LOW COST MICROMINIATURE REFRIGERATORS FOR LARGE UNIT VOLUME APPLICATIONS

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ABSTRACT

Photolithographic techniques have been employed to fabricate small Joule-Thomson refrigerators in laminated substrates. The gas passages of a J-T refrigerator are formed by etching channels as narrow as 50 microns and as shallow as 5 microns in glass plates which are then laminated together. Circular refrigerators on the order of 1.5 centimeters in diameter and .75 millimeters thick have been produced which cool down to cryogenic temperatures in a few seconds, using Argon or Nitrogen, with no vacuum or radiation insulation. Even smaller refrigerators are being developed for both faster cooldown and low refrigeration capacity applications.

By using this technology, custom refrigerators can be designed to meet specific application requirements. These refrigerators can then be mass produced in a high yield process, which is expected to lead to low unit costs for large volume applications.

INTRODUCTION

Novel photolithographic techniques have been used to produce miniature cryogenic gas refrigerators. In this paper, I discuss the significant design capabilities and inherent low cost nature of this new microminiature refrigeration technology.

BACKGROUND

In the early 1970's, Little [1] recognized the need for refrigerators with cooling capacities much smaller than any then commercially available. Many electronic components such as infrared detectors, low noise amplifiers, solid state lasers, SQUID sensors and Josephson devices either require or significantly benefit from low temperature operation. Such components typically dissipate only a few microwatts to a few milliwatts while commercially available refrigerators have capacities ranging from one watt to many watts. This obvious mismatch between the refrigerators and the needs of the cryogenic electronic components suggested the need for a refrigeration cycle which could be scaled down to microminiature size and capacity [2].

After evaluating the numerous refrigerators which had been developed to achieve temperatures of 80K and below, Little focused on the Joule-Thomson refrigerator because it had no moving parts in its cold stage. This simplified the scaling problems and had the additional advantage of being free of vibration at the cold end. The advantages and disadvantages of the Joule-Thomson refrigerator as well as the scaling laws subsequently developed by Little have been presented in a series of articles [3], [4], [5], [6]. These scaling laws indicated that channel dimensions of a few microns would be required in the lower capacity J-T coolers, which effectively ruled out the small capillary tubing used in conventional coolers and provided the impetus for developing the photolithographic techniques to produce the micron sized channels.

The first microminiature refrigerators were constructed in silicon; however, this proved only partially successful because the silicon wafers used for the heat exchanger had to be made excessively thin due to the high thermal conductivity of silicon and proved to be too fragile to hold the high operating pressures. Glass was then selected due to its high strength and low thermal conductivity.

A set of novel photolithographic techniques have subsequently been developed to etch and bond together the thin slides of glass to form the present generation of microminiature Joule-Thomson refrigerators [7].

FABRICATION-TECHNIQUES

To form the heat exchanger, channels of 50 microns width and 10 microns depth are precisely etched in thin glass plates by an abrasive etching technique. This is done by the application of a special photo resist to the glass slides which is then exposed and developed to define the pattern of channels for a J-T refrigerator. These channels are then etched using a fine particle sandblasting technique, Figure 1. Next, the slides are cleaned and bonded together to form the encapsulated gas passages of the refrigerator.

In mass production, a step and repeat process is used to produce a mask of many images of the channel pattern. This allows one to generate multiple copies of the refrigerators on one large sheet of glass. These are then diced and laminated. Figure 2 shows a plate of multiple slides for a fast cooldown refrigerator discussed later in this paper. This fabrication process has proven to be reliable and consistent, leading to low unit costs for high volume production runs.

DESIGN CAPABILITIES

Figure 3 shows an early model microminiature refrigerator produced with the techniques described above. During operation, high pressure gas, such as N_2 at 1800 psi, is introduced to this device through one of the holes at the right. It then flows through the narrow channels in the counterflow heat exchanger to the single capillary channel where it drops to a low pressure approaching one atmosphere. This isenthalpic reduction of gas pressure causes the temperature of the gas to fall a few degrees. The cooler gas then flows into the boiler cavity at the left end of the refrigerator, continues through a hole in the central plate of glass, and finally flows out through the wide, shallow outflow channel. During initial cooldown, the outgoing gas in the counterflow heat exchanger causes regenerative cooling of the incoming gas until liquefaction occurs in the boiler cavity. The temperature of this liquid is determined by the pressure at the boiler, which in turn is determined by the pressure drop of the gas as it flows through the outflow channel. For example, LN_2 at one atmosphere boils at 77K, while at two atmospheres it boils at 84K. Hence, as in all Joule-Thomson refrigerators, the pressure drop in the outflow channel limits the minimum temperature.

