Measurements of thermal conductivity in a crystal quartz substrate at 1.4 K

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We carried out measurements of thermal conductivity in a crystal quartz substrate (900 μm thick) at temperatures of 1.4 K by using a pumped ^{4}He cryostat. We applied a varied input power from 0.1 up to 1 mW to the heater placed at the end of the substrate, and we observed that the measured data give a temperature dependence of $k = 0.12T^{2.7}$ W/cm·K.

Keywords: Thermal conductivity; crystal quartz.

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1. Introduction

Since the early 1950's, the thermal properties of insulating crystals have been well studied [1-3], demonstrating that their thermal conductivity increases by decreasing the temperature because the anharmonic umklapp processes become less frequent, and hence the phonon mean free path increases. Most of these studies concluded that at temperatures below 1 K the thermal conductivity is nearly proportional to T^3 and to the smallest crystal dimension. While at high temperatures and high pressures, the thermal conductivity presents different behavior [4]. Recent studies also report optical constants of solid crystals such as the refractive and absorption index when the samples are exposed to an electromagnetic radiation at different wave lengths [5].

Large brand of industrial applications require low thermal conductivity materials and one way to reduce it can be by introducing porosity, but in consequence, the strength of such materials will be also reduced. It is well known that several amorphous materials present low thermal conductivities but depending on the technological application the use of crystalline solids could be essential, for instance: when the crystal is used as substrates for microelectronics devices [6], or when the crystal is used as insulator in low temperature experiments for choosing the best conductive bonding agent [7].

The new developments of superconducting-insulator-superconducting (SIS) mixers for astronomical applications in the millimeter and sub-millimeter ranges require the study of thermal properties of solid and crystalline materials for fabricating junction's circuits to be integrated into the low-noise heterodyne receivers [8] in order to achieve the lowest noise temperatures.

In this paper we report measurements of the thermal conductivity in a crystal quartz substrate which will be used for testing on-chip integrated circuits to separate lower and upper sidebands acting as planar couplers of a SIS mixer into a junction circuit.

2. Setup and technique

All measurements were taken with a potentiometric conductance bridge (S.H.E. Corporation), applying the steady-state heat flow method and using a heat sink attached to the cold plate of a pumped ^{4}He cryostat, as is shown in Fig. 1a).

Referring to Figs. 1 b) and c), the heater is composed by 25 cm length of insulated manganin wire ($\phi = 20$ μm; 4.17 kΩ/m) wound to one end of the crystal, which is covered with cigarette paper and impregnated with IMI 7031 varnish (GVL Cryoengineering) to get electrical insulation and good thermal contact. The heater provides the heat Q, which flows through the crystal whose dimensions are 0.9×10×30 mm^3. The heat is dissipated into the heat sink. The heat sink is composed by two copper blocks thus forming a clamp with a threaded cylindrical cavity to hold a screw which in turns is in direct contact and tightened manually. A piece of indium foil is placed between the crystal and the clamp to provide good thermal contact. The thermometers T_1 and T_2 (100 kOhms TMi-A1 CCS/F2 carbon-ceramic resistor, IDB Ingenierburo, Dietmar Budzylek) were previously calibrated in the manner of Clement and Quinell [9] and glued with IMI varnish. Finally, the full device was mounted using a copper screw and an intermediate layer of varnish between the heat sink and the cold plate of the cryostat to get thermal contact. Electrical connections are apart in a piece of PC board with gold printed micro strips attached with Stycast Epoxy (Emerson and Cuming, Inc.) to a cooper block to provide electrical leads outside the cryostat.

The temperature measurements were realized stabilizing T_1 and T_2 first within few mK, then we applied a varied input power Q, from 0.1 up to 1 mW. T1 and T2 measure the temperature gradients. From the Fourier's law of conduction, the thermal conductivity k for this crystal is defined by

