

Heat transfer at a sapphire – indium interface in the 30 mK – 300 mK temperature range

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Abstract. Within the framework of the AEGIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) project a direct measurement of the Earth's gravitational acceleration on antihydrogen will be carried out. In order to obtain satisfactory precision of the measurement, the thermal movement of the particles should be reduced. Therefore a Penning trap, which is used to trap antiprotons and create antihydrogen, will be placed on a mixing chamber of an especially designed dilution refrigerator. The trap consists of 10 electrodes, which need to be electrically insulated, but thermally anchored. To ensure that the trap remains at a temperature below 100 mK, the heat transfer at the metallic-dielectric boundary is investigated. A copper – indium – sapphire – indium – copper sandwich setup was mounted on the CERN Cryolab dilution refrigerator. Keeping the mixing chamber at a constant low temperature in the range of 30 mK to 300 mK, steady-state measurements with indium in normal conducting and superconducting states have been performed. Obtained results along with a precise description of our setup are presented.

1. Introduction

The AEGIS - Antihydrogen Experiment: gravity, Interferometry, Spectroscopy, one of the CERN antimatter experiments, aims at measuring if the Earth's gravitational force on antihydrogen is the same as for a normal hydrogen [1]. In this experiment antihydrogen is created in a Penning trap from antiprotons and positronium excited by a laser. Antihydrogen particles are accelerated horizontally towards a detector, where they annihilate. Knowing the place where they annihilate and their time of flight, one can calculate the vertical acceleration. In order to measure it within 1% accuracy, antimatter particles must be kept in an environment cooled down below 100 mK to minimize their random thermal movement [1]. The electrical potential between the neighbouring electrodes of the Penning trap reaches 1 kV, which requires a proper electrical insulation. It is thus necessary to use a dielectric material, but keeping maximum possible heat conductivity of the interface to the heatsink. Therefore, the electrodes are made of sapphire covered with gold and they will be placed on a mixing chamber (MC) of a dilution refrigerator [2]. In this paper we present heat transfer measurements through a sandwich-like setup, which is simulating the dielectric sapphire electrode on a metallic mixing chamber in the temperature range of 30 mK to 300 mK. Similar measurements of a thermal boundary resistance in higher temperature ranges were performed before and are explained at the basis of the acoustic mismatch [3]. Neepner and Dillinger [4] focused on the indium-sapphire thermal resistance between 1.1 K and 2.1 K. Papk and Narahara [5]



discussed possible contributions to the heat transfer caused by the couplings of conduction electrons and surface waves. Peterson and Anderson [6] developed a theory describing the scattering of phonons not only at the interface itself but also in the material near the interface. Schmidt and Umlauf [7] investigated the influence of the surface quality on the Kapitza resistance [3].

2. Experimental setup

On a copper platform, which is the base of the setup, a 1 mm thick and 20 mm diameter sapphire disk is placed and it is pressed to the platform with a copper stamp. A 3 μm layer of indium was deposited on the polished top and bottom surface of the sapphire, and a 125 μm thick indium foil was placed between the sapphire and the copper on both sides (see figure 1). The setup was compressed with 2.5 kN force, applied by 4 bolts. In the second measurement run the force was released. Another set of 4 bolts M5 keeps the platform pressed to the lid of the mixing chamber, with a layer of 125 μm thick indium foil in between. Such design allows to dismount the setup from the mixing chamber and perform measurements at higher temperatures, keeping the sandwich at the same mechanical conditions. Below 3.4 K indium becomes superconducting [8] and changes its thermal conductivity. An outer magnetic field is used to switch indium from superconducting (SC) to normal conducting (NC) state, and compare its heat transferring performance in the setup. To avoid a bypassing heat flow from the stamp to the platform via the bolts, a series of 20 washers made of G10 is placed in the mounting structure. Except for the brass screws and spring washers, which are meant to keep the tensile force constant during and after the cool down, other elements of the structure are made of stainless steel, which has a very low thermal conductivity at ultra-low temperatures [9]. Two types of Ruthenium Oxide temperature sensors were used: a bare chip resistor on the stamp, and a LakeShore RX-102A-AA [10] on the platform. They were calibrated with use of a fixed point device SRD1000 [11] in the range 20 mK to 1.2 K with an accuracy ± 2 mK below 300 mK. Typical standard deviation of the stamp temperature measurement was around 0.04 mK at 30 mK, 0.07 mK at 100 mK and 0.15 mK at 200 mK. For the platform it was around 0.07 mK at 30 mK and decreased to 0.06 mK at 100 mK. The standard deviation of few singular measurement points exceeded 0.2 mK.