The scaling laws developed for MicroMiniature Refrigerators indicate that as the mass flow through the channels drop, turbulent flows cannot be maintained without a significant increase in the pressure drop. While in conventional heat exchangers, turbulent mixing of the gas is essential for adequate heat transfer; in these planar microminiature refrigerators, adequate heat transfer can occur in relatively wide, shallow outflow channels through conduction alone because of the small mass flow.

As an example, one should note that in the refrigerator of Figure 3 there are twenty narrow inflow channels in parallel which are bracketed together to feed the single capillary channel. This type of interconnecting would be difficult and costly with traditional plumbing techniques, but with photolithography, the only difficulty lies in preparing the initial artwork. More advanced models of microminiature refrigerators have been produced which rely on complex networks of interconnecting channels, which accomplish a number of design objectives not practical in 'standard plumbing' Joule-Thomson refrigerators. For instance, most microminiature refrigerators have redundant inflow channels to minimize the clogging problems normally associated with J-T refrigerators. Also, a two J-T stage Linde refrigeration cycle is often designed into refrigerators which must operate at temperatures near the 1 atmosphere boiling temperature of the refrigerant [8].

Microminiature refrigerators with Linde cycles, or even more complex cycles, can be fabricated for only slightly more cost then ones with single J-T stages.

NEW REFRIGERATOR MODELS

Most microminiature refrigerators produced to date are similar in size to the one in Figure 3 and are typically designed to achieve 80K using N_2 at 1800 psi at 1.5 liters per minute (STP) with a net refrigeration capacity of 250 milliwatts and a cooldown time of 8 to 12 minutes.

However, the potential commercial and non-commercial applications for this technology have stimulated development in two directions:

Lower Flowrate Models: These refrigerators are designed to minimize the gas flow required for a particular application. Hence, efficiency is maximized by retaining the long thin design which isolates the cold end from the warm end by a narrow counterflow heat exchanger of low thermally conductive glass. Figure 4 shows the inflow slide of such a device designed to have 25 milliwatts capacity using 1800 psi N_2 with a flow of about 0.1 liter per minute. The cooldown time will vary from one to several minutes depending on input pressure and the mass being cooled.

Figure 5 illustrates a low flowrate refrigerator cooling an electronic device in a hermetic package. The planar nature of the refrigerator lends itself to this type of hybrid packaging. Such packages are potentially lower in cost than the double walled glass/metal dewars used with traditional J-T coolers.

Fast Cooldown Models: In many applications such as cooling IR detectors in tactical missiles, the primary objective is rapid cooldown. Efficiency is of secondary importance. In these cases, cooldown rate is optimized by changing the refrigerator configuration so that the amount of material being cooled, including that in the refrigerator itself, is minimized -- while at the same time maximizing the cooling capacity in the refrigerator. These objectives are achieved in the fast cooldown model shown in Figure 6. The cooling in this model takes place in the central portion of the disc shaped refrigerator, with the heat exchanger extending radially outward so that the outer perimeter is at room temperature. Hence, this refrigerator can be supported around its perimeter, providing a sturdy device capable of withstanding the high 'g' forces that occur during launch of tactical missiles. The device in Figure 6 has a cooldown rate under 4 seconds using 3500 psi Argon with a 9 liter per minute (STP) flowrate. This performance is in the absence of any vacuum insulation.

One possible way of packaging a fast cooldown refrigerator for cooling an electronic device is illustrated in Figure 7. Since no vacuum insulation is required with these devices, this package could be backfilled with a dry gas which will yield a longer shelf life package than one with a vacuum shroud.

CONCLUSION

The use of photolithography to produce microminiature refrigerators has enabled the production of refrigerators with cooling capabilities on the order of 10 to 100 times smaller than those of other commercially available refrigerators. A few significant side benefits have also resulted from this approach. The fabrication process is ideal for mass production with high yields, leading to low unit costs for high volume applications. J-T coolers can now be custom tailored for particular applications and packaged in low cost hybrid packages.

Open cycle microminiature refrigerators are finding applications in laboratories, certain scientific equipment and tactical missile guidance systems, where gas cylinders or small gas bottles can be used. Also, MMR Technologies is currently developing a miniature diaphram compressor under ONR contract N00014-78-C-0514 which will allow for closed cycle operation of microminiature refrigerators. The initial compressor prototype is designed to produce 2 liters/minute gas flow at 1400 psi while operating at 2 hz. If a miniature compressor such as this can achieve reliable life performance in excess of 2,000 hours, then closed cycle microminiature refrigerator systems are likely to find broad applications in military and commercial instruments for cooling low heat dissipating devices and specimens.

