Cooling of electrically insulated high voltage electrodes down to 30 mK–Dynamic measurements

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Abstract

AEgIS [1] is an antimatter experiment, using high voltage electrodes at 100 mK. Two possible principles to cool these electrodes with a dilution refrigerator are investigated: the Rod and the Sandwich. Both designs are described in detail in [2]. The Sandwich design is discussed in the present work. It consists of an electrically insulating sapphire plate covered with indium on both sides. Dynamic measurements are performed in order to estimate the influence of time depending heat loads on different Sandwich designs. From these data the Sandwich's thermal diffusivity is derived and compared to previous measurements using a static heat load.

The lowest resistivity of the Sandwich is achieved with an indium vapor deposition onto polished sapphire (26 cm^2K^4/W at 30 mK). The same sandwich shows the best, i.e. highest thermal diffusivity (0.23 mm^2/s at 70 mK). However, the results of the static and the dynamic measurements show some interesting and contrary tendencies.

Keywords:

dynamic measurements, electrical insulator, high voltage, Kapitza resistance, thermal diffusivity

1 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 only continuously operating 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. In a previous work [2] two possible principles to cool the electrodes were investigated: a metallic Rod and the Sandwich. The heat transfer of the Rod design is dominated by electrons, but also phonons are present, whereas the heat is transferred over the Sandwich by phonons only. Both designs and their thermal performance for applied static heat loads are discussed in [2]. In the present work the Sandwich design is considered only.

In many practical applications the heat load can often be split in two fractions of which one is constant over time and the other is time depending. This is as well the case for the electrodes of the Penning trap. The intermittent heat loads are caused by the pulsed creation and annihilation of antimatter. The question arises: How can the Sandwich design be optimized, in order to transfer the heat load as fast as possible towards the mixing chamber of the dilution refrigerator? The property determining this temperature propagation is in the present report referred to as the Sandwich's thermal diffusivity α^*, analog to the thermal diffusivity α of a homogeneous material.

In a material a given variation in temperature over time at one place will propagate through it causing an altered variation of temperature at any other place with a certain delay. The material property thermal diffusivity is calculated by dividing the thermal conductivity λ by the volumetric heat capacity [3]. The volumetric heat capacity is in this case described by the bulk density ρ and the specific heat capacity c:

$$\alpha = \frac{\lambda}{\rho \cdot c}. \qquad (1)$$

If a material has a low thermal conductivity and a high specific heat, hence a low thermal diffusivity, the temperature variation alters stronger and the delay is greater for a fixed propagation length. In the investigated temperature range the thermal diffusivity is ideally constant for pure materials. It amounts to about 1 m^2/s for copper and 2 m^2/s for sapphire[1].

Considering only the bulk of copper or sapphire the Sandwich's thermal conductivity α^* should thus be approximately constant. The thermal boundary resistance is however significant and reduces the Sandwich's thermal diffusivity considerably. Thermal measurements are therefore performed in order to derive the influence of the boundary resistance on the thermal diffusivity α^* to be able to find an optimized Sandwich design.

2 Experimental setup

The experimental setup of the Sandwich design, integrated in the lid of the mixing chamber of a dilution refrigerator, is shown in Figure 1. The electrical insulation of the Sandwich is achieved by a monocrystalline sapphire plate, pressed between the electrode and the mixing chamber lid. In order to increase the thermal contact conductance the sapphire is covered with layers 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. [4] found that the thermal conductance of pressed contacts covered with indium does not depend critically upon the pressing force in the very low temperature range.

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[1] The thermal diffusivity is calculated with values taken from [5, 6] and [7, 8] for copper and sapphire, respectively. The sapphire values are taken at 1 K.

