Cooling of electrically insulated high voltage electrodes down to 30 mK

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AEgIS [1] is an antimatter experiment, using high voltage electrodes at 100 mK. In this work two possible principles to cool these electrodes with a dilution refrigerator are described: the Rod and the Sandwich. The metallic Rod is electrically insulated by a ceramic and connects a single electrode directly with a heat exchanger placed in the mixing chamber. The Sandwich consists of an electrically insulating sapphire plate, at both sides covered with indium. The total thermal resistivities of the Rod and of different Sandwich samples are measured between (30 and 130) mK. The lowest resistivity of the Sandwich is achieved with indium vapour deposited on polished sapphire (26 cm^2K^4/W at 30 mK). The resistivity of the Rod is significantly lower (0.5 cm^2K^4/W at 30 mK).

INTRODUCTION

In the AEgIS experiment [1] a Penning trap is formed by several high voltage electrodes, which have to be cooled down to 100 mK. This temperature level of the electrodes requires an excellent thermal contact between the electrodes and the cooling source. The standard cooling source for temperatures between 800 mK and 5 mK is a dilution refrigerator.

High voltage electrodes of a Penning trap are charged with time depending voltages up to several kilovolt, and have to be individually electrically insulated. The electrical insulation implies a very poor thermal contact, depending on the thermal conductivity of the bulk materials and on the usually dominant thermal boundary resistances. The thermal boundary resistance R_{TB} determines the transferable heat $\dot{Q}$ for a given temperature difference ΔT:

$$\dot{Q} = \frac{1}{R_{TB}} \Delta T \, . \tag{1}$$

The thermal boundary resistance increases significantly with decreasing temperature. For small temperature differences R_{TB} is inversely proportional to the heat transfer cross section A and the temperature T [2]:

$$R_{TB} \sim \frac{1}{AT^{C}} . \tag{2}$$

The constant C is determined by the dominant heat carriers, which are either phonons or electrons. C equals to 3 for interfaces where the heat is transferred via phonons, e.g. a contact to a dielectric surface. For contacts with a low electrical resistance, for instance between metals with clean surfaces, the electrons dominate the heat transfer and C is equal to 1. The two investigated designs rely on the described heat transfer mechanism.

The thermal anchoring between the electrodes and the mixing chamber of the dilution refrigerator has to be designed, taking the experimental conditions into account. The investigated designs consider the following environmental conditions and arising requirements:

- The particle radiation requires radiation hard materials. This constraint excludes the usage of most glues;
- In case of the presence of a homogeneous magnetic field, only non or low-magnetic materials should be considered in order to preserve the field homogeneity. Standard brazing techniques should not be applied due to the high content of nickel in the brazing agent. Nickel has a very high magnetic susceptibility and could influence the homogeneity;
- Ultra High Vacuum (UHV) reduces the annihilation of antimatter and diminishes the heat load due to conduction in the residual gas. Only low outgassing materials and reliable, leak tight joints guarantee UHV conditions;
- Joining processes using high temperatures might be critical, because fragile feedthroughs and joints could be damaged. Only local heating, as it is in the case of electron beam welding, should be considered.

EXPERIMENTAL SETUP

The experimental setup of the Rod and the Sandwich design, integrated in the mixing chamber lid of a dilution refrigerator, is shown in Figure 1. The Rod, made of Oxygen Free High Conductivity (OFHC) copper, connects a single electrode directly with the heat exchanger, located inside the mixing chamber. The Rod passes through a sintered Al_2O_3-ceramic, electrically insulating it from the mixing chamber lid. The helium inside the mixing chamber electrically insulates the Rod and the connected heat exchanger from the mixing chamber. One of the challenges of this design is the leak tight connection between the Rod and the ceramic, since standard brazing techniques cannot be applied. Two copper rings are butt brazed in vacuum to the ceramic. Silver is used as an agent for this active brazing technique. The two rings are electron beam welded to the Rod and to the mixing chamber lid. The soft copper rings allow some flexibility and compensate the different thermal expansions of the copper and the polycrystalline Al_2O_3. The reliability and robustness of the Rod design is proved by several fast thermal cycles down to 80 K with cooling rates of approximately 2 K/s.

