deposition inside the restriction [8]. The cleaned gas flows through the micro cold stage which is situated inside a vacuum chamber. At the low-pressure side, the pressure is measured using a pressure sensor and the outflow is measured using a mass-flow meter. A valve at the outlet maintains an absolute pressure of 6 bar preventing air from the lab to flow into the system.

The temperature of the cold tip is measured using an E-type thermocouple, with a wire diameter of 250 μm, that pushes against the evaporator part using its spring force. To minimize parasitic heat loss, no heat sink paste is used between the cold tip and the thermocouple. An SMD (Surface Mounted Device) resistor, which is glued on the cold tip, can be used to apply heat to the tip and thus measure the cooling power. The parasitic heat load on the cold tip because of the thermocouple, the two manganin wires and the SMD resistor, is calculated and depends on the chosen emissivity of the manganin wire and resistor surface. It typically ranges from 6 to 10 mW.
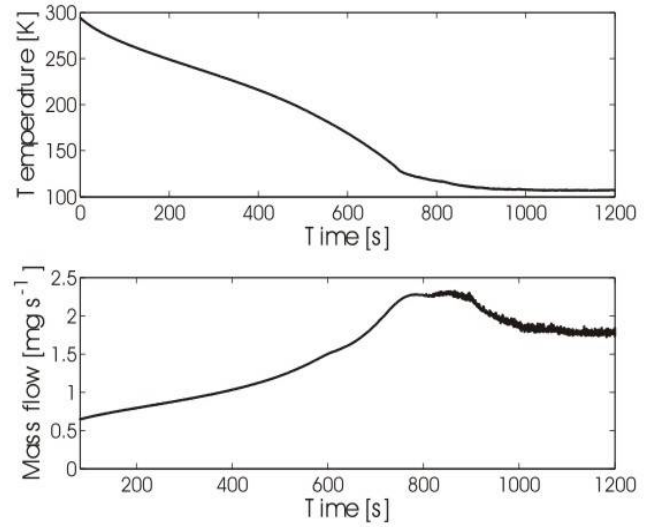

Figure 4. Cool-down registration of microcooler prototype 3

B. Results

Fig. 4 shows a typical cool-down curve of cold stage 3. Two graphs give the temperature of the cold tip and the mass flow through the system both versus time. The variation of the flow with temperature is caused by the temperature dependence of the gas density and viscosity. The micro cold stage cools down from 300 K to 107 K in about 800 seconds. At t ≈ 800 s, the mass-flow curve starts to fluctuate which is an indication that liquid nitrogen is being formed inside the evaporator. It can be seen that the temperature as measured does not reach the predicted 96 K. This is caused by the heat resistance of the thin layer of glass and the heat flow through the thermocouple from the environment to the cold stage. This can easily give a temperature difference of about 15 K. After 1000 s, the cold stage stabilizes at constant tip temperature and mass flow.

Table 1 summarizes the results for all prototypes depicted in Fig. 2. The net cooling powers as measured and as calculated are given in which parasitics, as discussed above, are taken into account. The characterization experiments are more extensively discussed in [9].

TABLE 1. MEASURED AND CALCULATED COOLING POWERS OF THE MICROCOOLER PROTOTYPES

Prototype number	1	2	3	4	5
CFHX channel width (mm)	2.0	2.0	2.0	2.0	4.0
CFHX channel length (mm)	25	15	25	35	25
mass flow (mg/s)	1.0 ± 0.06	1.0 ± 0.06	2.0 ± 0.06	2.0 ± 0.06	2.0 ± 0.06
net cooling power calculated (mW)	12.6	7.8	20.0	24.1	25.5
net cooling power measured (mW)	11 ± 2.1	9 ± 2.1	19 ± 2.6	24 ± 2.1	26.5 ± 2.6

V. Discussion

Micro Joule-Thomson cryocoolers, of which the production process is fully based on MEMS technology, have been developed and tested. The design of the cold stage has been optimized for maximum performance in combination with minimal dimensions. The dimensions of a cold stage are typically 30 x 2.2 x 0.5 mm with a net cooling power of 10 to 20 mW. Five different micro cooler designs, varying in cold stage dimensions and mass flow, were fabricated and tested. In one of two new research projects at the University of Twente, the microcoolers will be combined with sorption compressors in order to realize a closed-cycle system [10,11]. In the second project, integration of optical detectors with microcooler tips is investigated for space applications [12]. The microcoolers are made available through a new university spin-off company [13].

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