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AlN ceramic thermal guide for cooling a SQUID and its effect on thermal magnetic noise

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We evaluated the thermal conductivity of AlN ceramic plates as a potential material of a thermal guide for cooling SQUID in cryocooler cooled SQUID systems. We found that the AlN ceramic plate does not show a good thermal conductivity at very low temperature. We tried to enhance its thermal conductivity by attaching a lot of thin insulated copper wires in parallel with each other to cover a back plane of the plate. With this enhancement we succeeded to operate a double relaxation oscillation SQUID (DROS) first-order gradiometer. Comparison of measurement results on white noise level between two cases where DROS was attached to a copper plate thermal guide and where it was attached to a modified AlN thermal guide shows almost 5 time reduction in noise floor with the latter plate.

Key words: *Thermal magnetic noise, Magnetic measurements, SQUIDs*

1. Introduction

Superconducting quantum interference devices (SQUIDs) are used to measure magnetocardiogram (MCG) and magnetoencephalogram (MEG), which are used to diagnose heart diseases and map brain functions. One of prerequisites for the operation of SQUIDs is the low temperature sources that usually obtained with liquid helium. Closed cycle cryocoolers are potential low temperature sources for SQUID systems. If use of such cryocoolers for cooling SQUIDs becomes possible, costs for liquid helium and its handling will be eliminated. The most critical issue for use of such systems for cooling SQUIDs is an impact of the cooler noise on the operation of the SQUID system [1,2]. Among the several types of cryocoolers available, the pulse tube cryocooler (PT) is more stable than the other types such as Gifford-McMahon (GM) cryocooler [3], in respect of physical vibrations and magnetic noise, because, unlike the GM cryocooler, the PT cryocooler has no moving part in the cold stage. Therefore we used a two-stage PT cryocooler in our investigation.

In cryocooled LTS-SQUID systems, copper sensor holder could be used as a thermal guide, but white noise level due to the thermal magnetic noise is high [4]. Therefore finding insulating materials with high thermal conductivity at very low temperatures is of great importance. AlN ceramic is an insulating material that shows good thermal conductivity at the room temperature. Its thermal conductivity at the room temperature is nearly half of that of the copper. We examined the thermal conductivity of AlN ceramic as a potential material for the thermal guide in a cryocooler cooled SQUID systems. We found out that the AlN doesn't show very good thermal conductivity at very low temperature, therefore by implementing thin copper wires on one surface of the AlN thermal guide, we tried to enhance its thermal conductivity and succeeded to operate it. Finally we compared the noise floor of the DROS attached to AlN thermal guide and copper thermal guide and show that by using AlN the noise floor could be reduced by a factor of 5.

2. Experimental Setup

For examining the thermal conductivity of AlN, an AlN thin rectangular plate was prepared with dimensions of 3 mm in thickness, 12 cm in length and 4 cm in width. A thick L-shape copper plate attachment was used to fix the AlN thermal guide to the second cold head of our two-stage pulse tube cryocooler.

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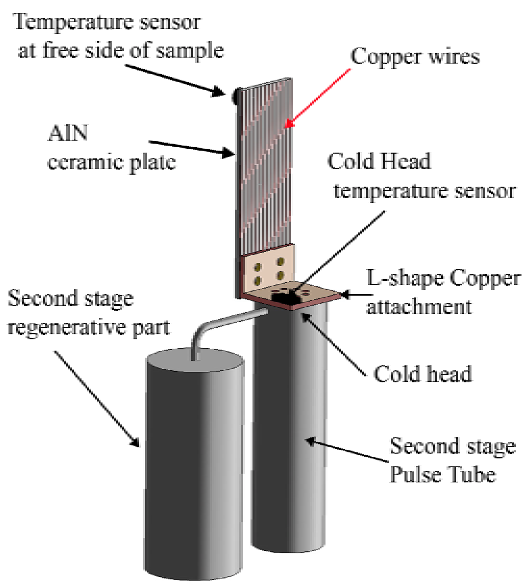
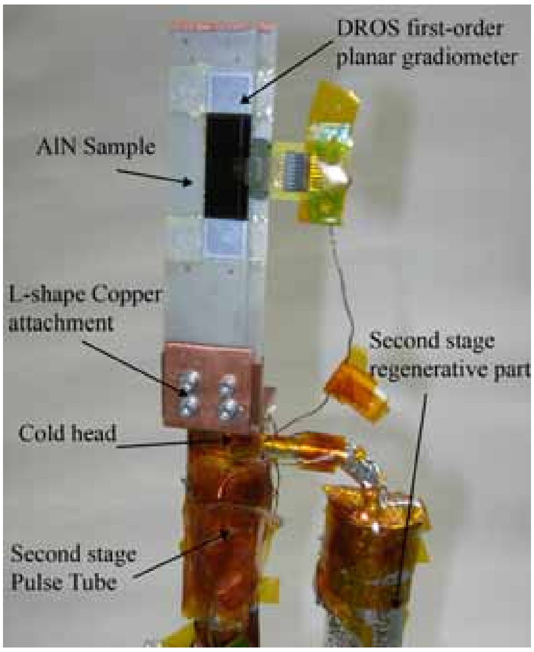