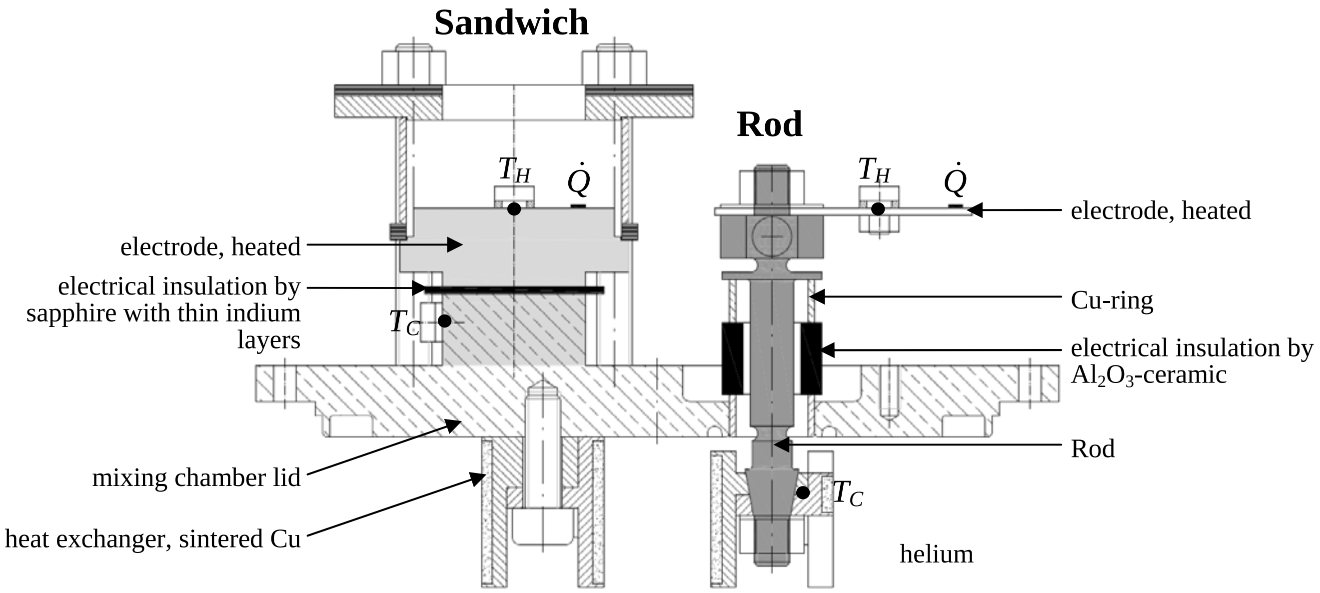

Figure 1 Sandwich and Rod design with the positions of heaters and temperature sensors.

The Sandwich design applies a different technology. The electrical insulation of the Sandwich is achieved by a monocrystalline sapphire plate, which is pressed between the electrode and the mixing chamber lid. In order to increase the thermal contact conductance, the sapphire is covered with a layer of ductile indium. The Sandwich is pressed for several days at room temperature with approximately twice the yield strength of indium. This allows the indium to creep and to wet the sapphire surfaces. During the measurements at cold a pressing force is maintained by springs to keep the Sandwich parts in contact. Nevertheless Salerno et al. [3] found the thermal conductance of pressed contacts augmented with indium does not depend critically upon the pressing force in the very low temperature range.

Indium at zero magnetic field has a superconducting transition temperature at 3.41 K. The superconducting state is characterised by a very poor thermal conduction. For this reason a magnetic field is applied to destroy the superconductivity of indium. The transition from superconducting to normal state was observed during the measurements by a reduced temperature gradient. Four different Sandwich cases are investigated. Their main characteristics are summarized in Table 1.

Table 1 Characteristics of different Sandwich cases.

Case of Sandwich	**Sapphire dimensions** (mm x mm)	**Sapphire roughness** R_a (nm)	**Indium thickness** (μm)
A	Ø 20 x 1.5	2.6 (polished)	250 (foil)
B	Ø 20 x 1.5	370 (rough)	250 (foil)
C	Ø 20 x 1.5	2.6 (polished)	3 (vapour deposited), 125 (foil)
D	Ø 20 x 1.5	370 (rough)	3 (vapour deposited), 125 (foil)

The sapphire plates feature either rough or polished surfaces. Their surface roughness was investigated with a vertical scanning interferometer. The samples have a purity of 99.99 %. An indium layer of roughly 3 μm thickness is vapour deposited on the sapphire samples C and D.

