Thermal Conductivity Measurement With 3ω Method

Background and Synopsis of Its Implementation

Fiifi Blankson, College of Engineering

Abstract

Continued advances in nanostructured materials have made it necessary to develop materials with specific thermoelectric properties. The 3ω Method provides an accurate measurement of one such property, thermal conductivity. It will be used in this research to find high electrical conductivity alloys with low thermal conductivity.

Physical Background of 3ω Method

According to Wiedemann-Franz law, for conductors,

$$\kappa = \sigma L T$$

where κ, σ, L, T are thermal conductivity, electrical conductivity, Lorenz number and absolute temperature respectively.

Thermal and electrical conductivities are directly proportional properties. This restriction determines the choice of alloy to test.

Definition of 3ω Method

It is a transient method of measuring thermal conductivity and specific heat capacity of a thin film of metal.

Advantages

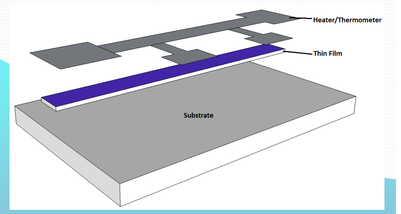
- No need to wait till temperature reaches a stable value before taking measurements.
- No parasitic heat loss through substrate nor by radiation.

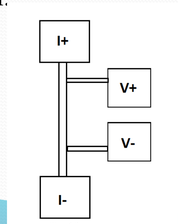
Disadvantages

- Realistic model analysis is complex and cumbersome.
- Yields inaccurate results when ran at frequency extremes.

Setup

- The test material is sandwiched between a substrate and a film which acts as both a heater and thermometer.





Top View

- Voltage and current measurements are read from the thermometer and used in calculations to obtain thermal property values

Advantages

- Allows the setup to be modeled as an easier 1D problem.
- More accurate measurements since heater and thermometer are the same element.
- Thin film maintains structure since it is not moved
- Experiments can be performed repeatedly

Mathematical Background of 3ω Method

Heat equation in frequency domain is of the form

$$-i\omega c_p T(x,\omega) = \kappa \frac{\partial^2 T(x,\omega)}{\partial x^2}$$

and has solution as

$$T(0,\omega) = T_\omega \cdot e^{i\varphi}$$
$$\Delta T = T_\omega \cdot cos(\omega t - \varphi)$$

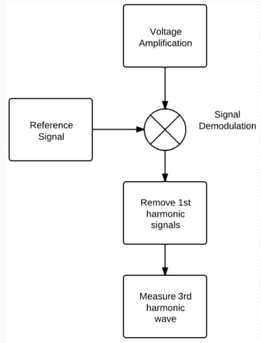
Choosing $I(t)$,

$$I(t) = I_0\, cos(\omega t/2)$$
$$P = I^2(t)R(t) = R(t) \cdot I_0^2\, cos^2(\omega t/2)$$
$$= R(t) \cdot \frac{1}{2} I_0^2 \cdot (1 + cos(\omega t))$$
$$But\ R(t) = R_0(1 + \alpha \Delta T)$$
$$\therefore R(t) = R_0(1 + \alpha\, T_w cos(\omega t - \varphi))$$
$$V(t) = I(t) \cdot R(t)$$
$$= I_0 R_0 \left[cos\left(\frac{1}{2}\omega t\right) + \frac{1}{2}\alpha T_w cos\left(\frac{1}{2}\omega t - \varphi\right) + \frac{1}{2}\alpha T_w cos\left(\frac{3}{2}\omega t - \varphi\right) \right]$$

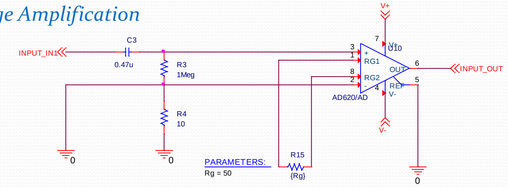
But $V(t)$ is minuscule and 3rd harmonic needs to be extracted. Enter the Lock-in Amplifier (LIA)

Implementation of Lock-In Amplifier

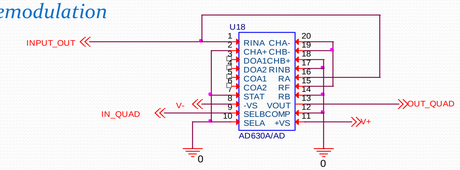
The lock-in amplifier boosts the resulting voltage signal and filters out noise. Its implementation follows the flowchart shown



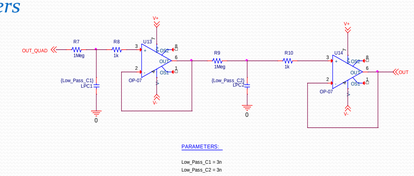
Voltage Amplification



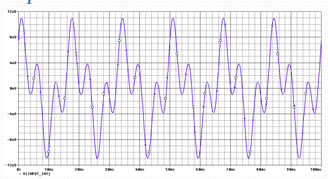
Signal Demodulation



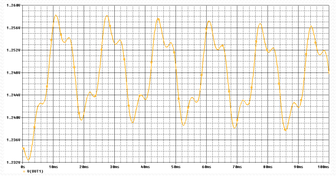
Low-Pass Filters



Inputs



Results



UNLV
UNIVERSITY OF NEVADA LAS VEGAS