Heat transfer at dielectric - metallic interfaces in the ultra-low temperature range

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Abstract. In the framework of the AEgIS project a series of steady state and dynamic heat transfer measurements at ultra-low temperatures was conducted in the Central Cryogenic Laboratory at CERN. Two sandwich setups, simulating the behaviour of ultra-cold AEgIS electrodes, were investigated and compared, namely: a sapphire – indium – copper and a sapphire – titanium – gold – indium – copper sandwich. The total thermal resistivity of both sandwich setups was evaluated as a function of the influence of normal and superconducting thin layers and multiple dielectric – metallic interfaces in terms of Kapitza resistance. The resulting limitations of the electrode’s design are presented.

1. Introduction

The ultra-cold electrodes forming a Penning trap in the AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment at CERN [1] should be cooled-down to below 100 mK. Such a low temperature is necessary to diminish the thermal movement of the particles to achieve the planned measurement precision of 1%. The electrodes must fulfil a series of very demanding requirements, like compliance with ultra-high vacuum of $10^{-12}$ mbar and radiation-hardness. Some of the electrodes have to be divided into 4 separate sectors, creating the required quadrupole electric field. The electrical insulation between neighbouring electrodes, and between the sectors of the same electrode must withstand a potential difference of 1 kV. The fact, that the electrodes should be on the one hand sufficiently thermally conductive to remain at a temperature below 100 mK, and on the other hand completely electrically insulated, is a huge engineering challenge. To meet the requirements, the electrodes are proposed to be made by depositing golden sectors on a base of a sapphire crystal.

Several studies conducted in the CERN Central Cryogenic Laboratory (Cryolab) [2, 3, 4], showed, that the thermal boundary resistance determining the thermal anchoring to a mixing chamber of a dilution refrigerator (DR) and the mechanical robustness of this connection are the critical features of the design. According to the Acoustic Mismatch Model (AMM) the transmitted energy flux passing an interface with temperatures $T_h$ and $T_c$ on the hot and cold side respectively can be expressed as [5]:

$$\dot{Q} = \frac{1}{4\kappa} (T_h^4 - T_c^4)$$

(1)

Here, $\dot{Q}$ is the heat flow per unit time (W), and $A$ is the thermal interface area (cm$^2$). The factor $\kappa$ depends on the material densities and speeds of sound at both sides of the interface.
In the practical case of a relatively small temperature difference across the interface, the thermal resistance $R = \dot{Q}/\Delta T$ results as $\kappa/AT^3$. We define $\kappa$ as the sandwich resistivity in units $(\text{cm}^2\text{K}^4/\text{W})$, that takes into account the Kapitza interface resistivity [6] and the resistance of thin layers.

2. Experimental setup

The experimental setup, depicted in figure 1, contains all the normal conducting (nc) and superconducting (sc) thin layers and dielectric-metallic interfaces as the design of the electrode, but it has a shape enabling parametric studies of various features and can be relatively easily mounted on the mixing chamber of the DR. Two versions of the experimental setup were designed. The first design consists of a minimum amount of materials and interfaces necessary to provide an attachment of the electrode to the mixing chamber. It includes the following elements: the stamp made of OFHC copper, 125 $\mu$m thick indium foil, 2 $\mu$m of vapour deposited indium, 1 mm thick sapphire disk with flat, parallel, polished surfaces, and symmetrical vapour deposited indium, indium foil and the platform made of OFHC copper. In the second sandwich setup titanium and gold were sputtered on the sapphire disk instead of vapour deposited indium, representing a configuration that could significantly simplify the manufacturing of the electrode, and according to the AMM provide comparably good thermal contact. It consists of: the stamp, 125 $\mu$m thick indium foil, 750 nm gold, 50 nm titanium, 1 mm thick sapphire disk with flat, parallel, polished surfaces (with the same layers symmetrically on the other side of the disk).

Both sandwich setups were compressed with a clamping structure designed to provide a uniform pressure distribution on the sapphire disk. Four M5 bolts tightened with a torque of 1.2 Nm generate a compression force comparable with the force applied in previous measurement campaigns [2, 4]. The torque was re-tightened several times to make sure the force exceeded the yield limit of indium and the sandwich was kept under pressure for about a week. During that time the indium bonds to the surrounding metallic layers, and provides a solid mechanical and thermal connection. In figure 1, the clamping structure has been removed before the installation in the CERN Cryolab DR and the temperature sensors and electric heaters were installed.

![Figure 1.](image-url)
3. Measurement results

The steady state measurements were done by applying a heat load at the stamp and measuring the temperatures at the stamp and the platform. The interface resistivity was calculated according to eq. (1). Indium is superconducting below 3.41 K, and titanium below 0.39 K. An external magnetic field of approx. 32.3 mT [2] was used to force transitions from the superconducting to the normal state. The mixing chamber temperature was kept at 30, 50, 70, 100, 165 and 300 mK for the first setup, and at 30, 50, 100, 180, 245 mK for the setup with Ti and Au. The results are plotted as a function of the stamp temperature.

The total thermal resistivities of both setups as a function of the stamp temperature, with indium and titanium in the normal conducting state are presented in figure 2.