Both designs are thermally anchored to the helium in the mixing chamber by heat exchangers, as shown in Figure 1. The heat exchangers [4] are based on sintered copper structures which improves the heat exchange cross section in order to reduce the influence of the high thermal boundary resistance between the metal surfaces and the helium (Kapitza resistance [5]).

The electrodes are made of annealed OFHC copper to assure minor temperature gradients. In order to perform precise measurements, a parasitic heat flow bypassing the Sandwich or the Rod has to be avoided. The clamping arrangement of the Sandwich is therefore thermally insulated by twenty G10 plates (fibreglass with epoxy resin, 0.2 mm thickness). The large number of thermal boundaries between the G10 plates reduces the heat leak efficiently. The Rod is thermally insulated from the mixing chamber lid by the Al_2O_3-ceramic.

The measurement procedure is identical for all cases presented. The electrodes are supplied with a static heat load. During the measurements the helium temperature inside the mixing chamber is kept constant at (30, 50 or 70) mK. Resistance thermometers of the RuO_2 type, calibrated against a reference thermometer from Lake Shore Cryotronics Inc., are used. Their positions are shown in Figure 1.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to compare the performance of the Sandwich cases A to C and the Rod design, the total thermal resistivity $R_T T^3 A$ is plotted in Figure 2 versus T_H. The resistivity is calculated using [2]:

$$R_T T^3 A = \frac{A(T_H{}^4 - T_C{}^4)}{4\dot{Q}} \tag{3}$$

with A as the heat transfer cross section of the Sandwich or the surface occupied by the Rod design, T_H the temperature of the heated electrode, T_C the cold temperature of the Sandwich or the cold temperature of the heat exchanger for the Rod design and $\dot{Q}$ the transferred heat load .

As can be seen in Figure 2, the total thermal resistivities of the four Sandwich cases differ considerably and the following trends can be observed:

1) A rougher sapphire surface increases the thermal boundary resistance, which is in contradiction to the results of Schmidt and Umlauf [6]. They compared a polished surface with a 7 μm rough surface at temperatures > 1 K. They explained the reduced resistance for the rough surface by the increased contact surface. The now observed discrepant behaviour can be explained by a worse contact between the indium and the rough sapphire, a damage of the sapphire near the surface or phonon scattering effects as described by Swartz and Pohl [7].

2) A good contact between indium and sapphire is essential to reach low thermal boundary resistances, especially for rough sapphire surfaces. Covering the sapphire on both sides only with an indium foil and applying a pressing force does not seem to produce these good interfaces. In order to improve the interfaces, indium is vapour deposited on the sapphire. Ultrasonic soldering of indium was not applied, since the sapphire surface is found to be fissured due to the process [6].

