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Magnetic field independent capacitance thermometers at very low temperatures

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Abstract

We have established the magnetic field independence up to 20 T of two capacitance thermometers based on different dielectric materials: amorphous borosilicate and the incommensurate ferroelectric $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$. The obtained sensitivity of the thermometers, $d\ln C/d\ln T$, is 8×10^{-4} and 5×10^{-3} for the borosilicate and the $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ samples, respectively.

1. Introduction

Almost all thermometers used at low temperatures are influenced by the application of a magnetic field, which makes them essentially unsuitable for high field experiments. Clearly, it would be desirable to develop a type of thermometer that is completely magnetic field independent up to the highest presently attainable fields and down to mK temperatures.

Negligible coupling to a magnetic field is expected for dielectric materials where no free electrons or magnetic dipoles are present. For this reason capacitance thermometers based on dielectric materials are the most suitable candidates for low temperature thermometry [1] in high magnetic fields [2]. A second advantage of capacitative thermometers is the low self-heating even with a few volts excitation, which makes these thermometers especially useful for low temperature measurements in a noisy environment.

We have studied the magnetic field dependence of two capacitance thermometers based on different dielectric materials: a crystalline $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ sample which already proved to be a good and sensitive capacitance thermometer for temperatures above 1 K [3] and an amorphous sol-gel derived borosilicate sample, reported in Ref. [4]. The low temperature behaviour of the dielectric constant of $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ is expected to be glass-like. The reason for this is that due to the pinning of the incommensurate modulation of defects induced by the introduction of lead atoms into the cation sub-lattice of the pure compound $Sn_2P_2Se_6$, the incommensurate phase is transformed to a state which is similar to the so-called cluster glass.

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2. Setup

The $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ was grown using a Bridgeman technique. The crystal (typical size 10 mm x 25 mm) was cut and polished to obtain platelets (size $5 \times 5 \times 0.8\ mm^3$) perpendicular to the 1 0 0 direction. The sample had gold sputtered electrodes and was connected to SS coaxial wiring with silver paint and a small amount of epoxy. The borosilicate glass was prepared by the sol-gel process [4] and also had gold plated electrodes soldered to SS coaxial wires.

The two samples were mounted inside the mixing chamber of an adapted SHE dilution refrigerator, placed in a 20 T Bitter magnet [5]. The original metal mixing chamber had been replaced by a home-made, Kapton foil mixing chamber to avoid eddy current heating. The silver sintered heat exchangers were located about 1 m above the field centre, where the magnetic field is reduced by a factor of about 100. The lowest achieved temperature with this dilution refrigerator at 20 T was 16 mK.

Three types of thermometers were mounted in the mixing chamber: Speer 100 Ω carbon resistors, a CMN thermometer [6] and a vibrating wire thermometer [7]. Also in the entrance and exit tubes of the mixing chamber Speer 100 Ω resistors were mounted. The CMN thermometer was calibrated with the mixing chamber Speer resistor above 100 mK and reproduced the thermodynamically correct cooling power of the dilution refrigerator below 100 mK.

A reliable but somewhat cumbersome temperature reference in magnetic fields is given by the field independent, but temperature dependent, viscosity of the ^3He–^4He mixture in the mixing chamber and this was probed by the vibrating wire thermometer in magnetic fields above 1 T.

The vibrating wire was a 100 μm manganine wire, shaped in a semi-circle with radius 2 mm. This device has a mechanical resonance at a few kHz, which can be excited by a small alternating current through the wire in the presence of a magnetic field. The quality factor of the resonance is a measure of the viscosity of the surrounding medium. The magnetic field dependent quality factor in vacuum was measured at 4 K and the quality factor measured with the mixture present, Q_{3-4}, has been corrected for this.

3. Results and discussion

In Fig. 1, the capacitance of both samples is shown as a function of the temperature. Our measurements at different frequencies subscribe to the common behaviour of dielectric materials extensively reported in the literature and in our case T_{min} shifts with frequency approximately as $\omega^{0.3}$. The straight parts of the curves in Fig. 1 to the left of the minimum have sensitivities $d\ln C/d\ln T = 5 \times 10^{-3}$ and 8×10^{-4} for the $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ and the borosilicate sample, respectively. The reproducibility of the studied thermometers after warming to 1 K and cooling back is better than our measurement resolution. However, upon cycling between room temperature and 10 mK, slight changes in the value of the capacitance at the minimum and even in the slope for $T < T_{min}$ have been observed.

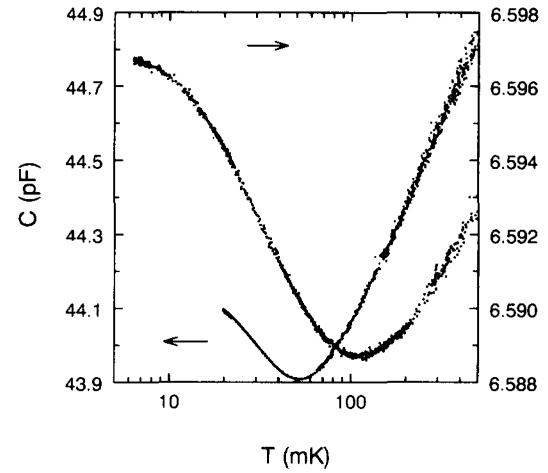

Fig. 1. Capacitance versus temperature for the $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ (←) sample at 0.75 V, and the borosilicate sample (→) at 7.5 V, both at 1 KHz.