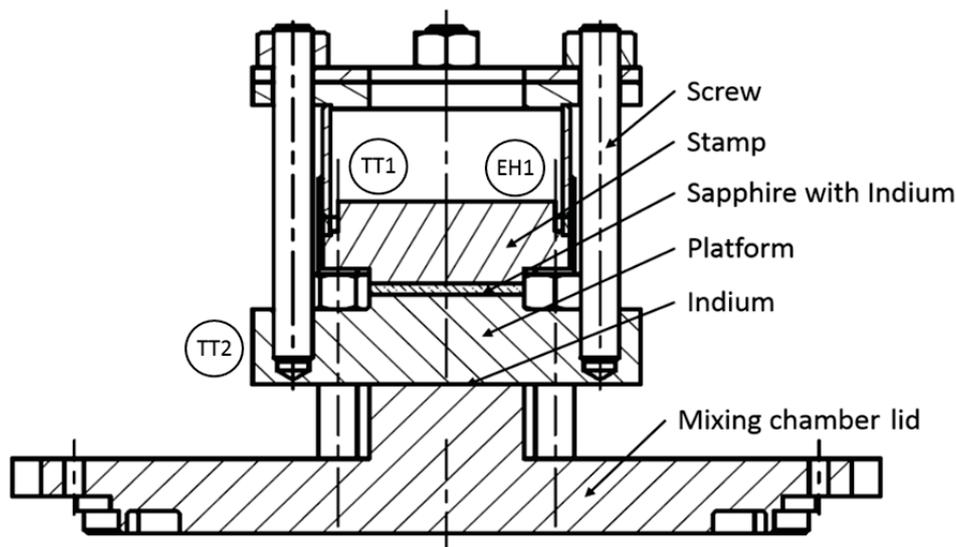


Figure 1. Sectional cut of the experimental setup. The copper stamp is heated by the electric heater (EH1) and the temperatures are recorded on the stamp and on the platform (TT1, TT2). The mixing chamber temperature is the base temperature of the experiment.

3. Steady-state measurements

During the steady-state measurements, the mixing chamber was kept at a constant temperature of 30 mK, 50 mK, 70 mK and 100 mK. For different heat loads on the stamp, the temperatures on the stamp and on the platform are recorded. Four configurations have been tested: the setup with and without compressing force, and for each case with and without magnetic field. The temperature increase depending on the applied heat load, for the case with compressing force and indium in a normal conducting state, is presented in figure 2. The difference between the stamp and the platform starts being visible from 10^{-2} μW heat load. For 30 mK base temperature the temperature of the platform increases from 2 μW , for 50 mK from 6 μW and for 70 mK from 11 μW . Without external magnetic field, indium becomes superconducting and introduces an additional thermal bottle neck, which is the layer of indium between the platform and the mixing chamber's lid. For this reason, as we can see in figure 3, the temperature of the platform starts rising already for lower power than in figure 2, and reaches higher values for high heat loads. It is worth noticing that above certain power ~ 20 μW , the final temperature of the platform is independent of the initial temperature. The same tendency is visible for the stamp at even lower powers.