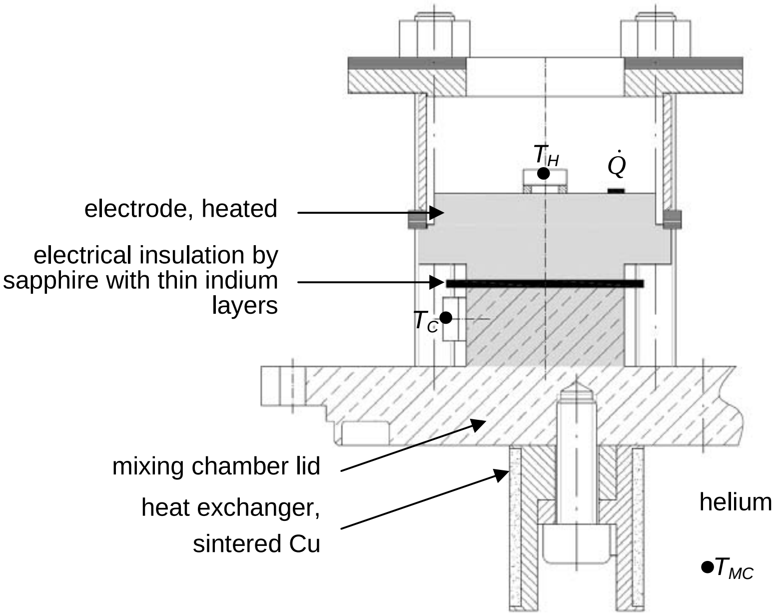

Figure 1: Sandwich design with the positions of the heater and the temperature sensors.

Indium at zero magnetic field has a superconducting transition temperature at 3.41 K. The superconducting state is characterized by a very poor thermal conduction. For this reason a magnetic field is applied to overcome 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.

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 vapor deposited on the sapphire samples C and D.

The electrodes are made of annealed OFHC copper to assure minor temperature gradients. In order to perform precise measurements, parasitic heat flows bypassing the Sandwich have 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 measurement procedure is identical for all cases presented. Analog to the sinusoidal heat wave [9], the electrode is supplied with a square heat wave having periods of 30, 40 or 60 seconds. During the measurements the helium temperature inside the mixing chamber is kept constant at either 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.

Table 1: Characteristics of different Sandwich cases.

Case of Sandwich	**Sapphire dimensions (mm x mm)**	**Sapphire roughness Ra (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 (vapor deposited), 125 (foil)
D	Ø 20 x 1.5	370 (rough)	3 (vapor deposited), 125 (foil)

3 Simulation of the Sandwich's thermal diffusivity

The heat propagation can be measured with different methods. Most common are the investigations of single heat pulses or sinusoidal heat waves. Both methods are convenient, since rather simple analytical equations can be derived from the Fourier's law [9], considering a one-dimensional propagation. There are several reasons, why these simple equations cannot be applied for the Sandwich.

- The temperature variation does not freely propagate in space, but is stopped by the fixed temperature in the mixing chamber.
- The temperatures on both sides of the Sandwich show a different average temperature.
- The resulting wave form differs considerably from a sinusoidal wave.

The Sandwich's diffusivity is thus simulated with the function *pdepe* provided by MATLAB®. The simulation uses following assumptions. The Sandwich is modeled as a one-dimensional homogeneous "rod". The rod's length is the thickness of the sapphire x_S plus a thermalization length x_{th}. The assumption of x_S implies the negligence of the metallic material due to its high thermal diffusivity. This approach is confirmed by the derived results.

The following Initial Conditions (IC) and Boundary Conditions (BC) are used for the simulation:

- IC: The homogeneous Sandwich temperature before heat application is equal to the measured helium temperature, see Figure 1: $T_H(t) = T_C(t) = T_{MC}$ at $t = 0$,
- BC: The top of the Sandwich has the measured temperature when the quasi-static state is reached: $T_H(t) = T_{H,meas}(t)$,
- BC: The end of the simulated rod has the measured helium temperature: $T_{MC} = T_{MC,meas}$.

The simulated temperature below the Sandwich $T_{C,sim}$ is the value to compare with the measured one $T_{C,meas}$. Its average value is optimized by changing the thermalization length. Its phase shift with respect to $T_{H,meas}(t)$ is optimized by varying the Sandwich's thermal diffusivity.

4 Experimental results and discussion

The simulated Sandwich's thermal diffusivity is only valid for the specific Sandwiches described in Table 1. The derived values of α^* versus the cold temperature of the Sandwich are depicted in Figure 2. The simulated diffusivity of the Sandwich is more than 6 orders of magnitude smaller than the thermal diffusivity of the copper or sapphire bulk. The significant influence of the thermal boundary resistances at the sapphire interfaces on α^* is obvious. The diffusivity reduces with diminishing temperature.

Furthermore the results can be distinguished for the Sandwich samples A, B and C, D. Apparently the indium vapor deposition onto the sapphire plates improves the contact significantly. The diffusivity is up to 2 times higher compared to the Sandwich samples applying indium foils only. The influence of the sapphire surface roughness is visible. It is stronger for the non-deposited samples and only minor for the indium deposited samples. Therewith the sapphire roughness is secondary. However, this behavior is contrary comparing the results of the measurements with a static heat load [2]. The static measurements showed a significantly higher Sandwich's thermal resistance for rough sapphire surfaces. The indium deposition onto sapphire reduced the resistance, but only minor. So the sapphire roughness is of greater importance for a static heat transfer. Therefore it can be concluded that different heat transfer mechanisms dominate the static and the dynamic measurements.