(a)



(b)

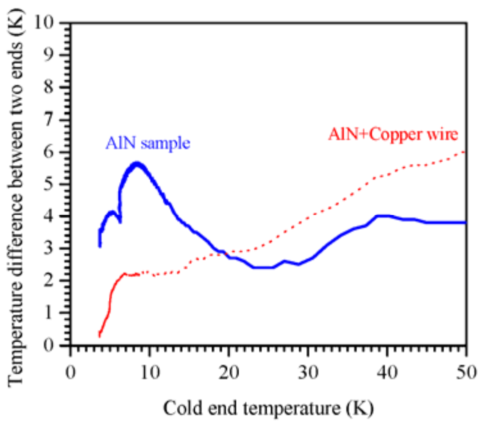
Fig.1 (a) Schematic of the experimental setup including PT cold head, L-shape copper stage, AlN sample and temperature sensors. (b) Photograph of the experimental setup.

Apiezon-N grease was used between AlN thermal guide and the L-shaped copper attachment. The temperature of the L-shaped copper attachment, which was attached to the cold head, was measured with a Pt-Co temperature sensor. The temperature of the free end of the AlN thermal guide was measured with a germanium temperature sensor which was attached to the AlN thermal guide with bolt and Apiezon-N grease. Output from both of the temperature sensors were acquired automatically with a DAQ board every 16 seconds. The experimental setup is shown schematically in Fig. 1(a). Fig. 1(b) is the photograph of the AlN ceramic plate attached to the L-shaped copper at Pulse Tube cold head.

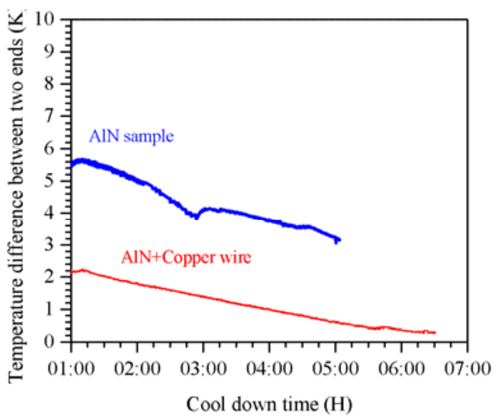
The SQUID used in our experiment was double relaxation oscillation SQUID (DROS). The pickup coil was a first-order planar gradiometer with two sets of square coils connected in series, and the baseline was 40 mm [10].

3. Result and Discussion

Results of the temperature measurement are shown in Figs. 2(a). In Fig. 2(a) the temperature difference between the colder end which is connected to the L-shaped copper attachment and the free end of the AlN thermal guide is plotted for the cold head temperature (solid line). As it is visible in this graph the free end of the AlN thermal guide in the best case is about 2 K warmer than the other end



(a)



(b)

Fig.2 (a) Temperature difference between the cold end of the AlN thermal guide and its free end (solid line). (b) same quantity for copper wire decorated AlN thermal guide (dotted line).

where the temperature of the cold end is 3.5 K, whereas when our cryocooler cold head reaches 3.5 K, the AlN thermal guide's warm end cannot reach the desired temperature for operating LTS SQUIDs which is 4.2K.

In order to enhance the cooling capability of the AlN thermal guide, 30 percent of one side of the AlN thermal guide was covered with a bundle of 0.1 mm thick insulated copper wires placed in a single layer. Because adjacent copper wires do not have electrical contact, electrons in the wires fluctuate only one dimensionally, hence, based on the Ref. [4,5] the thermal magnetic noise may be much lower than that observed with a thick copper thermal guide used as a SQUID holder. Photograph of both sides of the AlN ceramic plate is shown in Fig. 3. The temperature of the free end of the AlN thermal guide with the copper wire decoration has successfully reached 4 K about 1 hour after the cold head had maintained at 3.75 K. The result of examination of the thermal conductivity of this AlN thermal guide is shown in Figs. 2(b).