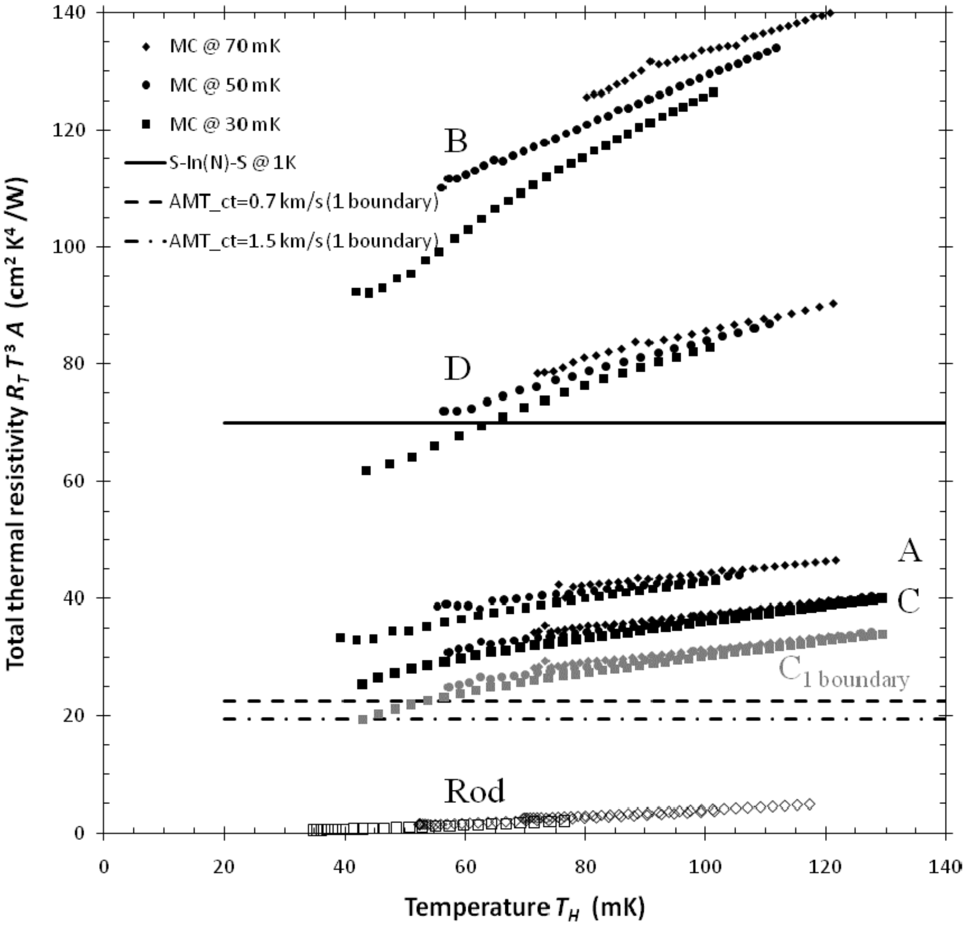

Figure 2 The total thermal resistivity for different Sandwich cases (see Table 1) and for the Rod. Furthermore a value for a Sandwich of sapphire-indium (normal state)-sapphire at 1 K and the thermal boundary resistivity of the Acoustic Mismatch Theory (AMT) between sapphire and indium, depending on the two different transverse sound velocities of indium [6], are shown.

3) The measurements suggest that the total thermal resistance depends on $1/T^C$ with C ranging between 2.6 and 2.7 for all investigated Sandwich cases. This temperature dependency is slightly better compared to previous experiments, where $C \approx 2.5$ was found [7]. The theoretical prediction for the Sandwich is $C = 3$.

4) The Sandwiches with polished sapphire have significantly lower total resistivities, ranging from (26 to 45) cm^{2}K^4/W for temperatures between (30 and 100) mK, respectively, compared to a sapphire-indium (normal state)-sapphire Sandwich with 70 cm^{2}K^4/W at 1 K [6].

5) In the presented Sandwich cases the total thermal resistance R_T consists of two thermal boundary resistances R_{TB} (indium-sapphire-indium) and the thermal resistances of the materials. Therefore the measured R_T cannot be simply compared with the theoretical R_{TB} of the Acoustic Mismatch Theory (AMT) which is applicable only for one boundary. Challis and Sherlock [8] found $R_T < 2\,R_{TB}$ for conduction dominated by phonons with large mean free paths compared to the distance between the boundaries, as it is for the sapphire at low temperatures. Hence the thermal boundary resistivity in Figure 2 is calculated, assuming that only one boundary has to be taken into account, namely where phonons impinge on the sapphire, and considering the thermal resistance of sapphire. The so calculated boundary resistivity for the Sandwich case C, shown as $C_{1\text{boundary}}$, is at low temperatures in good agreement with the

absolute values of the acoustic mismatch theory. The AMT values for an indium-sapphire interface are taken from [6] and the thermal conductivity of sapphire from [9].

6) The Rod design has a much lower total thermal resistivity than the best Sandwich case. The resistivity ranges between (0.5 and 5) $\mathrm{cm}^2\mathrm{K}^4/\mathrm{W}$ for the presented measurements. The total thermal resistance depends on $1/T^{1}$, which agrees well with the theory of the electron dominated heat transfer.

CONCLUSION

Sandwich and Rod are technically valid designs for the AEgIS experiment. The Rod has the advantage to transfer significantly more heat than the Sandwich for the same temperature difference.

For the Sandwich design an optimized contact of indium to the sapphire is essential, to achieve low thermal resistances. The contact to the sapphire is improved by indium vapour depositing.

The total thermal resistance of Sandwiches made with polished sapphire show a temperature dependence of approximately $1/T^{2.7}$ and are significantly lower than data found in literature. The calculated thermal boundary resistivity of the Sandwich agrees at low temperatures well with the absolute values of the acoustic mismatch theory.

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