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Design and Fabrication of a Capacitance Dilatometer for use in the Quantum Design Physical Property Measurement System

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SENIOR PROJECT - APPROVAL

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PROJECT TITLE: Design and Fabrication of a Capacitance Dilatometer for use in the Quantum Design Physical Property Measurement System

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

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Comments (Optional):

Design and Fabrication of a Capacitance Dilatometer for use in the Quantum Design Physical Property Measurement System

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This project consists of the research, design, and fabrication of a capacitance dilatometer. The design results from the synthesis of the strongest points of previous such devices with a special emphasis on the device's application in the Quantum Design Physical Property Measurement System (PPMS). Once the device has been fully tested and validated, it will be used at the Oak Ridge National Laboratory (ORNL) as well as the Tennessee Advanced Materials Laboratory (TAML) at the University of Tennessee.

I. Introduction

A capacitance dilatometer is the most sensitive instrument for measuring the thermal expansion of a material. The linear coefficient of thermal expansion is a fundamental property of all materials, and yet the capability of making such measurements is not readily available in most laboratories. The capacitance dilatometer takes advantage of our ability to accurately measure the changes in capacitance between two plates in a parallel-plate configuration. Such dilatometers are capable of measuring length changes on the order of an Angstrom. Aside from adding this capability to our laboratory, our capacitance dilatometer will be designed around its use in the Physical Property Measurement System by Quantum Design. This will enhance the temperature controlling abilities of our device while adding the capability of introducing magnetic field interactions into the thermal expansion measurements.

II. Theory

When energy is introduced into a material in the form of heat and a temperature change occurs the material also undergoes a change in its volume. This volume dependence on temperature is termed thermal expansion. When thermal expansion is measured in the lab, the measured quantity is usually the linear thermal expansion. This property is quantified by the linear coefficient of thermal expansion:

$$\alpha = \frac{1}{L}\left(\frac{dL}{dT}\right)$$

This is a change in the length of a material with respect to a change in its temperature compared to the sample material's original length. For isotropic materials, the coefficient of volumetric thermal expansion is merely three times the coefficient of linear thermal expansion.

In order to obtain a sample material's coefficient of thermal expansion, many discrete measurements of the sample's length are made as a function of temperature. This relation is then differentiated to get the dL/dT term.

III. Design Requirements

The capacitance dilatometer is specifically designed to operate in the PPMS. The PPMS is a large, low temperature dewar that is capable of generating temperatures between 1.9K and 400K with fields of up to 9 Tesla. It also features automated, on-board temperature controlling and measuring capability. While using the capacitance dilatometer in the PPMS does enhance the instrument's sensitivity and capabilities, it also imposes a few important design requirements for our particular instrument. The first requirement is that the device be of cylindrical geometry with a diameter of no more than one inch. The instrument must also be constructed of materials which adapt well to very low temperature environments. Finally, special equipment must be developed for mounting the dilatometer within the PPMS and for passing the temperature and capacitance signals out to our measurement equipment.

IV. Research

We researched past capacitance dilatometer designs in order to find the best combination of techniques and features for our design. Our design is modeled after a design by G. Brandli and Griessen as featured in their paper *Two capacitance dilatometers* (1973). This design features two notable advancements which we incorporated into our design.

The first feature is the use of dual parallel-plate springs to support the sample and capacitor plate assembly. This allows the capacitor plates to remain parallel through a relatively large range of sample length changes. A full analysis of the motion of parallel-plate springs is featured in *Parallel and Rectilinear Spring Movements* (Jones et al. 1951).

The second important feature of this design is the ability to very accurately and easily parallelize the capacitor plate. The design allows the bottom capacitor plate to be removed to expose the plate faces. The plate surfaces can then be polished to ensure that they are perfectly even with their respective guard rings. Thus when the plates are re-joined, they will be parallel and can be modeled as a parallel plate capacitor to a high degree of accuracy.

Another advantage of this design is that it does not require a great deal of precision in the sample material preparation. Whereas many previous capacitance dilatometers required the sample to be of very precise size and shape or to be gold plated, this design only requires that the sample fit into the sample holder (a 4cm high cylinder with radius 33mm).

The secret to the capacitance dilatometer's sensitivity is the method by which the changes in capacitance are detected. We will use a three-terminal capacitance measurement with a lock-in amplifier and capacitance bridge as described in *Measurement of Thermal Expansion at Low Temperatures* (White 1961). The three-terminal capacitance measurement is desirable because it negates any stray capacitance between the plates and anything grounded. Thus we can be fairly sure that the small capacitance we measure is due to the voltage potential between the plates.

V. Design Points

The capacitance dilatometer is constructed primarily from oxygen-free high purity copper (OFHC) due to copper's well-known thermal expansion properties and its high thermal and electronic conductivity. It uses a parallel spring suspension system and plate polishing capability similar to the Brandli/Gresson design. The capacitor plates are each surrounded by a 1mm width guard ring. These rings help to prevent the formation of fringe fields on the edges of the capacitor plates so that the plates approximate a parallel-plate configuration. The plates are insulated from their guard rings with refractory cement as suggested by my advisor Dr. David Mandrus in his unpublished paper on capacitance dilatometer construction. The capacitance cell also features a system of spacers to allow for a wide variety of sample lengths. Very close to the sample is room for two temperature sensors: at least one of which will be a Cernox resistive temperature sensor. These temperature sensors are particularly well suited for this application as they work well at very low temperatures and they can be used in the presence of high magnetic fields. All electrical connections for the capacitor plates and the grounded capacitance cell will use micro-coaxial cable.

VI. Support Equipment

I am currently working on the design and construction of the various support devices necessary to mount the capacitance cell in the PPMS. The cell will be supported from the top of the PPMS by a thin rod of G-10 (an inert, tough material with low thermal conductivity). The rod is threaded into a custom flange replacement for the top of the PPMS. This flange replacement both suspends the capacitance cell in the dewar and enables the coaxial cables for the capacitance and temperature readings to feed out of the PPMS and into the outside supporting electronics.

Temperature control will be provided by the highly accurate system built into the PPMS. We will use a standard Lake Shore temperature controller for the capacitance cell temperature measurements. The capacitance measurement will use a lock-in amplifier and capacitance bridge as described in the paper by White (1961).

Both the temperature controller and the lock-in amplifier support the GPIB serial communications protocol. This will enable us to automate the data-taking procedure with a small personal computer. This computer will simply take reading from the two devices and record it for later analysis.

References

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