169 KELVIN CRYOGENIC MICROCOOLER EMPLOYING A CONDENSER, EVAPORATOR, FLOW RESTRICTION AND COUNTERFLOW HEAT EXCHANGERS

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ABSTRACT

This paper presents the first cryogenic micromachined cooler that is suitable to cool from ambient temperature to 169 kelvin and below. The cooler operates with the vapor compression cycle. It consists of a silicon micromachined condenser, a flow restriction/evaporator and two miniature glass-tube counterflow heat exchangers, which are integrated with the silicon components using a novel gluing technique. The system was tested with ethylene gas from 20 to 1 bar, and produces a cooling power of 200 mW at 169 K with a mass flow of 0.5 mg/s.

INTRODUCTION

During recent years, there has been much interest to remove locally produced heat from chips, essentially around normal ambient temperatures [1]. Miniature applications operating below ambient temperature, such as a single low-noise amplifier chip or a superconducting chip, would benefit from very small cryocoolers [2]. Such coolers are not available. At the University of Twente, a closed-cycle microcooler is developed which consists of the microcooler presented in this paper connected to a sorption compressor. This precision engineered stainless steel compressor is able to produce the required gas pressures without the use of moving components, except for some high pressure check valves. These MEMS-based valves were presented at MEMS '99 [3]. A thermodynamic description and analysis of the complete cooler was presented earlier [4].

THEORY

Figure 1 shows a schematic diagram of the cooler; it operates with the vapor compression cycle [5]. The accompanying thermodynamic cycle in a temperature-entropy diagram is given in

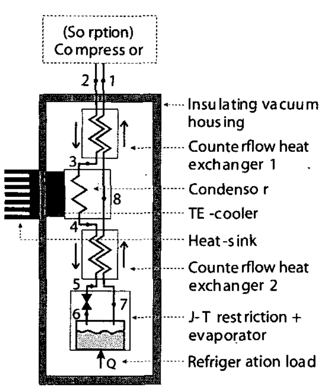

Figure 1. Schematic cooler diagram

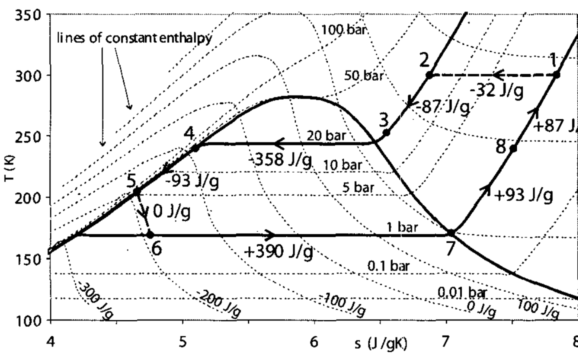

Figure 2. Thermodynamic cycle of the ethylene cooler in a T-s diagram.

figure 2. In the diagram, isobars and isenthalps are given, as well as the enthalpy changes that occur in the counterflow heat exchangers, condenser and evaporator, assuming ideal operation. After compression (1-2), the high pressure gas is precooled (2-3) by the returning low pressure gas (8-1) in the first counterfow heat exchanger. In the condenser, the high pressure vapor is condensed (3-4) using a miniature thermoelectric cooler (which cannot be used to cool directly to temperatures below about 210 K due to a dramatic reduction in performance). The condenser is not essential for operation of the cycle, but it increases the available cooling power per unit mass flow with a factor of ten. Further cooling (4-5) occurs in the second counterflow heat exchanger by the returning low pressure vapor (7-8). The low temperature is reached by a pressure reduction through Joule-Thomson expansion (5-6). Evaporation of the low pressure liquid in the boiler (6-7) produces the cooling power, which can be used by some thermal load connected to the silicon evaporator.

When the cycle operates ideally, the cooling power is given by $\dot{m}\ h_{67}$, where $\dot{m}$ is the mass flow and h_{67} the enthalpy change between states 6 an 7. To obtain a gross cooling power of 200 mW, for instance, an ethylene mass flow of 0.5 mg/s is needed. The majority of the enthalpy change h_{67} is created during condensation from state 3 to 4. A proper design of the condenser is, therefore, a major requirement so that the two-phase fluid reaches full condensation at state 4.