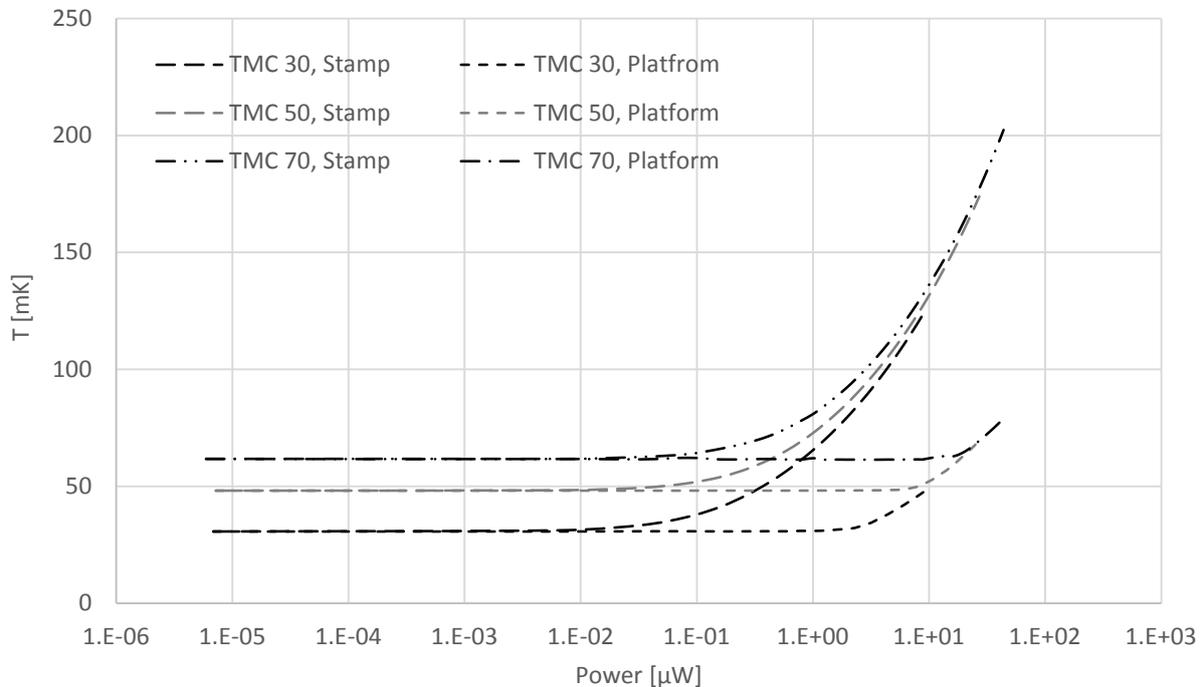


Figure 2. Temperatures of the stamp and the platform as a function of the heat load applied by the heater. The mixing chamber was kept at 30 mK, 50 mK and 70 mK. Force and magnetic field on (NC indium). “TMC 30” indicates the base temperature of the mixing chamber, eg. 30 mK. For visibility reasons the measurement points (~ 30 per line) are not shown.

Previous measurements done by T. Eisel [12] on a 1.5 mm thick sapphire disk showed, that for the MC base temperature at 50 mK and 1 μW of heat load, the temperature on the stamp raised to 89 mK, whereas in case of 1 mm disk it was 73 mK, which indicates a better heat transfer in 1 mm thick sapphire case compared to 1.5 mm. Results will be compared in figure 6 with resistivity values, which for metallic - dielectric interfaces are calculated, by analogy to the Kapitza resistance between copper and liquid helium according to the formula [13]:

$$R_{tot} = \frac{A}{4\dot{Q}} (T_{st}^4 - T_{pl}^4) \quad (1)$$

where A is the surface of the disk, \dot{Q} is the amount of heat deposited in the heater, T_{st} the temperature of the stamp and T_{pl} the temperature of the platform. One can see a clear dependency of the results on the presence of magnetic field with compressing force applied (figure 4). With indium in NC state thermal resistivity reaches low values of $7.3 \text{ cm}^2 \text{ K}^4 \text{ W}^{-1}$. The curves for lower base temperatures have a steeper slope than for higher base temperatures. Switching indium to SC state causes a significant increase of resistivity, with the lowest value of $26.4 \text{ cm}^2 \text{ K}^4 \text{ W}^{-1}$.