Acknowledements

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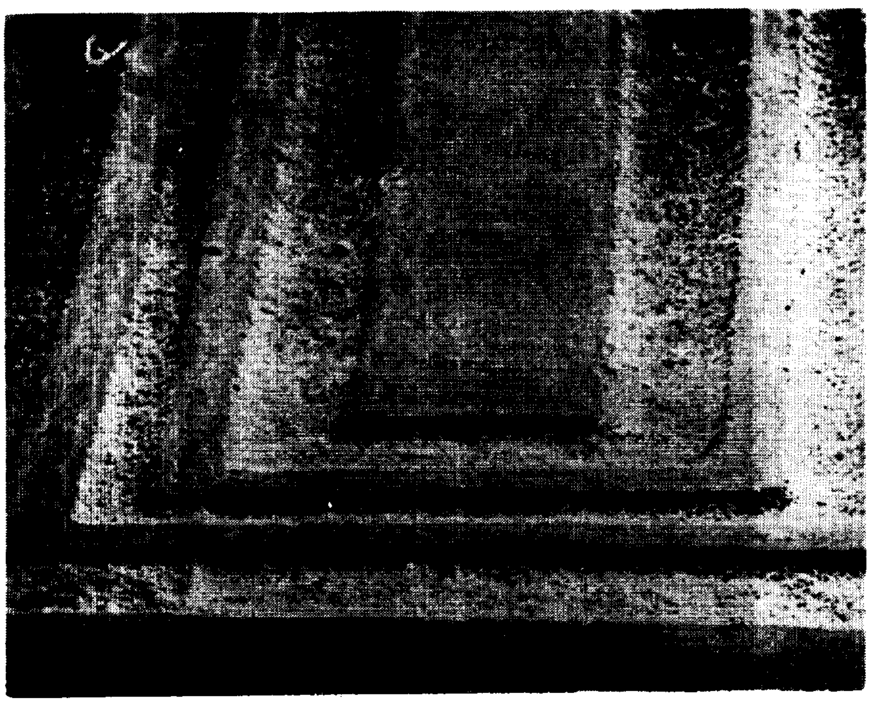

Figure 1. Scanning electron microscope picture of portion of etched glass plate used to form the heat exchanger. The wider grooves are about 200 um in width.

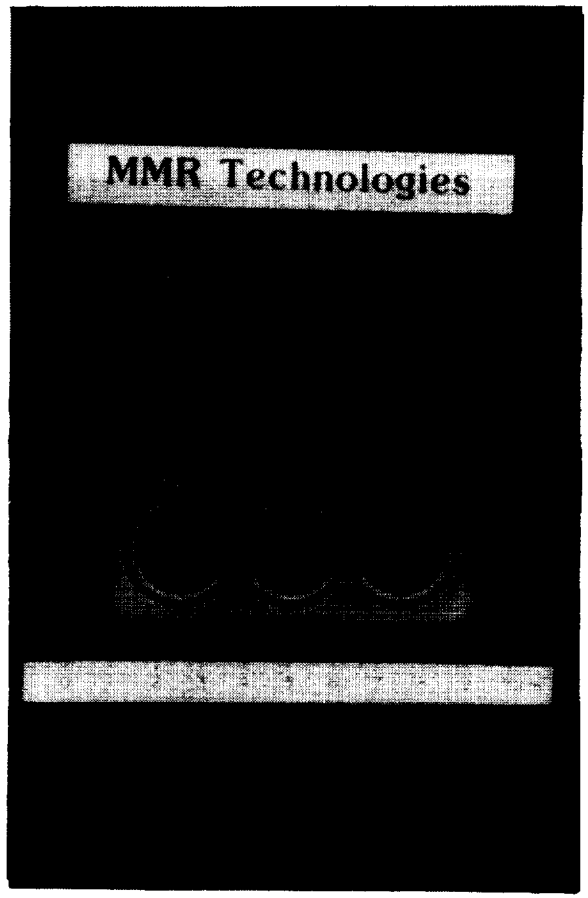

Figure 2. Plate of outflow channels for fast cooldown refrigerators before they are etched and laminated to other etched plates.