$$k(T) = -\frac{Qdl}{Ad\tau} \tag{1}$$

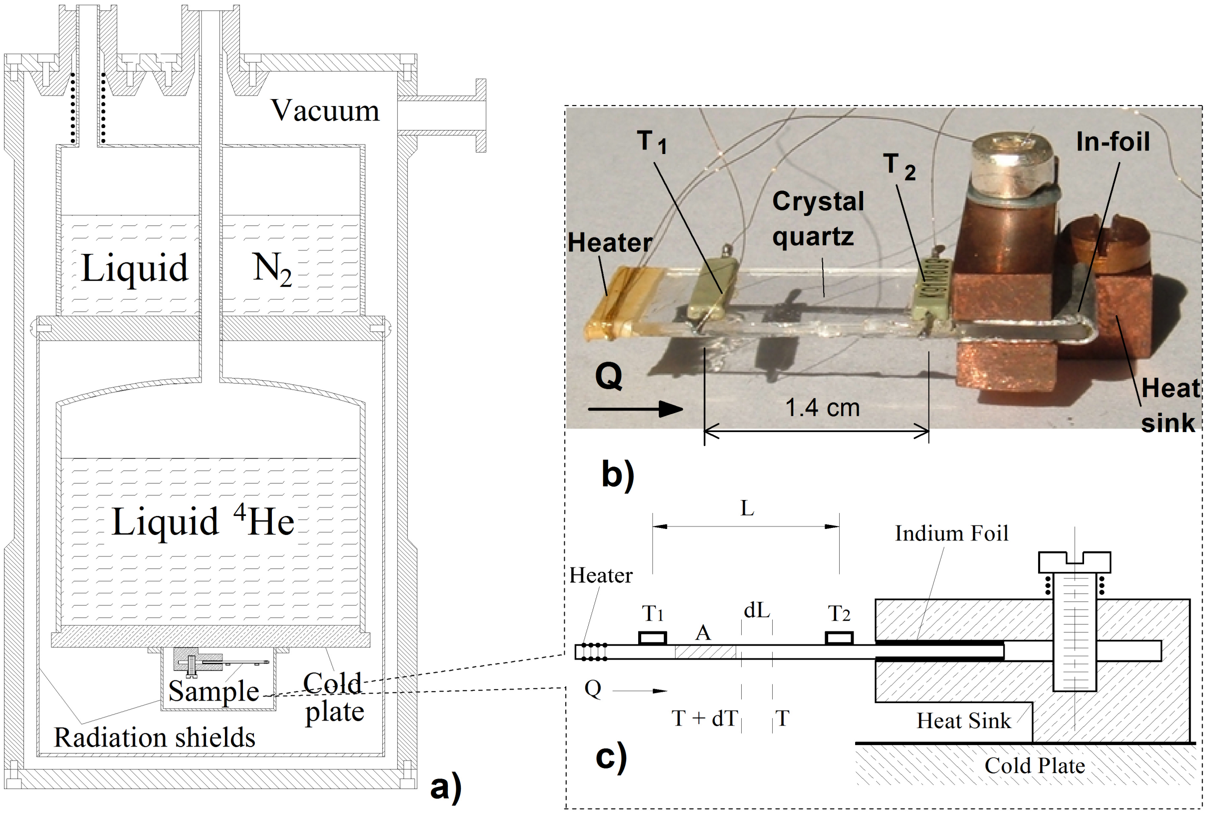

FIGURE 1. Schematic arrangement (not to scale) for measuring thermal conductivity. a) ^{4}He cryostat with the sample attached to the cold plate, b) Setup, and c) cross section of the setup.

The integration of (1) between T_1 and T_2, gives

$$\int_{T_1}^{T_2} k(T)dT = -q \int_0^L \frac{1}{A} dl \tag{2}$$

Considering A as a constant we get

$$k = -\left(\frac{L}{A}\right)\frac{Q}{\Delta T} \tag{3}$$

where Q is the input power, L is the thermometer's distance; A is the cross section area of the crystal, and ΔT is the temperature gradient.

3. Results and discussion

The results of our measurements are depicted in Fig. 2. Here, the temperature was considered as the average of T_1 and T_2. Three measurements were conducted to obtain the mean and a 2% of the estimated error. The data were fitted to a form $k = aT^b$. The fit gives: $a = 0.12$ W/cm·K with b = 2.7.

It has been mentioned above that below 1 K, the thermal conductivity is proportional to T^3, but it depends upon the purity of material, since any disturbance of the lattice periodicity may vary its thermal properties due to the acoustic mismatch limits the transmission of thermal phonons in the crystal. In deep studies, the constrictions caused by the irregularities at the edges, may also contribute to this variation of its thermal properties. However, our present study at temper-

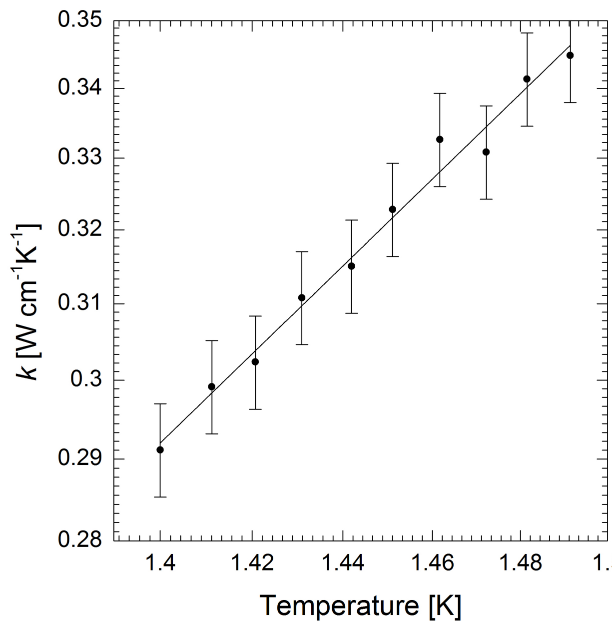

FIGURE 2. Thermal conductivity of crystal quartz as a function of temperature.

atures of 1.4 K is only focused to the thermal conductivity using a piece of commercial crystal quartz and considering it as a perfect rectangular prism. Hence, our measurements results are reliable compared with those reported in the literature.

4. Conclusions

We described a simple technique for carrying out measurements of thermal conductivity through a commercial crystal quartz substrate. The results provided useful information that can be applicable to a wide variety of cryogenic experiments where small heat leaks are permitted and involve the use of this kind of substrates. Even though these kinds of substrates have been commonly used before, their characterization for this application has not been reported until now.

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