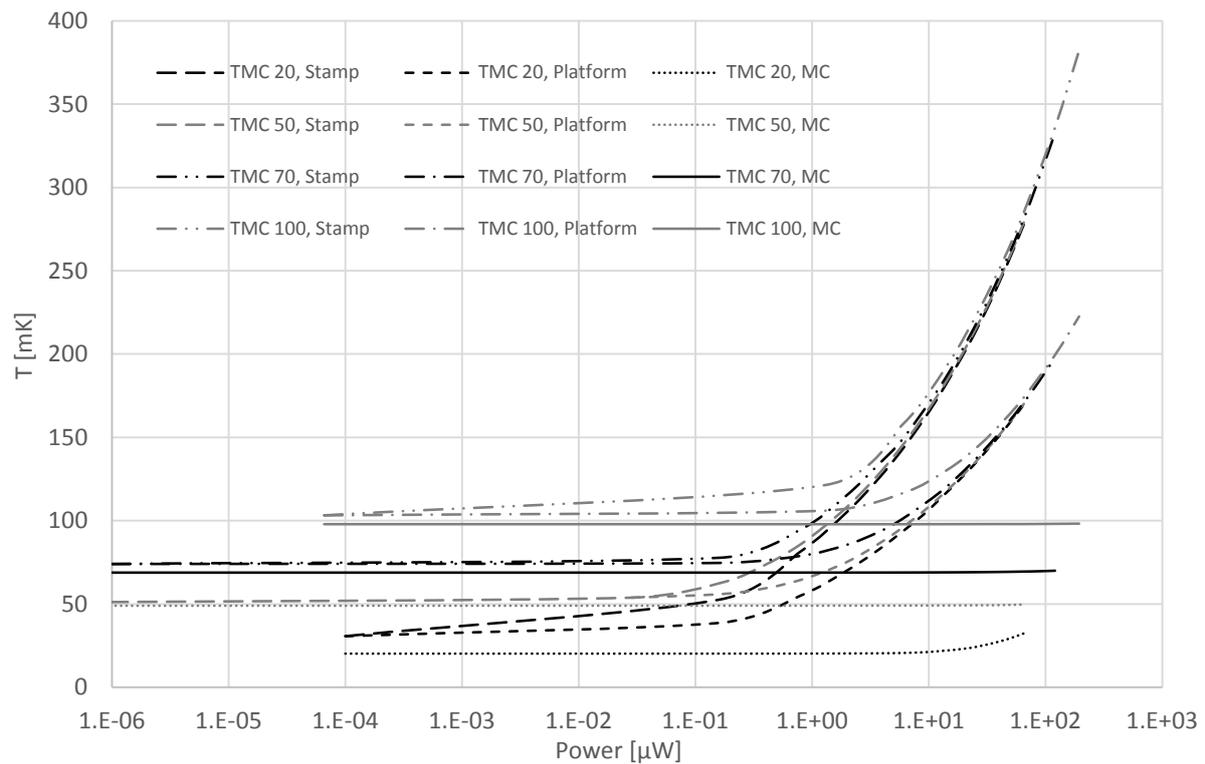


Figure 3. Temperatures of the stamp, the platform and the mixing chamber as a function of the heat load applied at the heater. The mixing chamber was kept at 20 mK, 50 mK, 70 mK and 100 mK, for compressive force applied and magnetic field off (indium SC). “TMC 30” indicates the base temperature of the mixing chamber, e.g. 30 mK. For visibility reasons the measurement points (~20 per line) are not shown.

Figure 5 presents the results of an analogical measurement but without the compressing force. The values of thermal resistivity for indium in NC state are close to those in figure 4 with applied compressing force. The lowest value for base temperature 30 mK reaches $10.3 \text{ cm}^2 \text{ K}^4 \text{ W}^{-1}$. On the contrary, resistivity values with indium in SC state are remarkably higher in the case of no compression, reaching almost $95 \text{ cm}^2 \text{ K}^4 \text{ W}^{-1}$ for $T_{st} = 250 \text{ mK}$ and base temperature of 100 mK, whereas in figure 4 the resistivity at these conditions is only slightly above $65 \text{ cm}^2 \text{ K}^4 \text{ W}^{-1}$. Again, the curves for lower base temperatures have a steeper slope than for higher temperatures. Moreover the lines in SC state are much more spread than before. For low base temperatures and small heat loads with compressing force, resistivity approaches the same, low values, for indium in SC and NC states (see figure 5, “TMC 30, Indium SC” and “TMC 30, Indium NC” for $T_{st} = 32 \text{ mK}$).