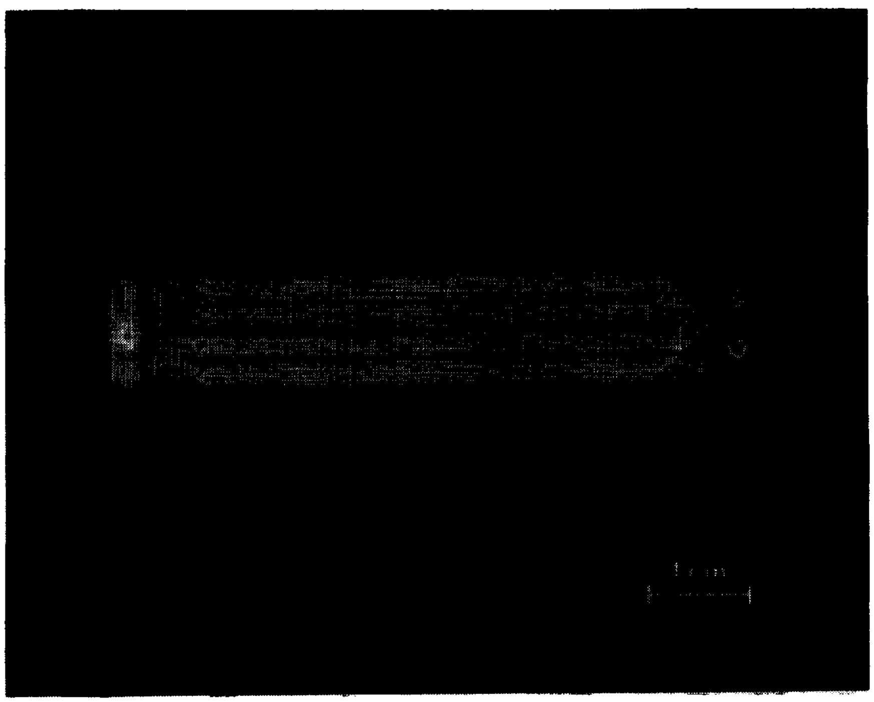

Figure 3. Original laminar flow glass Joule-Thompson refrigerator showing high pressure inflow channels, capillary, boiler and low pressure return.

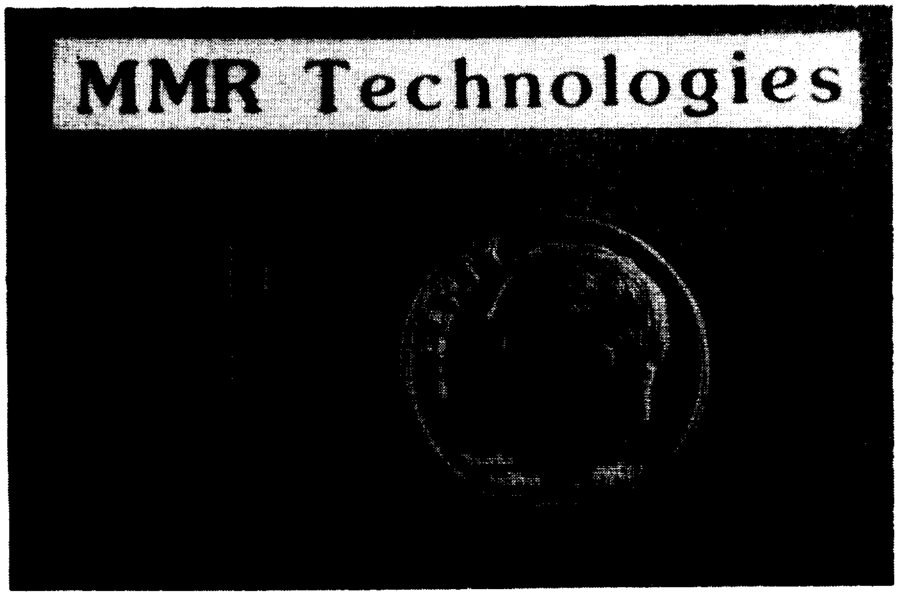

Figure 4. Inflow slide for low flowrate Microminiature Refrigerator.

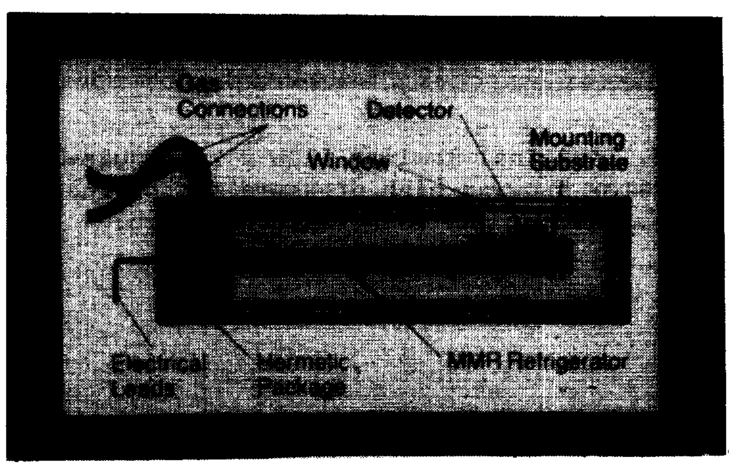

Figure 5. Possible package configuration for low flowrate model.