To obtain a significant net cooling power, the thermal losses on the cold stage (conduction and radiation) should be small relative to the gross cooling power. Also the conduction from the warm to the cold side of the counterflow heat exchangers should be limited. Because silicon has a very high thermal conductivity, a different material with a low conductivity such as glass should be used for the construction of the counterflow heat exchangers. In contrast, it is attractive to use a high conductivity material (silicon) for the condenser and evaporator to maintain uniform temperatures, independent of the supplied thermal loads.

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DESIGN

Figure 3 shows the design of the cooler. It is made of three micromachined silicon components, each with a size of 9 mm x 9 mm, with two glass-tube counterfow heat exchangers in between. All three silicon parts are constructed by fusion bonding of two 500 μm thick silicon wafers in which channels and spaces are etched by KOH etching. The applied glass tubes are commercially available [6] and have inner/outer diameters of 0.25/0.36 mm and 0.53/0.67 mm, respectively. Two glass support tubes are added parallel to the two counterfow heat exchangers to add more stability to the system.

The top silicon part is called the 'splitter', and makes it possible to supply separate connection lines to the high and low pressure channels of the first counterfow heat exchanger. In the condenser, the high pressure fluid is able to condense in the long meandering channel. The low pressure fluid returning from the second counterfow heat exchanger directly connects in the condenser to the low pressure annulus of the first counterfow heat exchanger. The high pressure fluid that enters the restriction/evaporator flows through an etched channel to the entrance of the flow restriction, which typically consists of a 4 mm wide, 1 μm shallow channel with a length of about 3 mm. The low pressure liquid that exits the

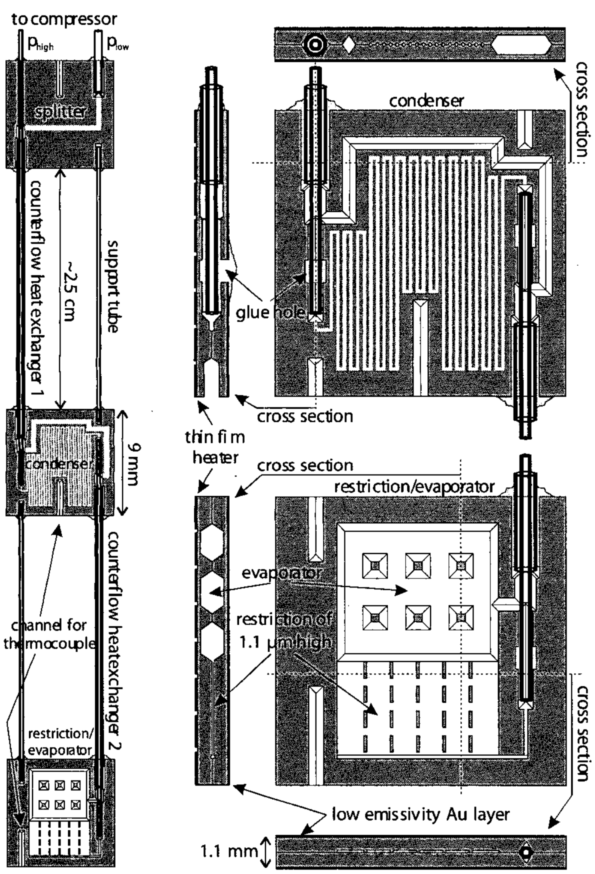

Figure 3. Cooler design (left) with enlargement of the condenser and restriction/evaporator structure (right).

flow restriction (in state 6 in figures 1 and 2) is collected in the liquid bath of the evaporator, which connects at the top side to the low pressure annulus of the second counterflow heat exchanger. In the present design, the orientation of the cooler is important: the low pressure exit of the liquid bath should be oriented vertically upward so that gravity keeps the liquid in the bath and only vapor exits the liquid bath, except when the liquid bath is full. Both the flow restriction and the boiler structure are supported by pillars to prevent excessive bending stresses due to the high gas pressure of 20 bar that may be present. Furthermore, the condenser and the restriction/evaporator contain etched channels that can be used to insert external 250 μm thick thermocouples to measure the temperatures of these cooler parts

The high pressure inner glass tubes are glued into the condenser and restriction/evaporator via a so-called 'glue hole', whereas the outer glass tube is glued at the entrance of the sample, see figure 3. This construction facilitates a robust separate connection of the high and low pressures.