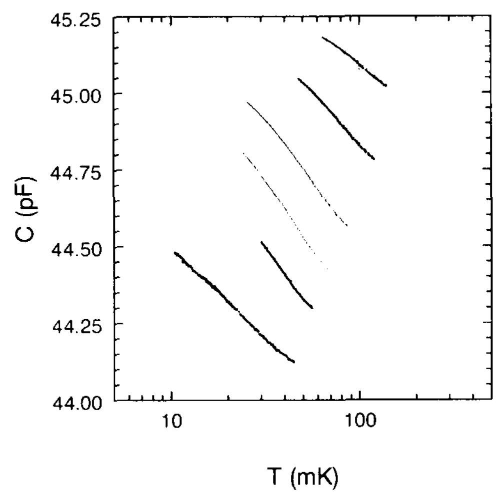

Fig. 2. The most sensitive part of the $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ sample for different excitation voltages ranging from 0.1 V (lowest curve), 0.25, 0.75, 1.5, 3.75 to 7.5 V (top curve).

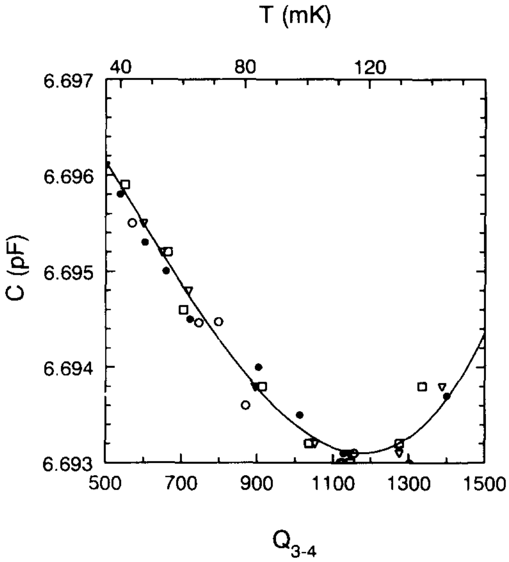

Fig. 3. Capacitance of the borosilicate sample at various magnetic fields; 1 T (○), 5 T (□), 10 T (▽) and 20 T (●), as a function of Q_{3-4}.

In Fig. 2 the most sensitive part of the capacitance curve is plotted for the ferroelectric sample measured at different excitation voltages. The excitation voltage dependence shown in Fig. 2 provides a useful property, namely the tunability of the most sensitive range of the thermometers to other temperature ranges. Alternatively, it should always be kept in mind that the calibration for these thermometers depends on the excitation voltage, at least on the low temperature side of the minimum.

In Figs. 3 and 4 the capacitance of the two samples is shown for magnetic fields ranging from 1 to 20 T as a function of Q_{3-4}, the vacuum corrected quality factor of the resonance of the vibrating wire thermometer. The upper horizontal axis is a conversion of Q_{3-4} to temperature using viscosity data from Ref. [7]. These temperatures are in agreement with the temperatures deduced from the Speer resistor in the exit tube of the mixing chamber *and* from the zero field calibration of the capacitance thermometers. Furthermore, the values of the capacitances at the minimum do not change from 0 to 20 T.

In conclusion, it has been shown that the capacitance thermometers are field independent for magnetic fields ranging from 0 to 20 T at least down to temperatures of 30 mK.

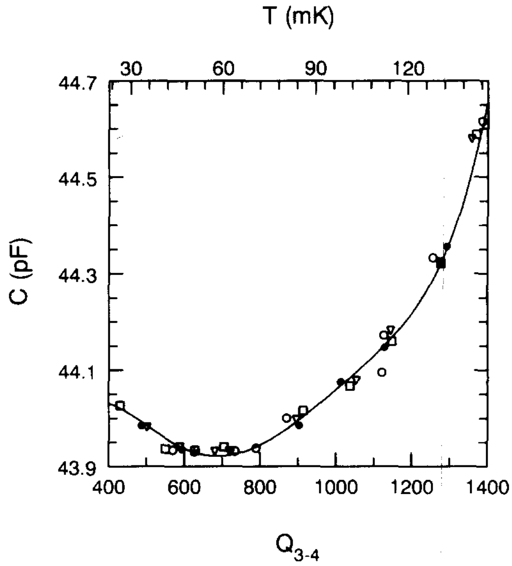

Fig. 4. Capacitance of the $(Pb_{0.45}Sn_{0.55})_2P_2Se_6$ sample at various magnetic fields; 1 T (○), 5 T (□), 10 T (▽) and 20 T (●), as a function of Q_{3-4}.

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