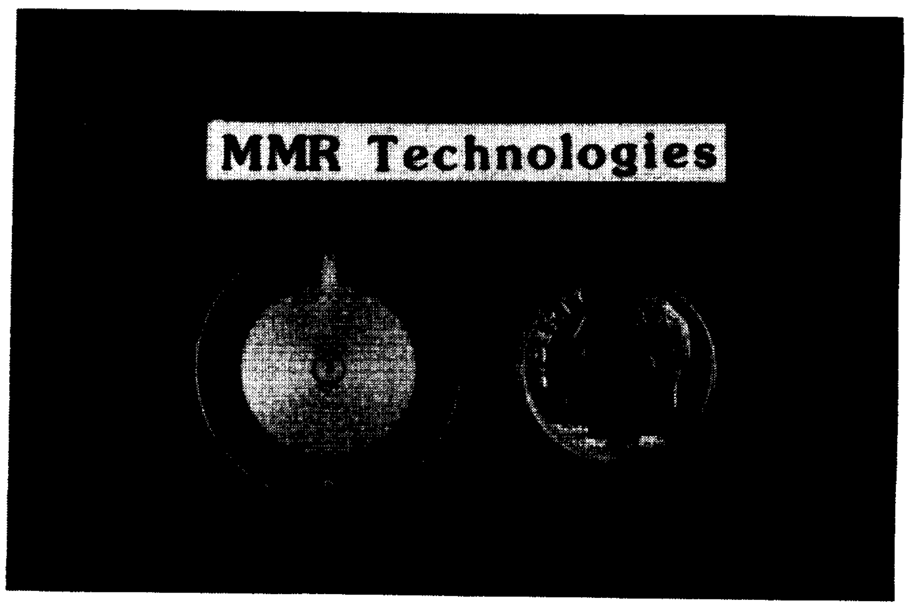

Figure 6. Fast cooldown Microminiature Refrigerator which cools in its center with heat exchange occurring radially outward.

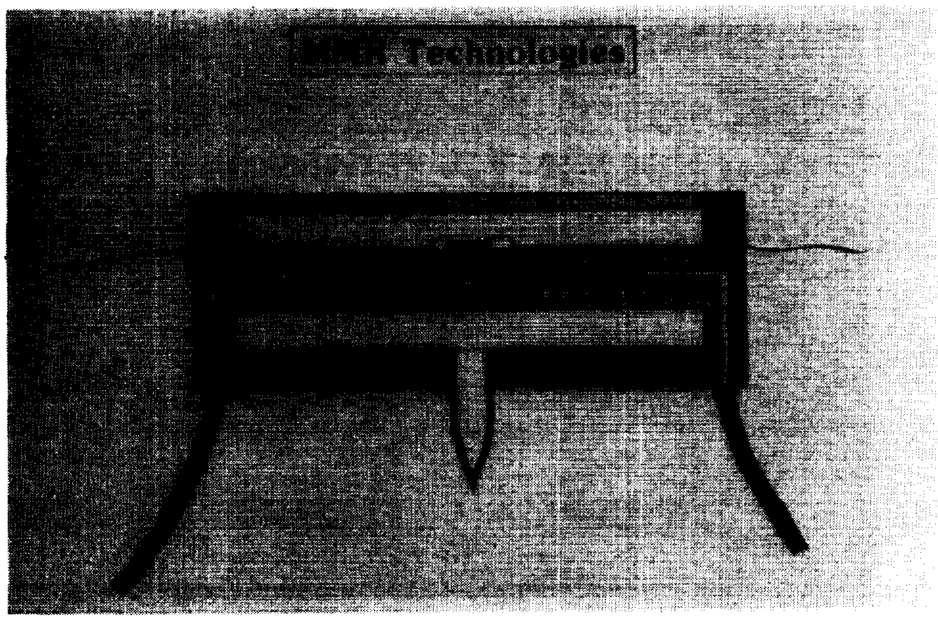

Figure 7. Possible package configuration for fast cooldown Microminiature Refrigerator with component being cooled mounted on the center cold spot and the electrical leads extending radially outward.

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