For operating DROS inside the cryostat, interfering high frequency current noises conducted through flexible hoses from an inverter driving the valve motor to the cryostat should be reduced. The detailed arrangement that we used for reducing the high frequency noise is described elsewhere [6]. The two stage pulse tube cryocooler contains magnetic regenerative materials such as Er_3Ni and $HoCu_2$ in its second stage regenerator section. Use of these materials is necessary for reaching the liquid helium temperature (4 K) in such cryocoolers. In our previous research, we found out that the temperature variation of these materials caused by helium gas excursion in the presence of background magnetic field produce low frequency magnetic interference to the SQUID attached to cold head [1]. We used superconducting lead shielding over the section containing magnetic regenerative materials and reduced the low frequency interference to the SQUID by a factor of 100. The cryostat was set in a cylindrical magnetic shield developed in our laboratory whose transverse shielding factor for a low-frequency time-varying magnetic field was as large as 40,000 when the magnetic shaking enhancement was on, whereas it was 140 along its axis [11]. After employing aforementioned methods for reducing high frequency EMI and low frequency magnetic interference, we measured the magnetic field by the DROS first-order gradiometer cooled by the pulse tube cryocooler attached to a copper thermal guide and on wire decorated AlN thermal guide. Results of these measurements are shown in Figs. 4 and 5.

Fig. 4 is the magnetic field spectrum while cryocooler is operating. From this graph it could be understood that by using AlN holder instead of copper holder the noise floor at 200 Hz reduces from about 500 fT/√Hz to less than 100 fT/√Hz. For evaluating the effect of using AlN thermal guide on noise floor at lower frequencies we measured the magnetic field by turning off the cryocooler. After turning off the cryocooler the SQUID could be operated for few minutes. To see the system noise without interference of cryocooler noise we quit the cryocooler. Result of this measurement is shown in Fig. 5 for the SQUID attached to AlN thermal guide and copper thermal guide.

One can see that using AlN reduces noise from 1 pT/√Hz to less than 300 fT√Hz at 10 Hz. Noise floor at 200 Hz with copper thermal guide is 500 fT√Hz, while it is less than 100 fT/√Hz with AlN thermal guide. Roughly speaking implementing AlN results in almost

Fig.3 AlN ceramic plate with copper wire attached to one side.

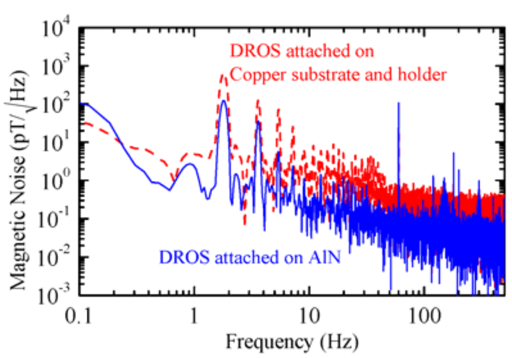


Fig.4 Noise floor comparison between DROS attached to a copper thermal guide (dashed line) and to that of AlN (solid line) while cryocooler operating.

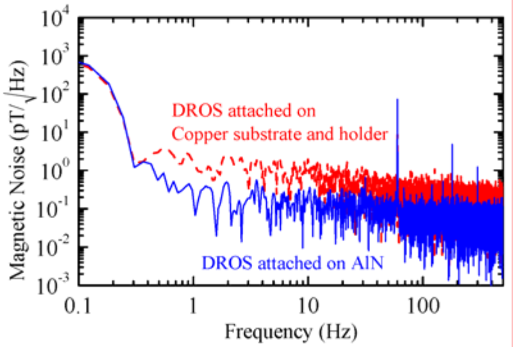


Fig.5 Noise floor comparison between DROS attached to a copper thermal guide (dashed line) and to that of AlN (solid line) while cryocooler is turned off.

5 times reduction in noise floor compared to the case with a copper plate. Magnetic noise level measured with DROS operated in liquid helium in a magnetically shielded room (MSR) at 200 Hz is around 6 fT/√Hz [9]. Therefore the noise floor in magnetic field measurement by DROS operated in PT cryocooler is 20 times higher than that operated in liquid helium in a MSR. One factor could be the existence of metallic parts such as bolts and thermal shield made of aluminum plate at first stage. Another factor could be the difference between the shielding factor of our cylindrical shield and MSR used in Ref. [9] and also difference between magnetic environments of two experiments. Therefore by exchanging conducting parts of PT cold head with proper insulating parts and improving the shield the noise floor could be reduced further.

4. Conclusion

We observed that the temperature of the free end of the AlN thermal guide hardly fell below 7 K even one hour after the cold head had reached 3.75 K. So we conclude that this material by itself cannot cool LTS SQUID sensors to operate. The cooling capability of the AlN thermal guide was enhanced by covering almost 30 percent of one side of it with 0.1 mm diameter insulating coated copper wires place longitudinally. The free end of AlN thermal guide successfully cooled down to 4 K. Therefore this material with the aforementioned improvement could be used as a thermal guide to cool SQUIDs. DROS first-order planar gradiometer successfully operated by implementing AlN ceramic plate as a thermal guide in two-stage PT cryocooler. The measurement results show that replacing copper thermal guide by modified AlN reduced the noise floor from 500 fT√Hz to less than 100 fT√Hz at 200Hz. Roughly speaking noise floor of a DROS gradiometer mounted on the AlN ceramic plate enhanced with copper wires becomes almost 5 times smaller than that of a DROS mounted on a copper plate.

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