The surface area of the condenser fits approximately to the surface of a two stage thermoelectric cooler, which is a MI 2012T-type fabricated by Marlow Industries [7]. In the same way, a thermal load (some device) can be attached to the restriction/evaporator. In the current design, however, for test purposes a thin film heater is deposited on the restriction/evaporator and on the condenser. This heater can be used to study the behavior of the cooler. To limit the radiation load on the cooler, a gold layer is deposited on both sides of the cooler.

Fluidic, thermal and mechanical modelling was applied to find the proper dimensions of the condenser, evaporator and counterfow heat exchangers [5].

FABRICATION

Figure 4 shows the essential processing steps for the cooler fabrication. Both wafers are double side polished wafers.

Wafer 1. (1) 1.0 μm LPCVD silicon nitride is grown on both sides and patterned by RIE as a mask for KOH etching of the deep channels and the glue holes. Next, the mask for the flow restriction is prepared by etching (RIE) the nitride to 0.5 μm thickness. (2) The deep channels are made by KOH etching; for narrow channels the depth is fixed by the width of the V-shaped channel and for wide channels the depth is fixed by the etching time. (3) The mask for the flow restriction that was etched in step 1 is now activated by

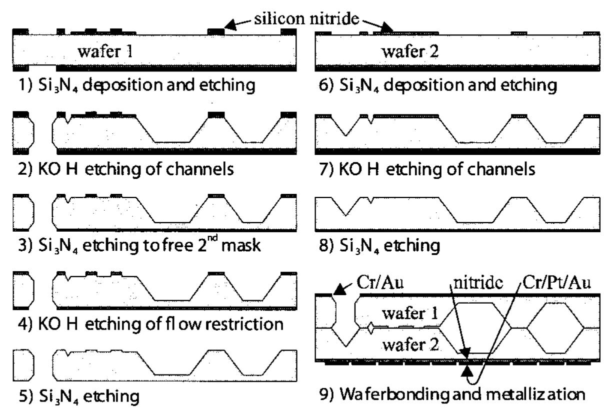

Figure 4. Processing steps for the cold stage fabrication.

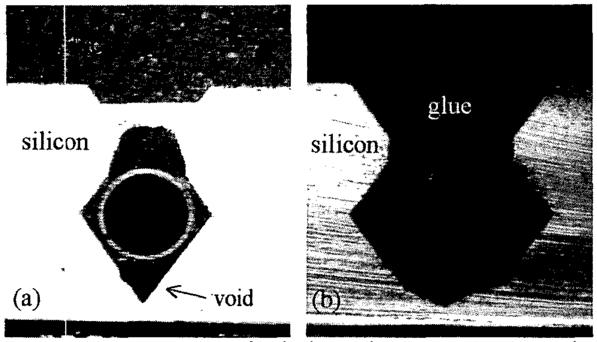

Figure 5. Cross section of a leaking glue-connection (a) and a proper glue-connection (b).

removing 0.5 μm nitride by means of 50% HF etching. (4) Next, the 1.1 μm deep flow restriction is etched by a very short KOH etching step. (5) Just prior to the bonding step, the nitride mask is removed using 50% HF etching.

Wafer 2. (6) 1.0 μm LPCVD nitride is grown on both sides of the wafer and subsequently etched back to 0.5 μm at the topside of the wafer by means of RIE. Next, the mask for KOH etching of the deep channels is patterned on the topside of the wafer by RIE. (7) The channels are etched by a KOH etching step similar to step 2. (8) Just prior to the bonding step, the 0.5 μm thick nitride mask is removed from the topside of the wafer using 50% HF etching, leaving 0.5 μm nitride on the backside of the wafer. This nitride layer will serve as an electrical isolation layer for the heater, which is deposited on top of the nitride in a later step.

Bonding and sample preparation. (9) Wafers 1 and 2 are connected using aligned direct wafer bonding techniques. The two wafers are annealed at 1100 °C in nitrogen atmosphere to enhance the bond strength. After this annealing step, a Cr/Au metal layer is sputtered on top of the two wafers to reduce the emissivity of the top surface; the 10 nm thick Cr layer serves as an adhesion layer. Next, a heater is made on the backside of the wafers by means of dry lift-off patterning. A stack of Cr/Pt/Au is used: 10 nm Cr is the adhesion layer, 400 nm Pt is the actual heater-resistance layer and the 50 nm Au layer reduces the emissivity of the backside surface. Finally, the wafers are sawed into strips of samples. Single samples are obtained by breaking the strips, thus freeing the heat exchanger entrance holes without contaminating the holes by sawing them.