![Figure 2](image-url)

**Figure 2.** The thermal resistivity of both sandwiches as a function of the stamp temperature at various base mixing chamber temperatures (TMC). Indium and titanium are in the normal conducting state.

The first sandwich contains only two interfaces involving dielectric-like behaviour: indium nc - sapphire and sapphire - indium nc. The measured values of the resistivity equal to approximately 22 cm²K⁴/W at 50 mK, and 44 cm²K⁴/W at 375 mK. The theoretical estimation of the single sapphire - indium interface resistivity for transverse values of the speeds of sound in both media gives a value of 22.9 cm²K⁴/W. The fact that the measured value for the two interfaces in series, at the lowest temperatures is almost equal to the theoretical value of one interface indicates, that the two interfaces can behave as one. At very low temperatures the phonons in sapphire don’t scatter significantly and those that entered the cone of acceptance of the Kapitza resistance on one side remain in the same cone on the other side. The so called “parallel plates assumption” was already described before in [7]. When the temperature increases, phonons scatter more in the sapphire, and the total resistivity approaches the theoretical value for two interfaces, equal to 45.9 cm²K⁴/W.
In the second sandwich setup there are also only two interfaces involving dielectric-like properties: titanium nc - sapphire and sapphire - titanium nc. Despite the theoretical estimation predicting the resistivity of a single sapphire - titanium interface to be lower than the sapphire - indium interface resistivity and equal to 18.3 cm$^2$K$^4$/W, the measured values are much higher than for the first sandwich. The total resistivity of the second sandwich setup takes a value of approximately 28 cm$^2$K$^4$/W at 38 mK and rises with temperature to 77 cm$^2$K$^4$/W at 407 mK. Titanium is known to have relatively low thermal conductivity at low temperatures [8]. Its temperature dependence of $\lambda_{Ti} \propto T^{1.5}$ indicates that there is a significant contribution to the thermal conductivity from the lattice, even when electrons are available for the heat transfer. At ultra-low temperatures the wavelength of dominant phonons in titanium exceeds the thickness of the thin layer. The behaviour of the second sandwich setup shows, that the 50 nm layer of a normal conducting titanium significantly limits the heat transfer in the sandwich.

Figure 3. The thermal resistivity of both sandwiches as a function of the stamp temperature at various base mixing chamber temperatures (TMC). Indium is in superconducting state and titanium changes from superconducting to normal conducting at 0.39 K, which significantly reduces the total thermal resistivity of the sandwich setup above approx. 0.4 K.

Both setups were measured also without external magnetic field, and the corresponding thermal resistivities are presented in figure 3. The resistivity of the first setup takes a value of 100 cm$^2$K$^4$/W at 62 mK and rises to 163 cm$^2$K$^4$/W at 341 mK. This setup contains four interfaces of two types: copper - indium sc and indium sc - sapphire. The theoretical estimation of the resistivity including the parallel plates assumption at the sapphire disk equals to 27.1 cm$^2$K$^4$/W, which is much lower than the measured values. It indicates that the copper...
- indium sc interface has a much higher resistivity than predicted by the AMM, what may be caused by formation of a metallic interlayer or another type of an ageing process [9].

The total thermal resistivity of the sandwich with thin layers of superconducting Ti and Au is higher than any other measured configuration in this study. It takes a value of 187 cm²K⁴/W at 63 mK and rises to 480 cm²K⁴/W when the stamp temperature rises to 400 mK. At this temperature of the stamp the thin layers of titanium start becoming normal conducting and the resistivity decreases significantly. In this setup there are 8 interfaces of 4 different types: Cu - In, In - Au, Au - Ti, Ti - sapphire. The theoretical estimation of the total thermal resistivity including the parallel plates assumption at the sapphire disk gives a value of 26.8 cm²K⁴/W, which is much lower than the measured values. Measurements on the previous configurations of the setup showed that an alloyed copper - indium interface and the thin layer of normal conducting titanium increases the total thermal resistivity of the sandwich. It seems that a thin layer of Ti sc, when the electrons are not available for the heat transport, or a combination of thin layers of Au and Ti sc with a possible interlayer and corresponding interface resistivity, create even a larger thermal bottleneck. At higher temperatures the reduction of the thermal conductivity of thin layers is known, when the mean free path of the heat carriers exceeds the dimensions of the sample [10, 11]. At ultra-low temperatures when the phonon wave length exceeds the thickness of the film, the apparent thermal conductivity could be reduced even several orders of magnitude [12], which would explain the very high resistivity of the setup with thin layers of Au and Ti sc. The presented resistivity for Ti getting normal conducting in fig. 3 is supporting that assumption.

4. Summary
The thermal resistivity of a sandwich setup with and without thin layers of gold and titanium normal and superconducting was compared. The resistivity of the sandwich with a 50 nm layer of Ti nc is two to four times higher than predicted by the AMM. The resistivity of a setup with Ti sc is more than ten times higher than the theoretical prediction. It shows an enormous influence of the thin superconducting layer on the total thermal resistivity of the sandwich in the milliKelvin temperature range. Therefore, the ultra-cold electrodes in the AEgIS experiment should be thermalised in a way that provides a direct mechanical and thermal contact between sapphire and indium, avoiding the deposition of the thin layers of Ti and Au on the interface to the cold source.

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