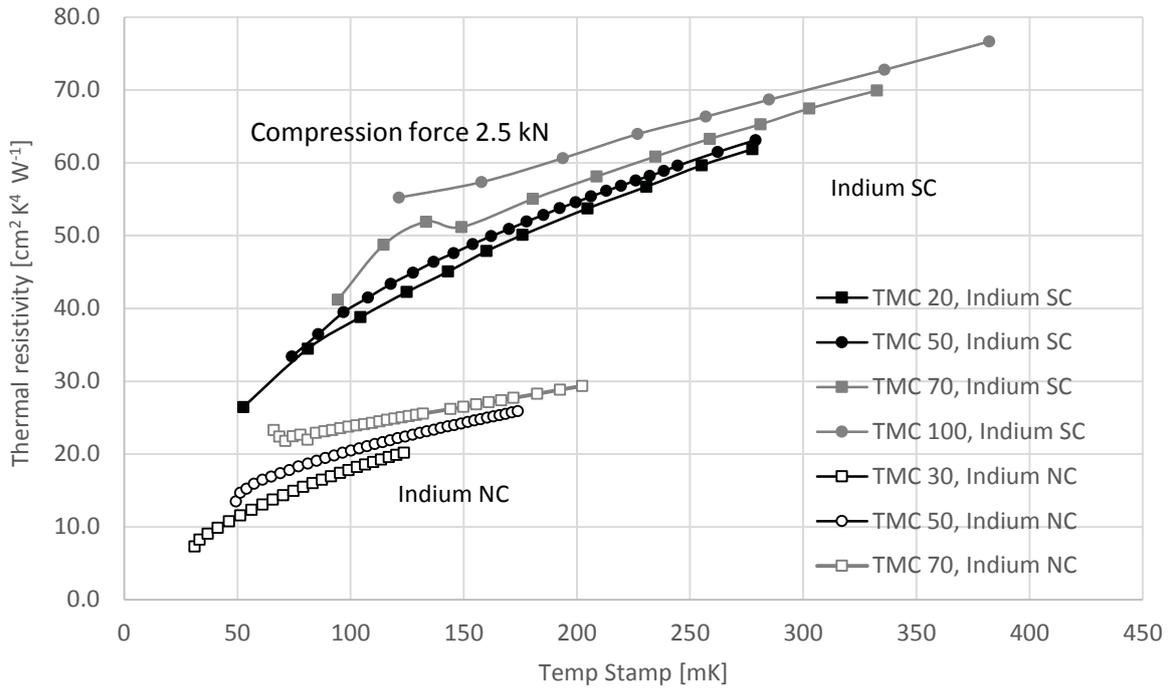


Figure 4. Thermal resistivity of a sandwich compressed with a force plotted versus the stamp temperature. The group of three lower lines corresponds to indium in NC state and upper lines for indium in SC state. The bump in the “TMC 70, Indium SC” line at around 130 mK is due to change of the range of data acquisition system. “TMC 30” indicates the base temperature of the mixing chamber, e.g. 30 mK.