Cold stage integration. Prior to gluing of the cold stage, the heater connection wires are soldered to the heater. Next, the capillary glass tubes for the heat exchangers and supports are accurately cut to the required length after which integration and gluing follows.

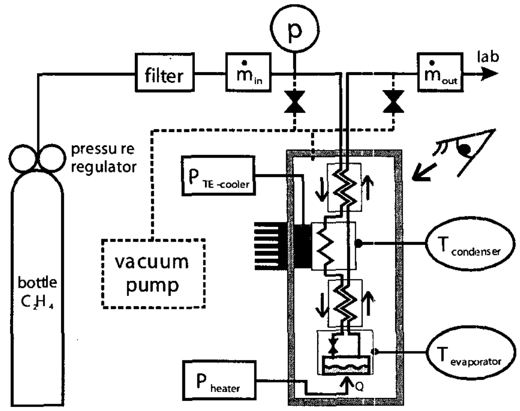

Figure 7. Schematic picture of the cooler characterization set-up.

Experiments were done to test the resistance of different epoxy glues to thermal cycling of the system. Varian's Torr Seal [8] was found to be suitable in this respect. Also, experiments were done to find a proper size for the glue hole. Figure 5a illustrates the result for a small glue hole: the glue could not reach all corners around the glass tube, resulting in a leaking connection of the tube. Widening of the glue hole resulted in properly sealed tubes, see figure 5b.

EXPERIMENTS

Different versions of the cooler were characterized in the set-up shown in figure 7. The high pressure input of a cooler was connected to an ethylene gas bottle, with a zeolite filter in between to trap possible contaminant gases. A data-acquisition system was used to measure and store the following parameters: the temperatures of the condenser and evaporator, the input powers into the TE-cooler and heater, the input high pressure and the mass flow going into the system and coming out of the system. A typical measurement is depicted in figure 8; the important steps are numbered in the figure and are discussed below.

(1) The high pressure is supplied to the cooler and the evaporator cools to a temperature slightly below ambient. The cooling power corresponding to the enthalpy change produced at ambient temperature, h_{12}, is too small to overcome the thermal losses and reach lower temperatures. (2) The TE-cooler is started

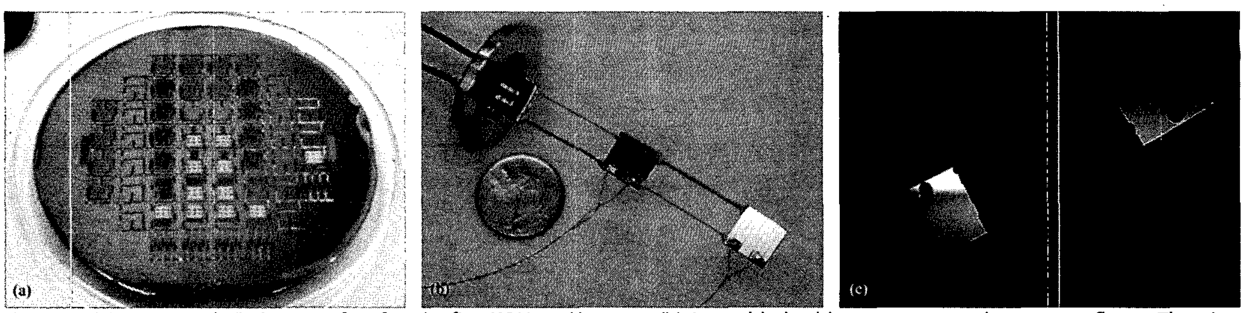

Figure 6. (a) Structured 4" silicon wafer after the first KOH etching step. (b) Assembled cold stage connected to a vacuum flange. The wires are soldered on the thin film heater. (c) Opposite side of the condenser and evaporator with excess glue on the glue holes.