The diffusivity is rather independent on the applied period times. There is only one exception for the Sandwich samples applying indium deposited sapphire plates. The diffusivity at 30 mK increases by a about a factor of 2 if the period time is halved. Unfortunately the data are too few, in order to give a reliable conclusion. Measurements with shorter periods could give evidence, but are not of importance for AEgIS. Nevertheless, this observation shows the complexity of phonon transport and scattering processes, which depend on many conditions like the phonon wave length, i.e. temperature, surface interfaces, surface roughness, materials, material purity etc. [10].

The error of the simulated thermal diffusivity is not estimated, since there are many uncertainties. These uncertainties are not only in the simulation, but also in the measurements. The derived values give nevertheless guidelines for an optimized Sandwich design.

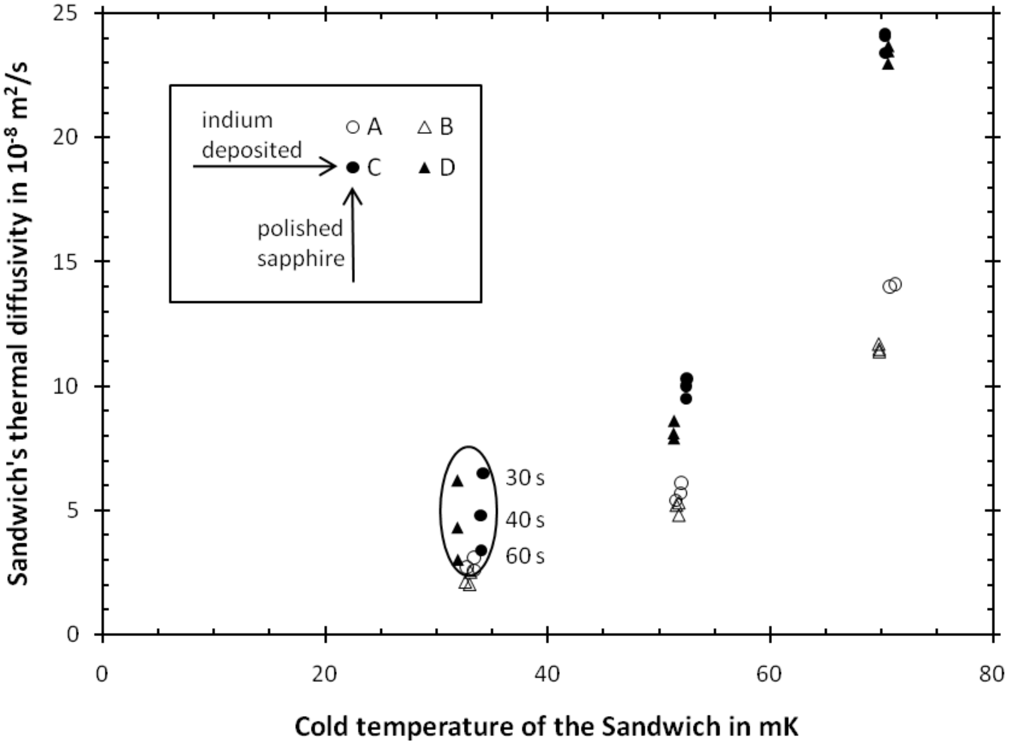

Figure 2: Shown is the simulated Sandwich's thermal diffusivity versus the cold temperature of the Sandwich. The samples are described in Table 1. A significant dependency on the period time is observed at low temperatures for the Sandwich samples with indium deposited sapphire plates. The periods are either 30, 40 or 60 seconds.

5 Conclusion

The thermal diffusivity is a property indicating how fast a given temperature variation will propagate through a material. Analog to this material property a Sandwich's thermal diffusivity of four different Sandwich samples is derived by applying a square heat wave. The diffusivity is simulated using the resulting measured temperature variations as boundary condition.

The Sandwich samples equipped with indium deposited sapphire plates show the highest thermal diffusivity, i.e. fastest temperature propagation over the Sandwich. A slight improvement is achieved with polished sapphire surfaces. The Sandwich's diffusivity reduces with diminishing temperature and is more than 6 orders of magnitude smaller than the diffusivity of the used materials. The boundary resistances determine thus the Sandwich's diffusivity.

The derived diffusivity is rather independent of the applied periods, apart for the Sandwich samples applying indium deposited sapphire plates. The diffusivity at 30 mK increases by about a factor of 2 if the period time is halved.

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