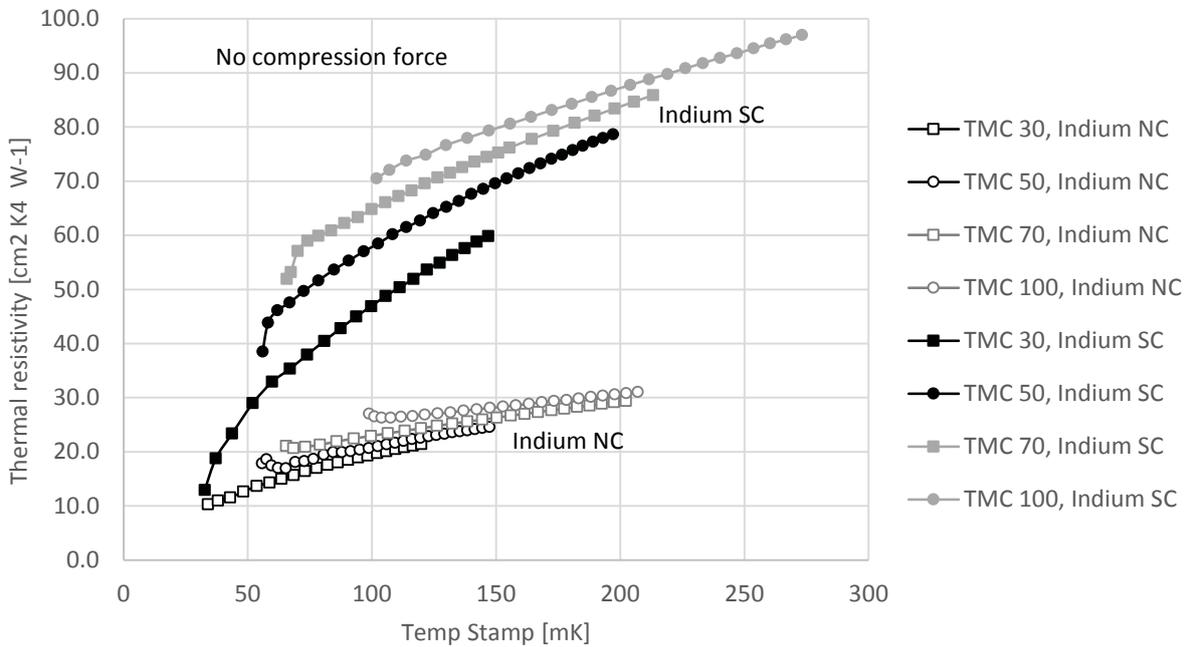


Figure 5. Thermal resistivity of the sandwich setup without compressing force versus stamp temperature. The group of four lower lines corresponds to indium in NC state and the upper lines for indium in SC state. “TMC 30” indicates the base temperature of the mixing chamber, e.g. 30 mK.