and temperature-controlled at 238 K, 6 K below the condensation temperature at 20 bar. As long as the condenser temperature is above 238 K, a maximum input power of 4.5 W is put in the TE-cooler. (3) The fluid starts to condense in the condenser. For a short period, the ingoing mass flow exceeds the outgoing mass flow to compensate for the liquid volume that is now being collected in the condenser. Also, the evaporator starts to cool more rapidly because of the increased cooling power of the liquid ethylene that now flows from the condenser to the evaporator. As long as the temperature of the evaporator is above the saturation temperature of ethylene at 20 bar (244 K), the produced liquid will evaporate upon reaching the silicon evaporator sample – thus providing cooling power to cool the sample. (4) The high pressure fluid now starts to enter the restriction as a liquid, which increases the mass flow because of changing fluid density and viscosity. This increase of mass flow requires more cooling power to condense the fluid in the condenser and, therefore, the input power of the TE-cooler increases. (5) The low pressure boiling temperature is reached and the boiler starts to fill with low pressure liquid. This explains why the ingoing mass flow exceeds the outgoing mass flow for a while. The outflow does not reach zero because of a partial evaporation of the produced liquid, caused by the heat load from the environment and cooling of the incoming high pressure liquid. Integration over time of the difference between the inflow and the outflow closely matches the amount of liquid that can be stored in the boiler, which is about 7 mg. (6) Because the cooling power exceeds the applied thermal load, two-phase fluid exits the evaporator. Capillary effects explain the variations in the outgoing mass flow. The excess low pressure liquid that flows from the evaporator to the condenser will first exchange heat with the high pressure liquid in the second counterflow heat exchanger, and then evaporate upon entrance of the condenser. This gives cooling power, which is subtracted from the TE-cooler. This explains the slight reduction of the input power of the TE-cooler after t = 420 s.

In the measurement of figure 9, the thin-film heater on the evaporator is used to determine the net cooling power. At an input power of 155 mW, the liquid in the boiler starts to evaporate which indicates that the total thermal load (heater + losses) exceeds the gross cooling power. The losses of approximately 55 mW are mainly caused by radiation on the evaporator and conduction through the 200 µm thick copper wires to the heater. The first two rapid temperature increases are caused by capillary forces, which play an important role because of the small channel dimensions.

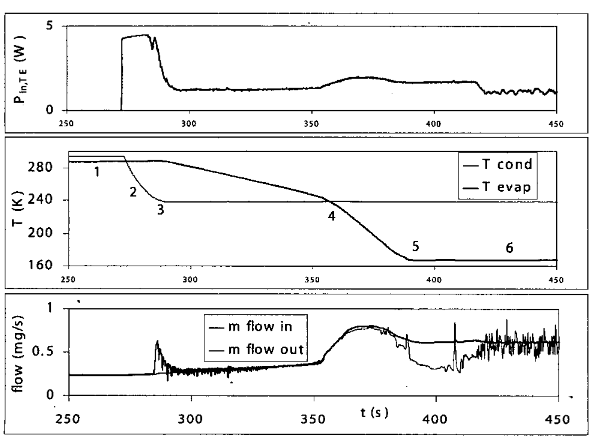

Figure 8. Typical measurement of a start-up of the cold stage.

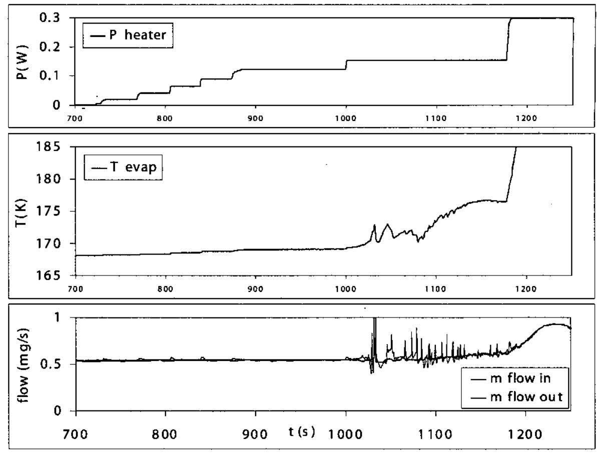

Figure 9. Step-by-step increase of the heater load on the evaporator. At P_{heater}=155 mW, the boiler contents evaporates.

CONCLUSIONS AND OUTLOOK

In conclusion we have shown that MEMS technologies can successfully be applied to construct components for use in cryocoolers. Counterflow heat exchangers made of glass tubes were successfully fabricated and integrated with silicon components using a novel gluing technique, resulting in a working 169 K microcooler. Other temperatures can be reached by replacing ethylene with a different refrigerant. Future opportunities exist in the development of an integrated MEMS micro-cryocooler with vacuum housing.

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