Heat diffusion

Objective

The objective of this laboratory is for you to use measurements of the diffusion of heat in a material to enhance your understanding of solutions of the diffusion equation. This laboratory also introduces the use of lock-in detection for the measurement of the amplitude and phase—or equivalently, the real and imaginary parts—of a signal.

Preparation

Read White Chapter 8; the three-page document “What is a lock-in amplifier?”; and the introductory section of Parker 1961.

Equipment and samples

- Pyroelectric detectors, lock-in amplifiers.
- High intensity LED; dc power supply; bread board and electronics for constructing an electronic chopper; signal generator.
- Sample disks made of graphite, steel, and glassy carbon; colloidal graphite.
- Computer, plotting software, computer-based oscilloscope.

Introduction

In MSE 307, we studied the heat capacity of materials. The heat capacity is a thermodynamic property; i.e., the heat capacity is a measure of how much an intensive thermodynamic variable (temperature) changes when a small amount of energy is added or subtracted from the sample. Thermal conductivity is a transport property; the thermal conductivity, usually written as the Greek letter “kappa” κ, is the linear transport coefficient that relates a temperature gradient to a heat flux. For an isotropic material or cubic crystal, κ is a scalar; for a non-cubic crystal or a material with an anisotropic microstructure κ is a tensor, although in most cases of practical interest, the κ tensor is diagonal.

The ratio of the thermal conductivity and heat capacity per unit volume C, is the thermal diffusivity, $D=\kappa/C$. The MKS units of diffusivity are m^2/s. We can get a rough idea of the time τ it takes for heat to diffuse some distance L from dimensional analysis $\tau=L^2/D$. For a Si wafer, L=500 microns, $D=1\ cm^2/s$, and $\tau=2$ msec. For polymers, D=0.001 cm^2/s and several minutes are needed for heat to diffuse 1 cm. Thus, the time-scales of heat diffusion in practical situations varies enormously. In scientific studies, the relevant time-scales of heat diffusion span an amazing 27 orders of magnitude: in my research group, we study heat diffusion in thin films on 10 picosecond time scales; planetary scientists are concerned with the diffusion of heat on the time-scale of billions of years.

Thermal conductivity can be measured directly but the most widely used experimental method for determination of thermal conductivity, flash diffusivity, actually measures thermal diffusivity. Thermal conductivity is then derived from diffusivity using κ=DC.

Session 1: Measure the frequency response of the pyroelectric detector using a chopped LED light source

- Build an "electronic chopper" from a dc power supply, signal source and a transistor. A circuit diagram is shown below.

- Allow a small amount of the light from the modulated light-emitting diode (LED) to fall on the pyroelectric detector. As you did for the pyrometry lab in MSE 307, observe the amplitude and shape of the signal but now go a step further and measure the signals using a lock-in amplifier and determine the amplitude and the phase of the frequency response of the detector. (The range of frequencies should be 1 to 100 Hz; your plots should use a log scale for the frequency so when you collect the data think about spacing the data points by a constant factor rather than a constant interval.) In the high frequency limit, the amplitude should decrease as $1/f$ and the phase should be $-\pi/2$ radians.

Session 2: Measure the thermal diffusivity of a material using heating by a chopped LED and a pyroelectric detector

- Measure the thermal diffusivity of a sample (currently 0.8 mm thick carbon-coated steel) by illuminating one side of the sample with the modulated LED heat source and measuring the amplitude and phase of the temperature response on the other side of the sample using the pyroelectric detector. The sample is installed in place of the window on the pyroelectric detector. Place the LED a few mm away from the sample.

- To do this, you will need to measure the amplitude and phase of the signal generated by the pyroelectric detector with the lock-in amplifier. The amplitude and phase of the temperature of the back-side of the sample is given by this response function measured with the sample installed divided by the response function of the detector measured in the first session. Compare your results to the functional form given in lecture $(qd\sinh(qd))^{-1}$ where $qd=i\omega d^2/D$, d is the sample thickness, and ω is the angular frequency.

- Repeat using a different thickness of sample and determine the thermal diffusivity of the samples using the condition qd=2.2 when the real and imaginary parts of the temperature response are equal.

January 25, 2009

Instrument procedures

Detector and oscilloscope

We use the SPH-CM-Test pyroelectric detector to measure the power of radiation emitted. The heart of the detector test box is a 5 mm diameter $LiTaO_3$ detector. The detector generates a voltage signal by detecting a temperature change due to incoming radiation with linear response up to 40,000 V/W. The detector test box has a BaF_2 window that is transparent to visible and IR radiation (up to 17.5 μm) to block air flow.

To collect the data, we use a DS1M12 oscilloscope. Turn on the detector and start the EasyScope II program. You want to trigger ***ChB*** with the sync output of the chopper. Adjust the T/Div and V/Div knobs to see a clear image of the signal. Adjust ***Gnd*** level if necessary. Pressing ***Meter A*** button will display useful readings, which you can customize by pressing configure.

Circuit diagram for electronic chopper