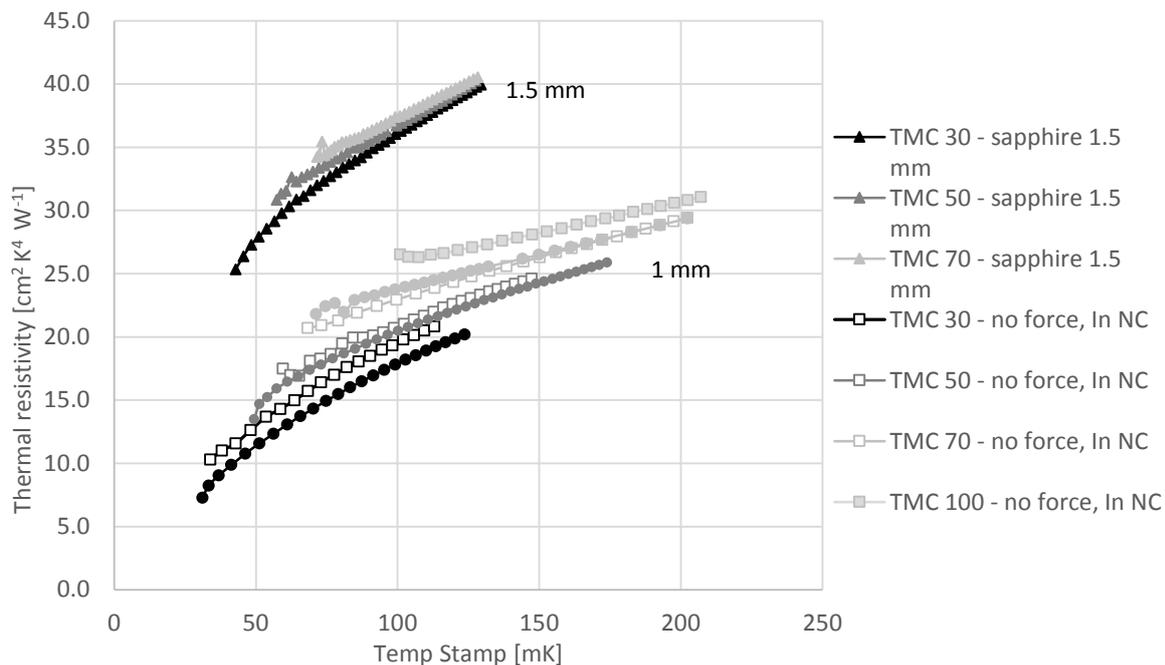


Figure 6. Thermal resistivity of the sandwich with NC indium under compressing force (full circles) and without compressing force (empty squares). In NC stands for normalconducting indium. Results obtained by T. Eisel [12], with the same compression force, indium normalconducting and 1.5 mm thick sapphire, showed as a comparison (full triangles). Base MC temperature set to 30 (black), 50 (dark grey), 70 (light grey) and 100 mK (light grey full squares). “TMC 30” indicates the base temperature of the mixing chamber, eg. 30 mK.

Figure 6 shows a comparison of the thermal resistivity values for the sandwich setup with indium in NC state in three cases: 1 mm thick sapphire with compressing force, 1 mm thick sapphire without force and 1.5 mm thick sapphire with compressing force. As one can see, the force, which is necessary to obtain a good connection between sapphire, indium and copper, sometimes described as a “cold weld” [2], influences the resistivity value much less than the thickness of the sapphire, provided indium is in NC state. For 1 mm thick sapphire, the biggest difference visible in figure 6 is for the coldest condition, i.e. TMC = 30 mK. At higher base temperatures, the difference in resistivity is in the order of a few percent. However, we should keep in mind that the applied force may change not only the resistivity of the interface, but also introduces stresses in the material. Any deformation of the crystalline structure of the sapphire, is an additional obstacle for the phonons transferring heat, and may decrease the overall conductivity, even if the interface conductivity was improved. Figure 6 shows also the comparison of our results with those obtained by T. Eisel [12]. One can see an increase of resistivity by about 100 % for the increase of sapphire thickness of approximately 50 % from 1 mm to 1.5 mm.

4. Discussion and conclusions

When indium is in NC state, the interface creating the main thermal bottleneck is between the sapphire and indium, as indium still exchanges heat with copper by both phonons and electrons. On the other hand while indium is in its SC state, electrons do not participate in the heat transfer at none of the four interfaces and the overall thermal resistance increases significantly. It explains why the resistance with SC indium is visibly higher than with NC indium, no matter if the force was applied or not.

Comparing the results in figures 4 and 5, for SC indium, the case without compressing force has a much higher thermal resistivity than the one with force. A conclusion can be drawn, that the indium itself, or the copper – indium interface, is more sensitive to the presence of a mechanical stress, than sapphire.

The layer of indium was compressed during the mounting with an increasing force, exceeding its yield limit, until it was permanently, plastically deformed. Therefore, its lattice structure is highly distorted and when the electrons are not available for heat transport, it conducts heat less effectively than an almost perfect crystal like sapphire. Since there is no indium vapour deposited on the copper side, one expects to see an improved mechanical contact with increasing compressing force, resulting in a decrease of the interface thermal resistivity, for indium in SC state. In the presented measurements, the effect of an improved mechanical contact at the interface seems to be dominant.

All plotted thermal resistances show a tendency to approach an asymptote with increasing temperature. Obviously, there's a series of resistances influencing the total resistance of the setup. Nevertheless, it is justified to expect that a part of it, probably the coldest interface, creates a stronger bottleneck for the heat transfer than the others. Thus it would be the most appropriate approach, to plot the thermal resistance versus the temperature of that interface instead of the temperature of the stamp. Mathematical and numerical modelling is necessary to estimate the temperature profile of the setup, and will be the subject of further investigation.

In the AEgIS experiment the presence of strong magnetic field assures, that the indium layer below the electrodes is always in NC state. The experiment showed, that once a "cold-weld" in the indium layer is created, the mounting structure of the electrode can be removed, as the influence of the compressing force in magnetic field is rather small. Steady-state measurements showed that in case of a disk shaped sandwich mock-up structure, a thinner layer of a dielectric results in a better heat transfer, but while designing the final shape of the electrode, one should pay attention to the possible influence of mechanical stresses, which may cause an additional scattering of the phonons in the sapphire crystal.

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