UNIVERSITI PUTRA MALAYSIA

EFFECTS OF ELECTRIC FIELD ON THE THERMAL DIFFUSIVITY OF CONDUCTORS IN THREE-LAYER SOLID CONFIGURATIONS

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March, 2015

DEDICATIONS

This work is dedicated to the memory of my late parents and brother who together, initiated me into this endeavour but who couldn’t live long to see me through it. May their souls rest in perfect peace.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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March, 2015

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In order to extract the thermal properties of thin films from their thermal responses an analytical model is developed by solving the heat diffusion equation. In this study, a novel mathematical theory essential for the experimental determination of thermal diffusivity of conductors in three-layer solid configurations by the Converging Thermal Wave Technique is developed. This is achieved by expressing the hyperbolic Laplace associated solution of the derived equation in negative exponential form. Binomial series expansion is then used to simplify the solution and hence, Laplace conversion tables, in place of the tedious integral inversion technique are finally used to retrieve the temporal temperature profile for the three-layer solid sample in real space and time domains. The equation is plotted using Mathematica Software and its accuracy is checked by performing sensitivity analysis on all the physical parameters contained in the derived equation. The result of the sensitivity analysis shows that the mathematical model is sensitive to all relevant parameters needed for the evaluation of the thermal diffusivity of the sample.

Using the Converging Thermal Wave Technique, three different sets of thermal diffusivity experiments are performed on previously prepared samples. The first set of experiment comprising four three-layer samples is performed to test the mathematical theory and calibrate the measuring scheme and apparatuses. Results obtained in this series of experiments show that the mathematical model and the measuring scheme adopted for the thermal diffusivity evaluation of the samples are accurate to within about 5% error.

The second set of experiments were performed on different three-layer solid samples when direct electric current pass across the samples. Results obtained here indicate that the thermal diffusivity value of the metal foils in three-layer solid configurations increase with the potential difference applied across the metal foils. It is also observed in this series of experiments that the temperature of the metal foils increases slightly as a result of the Joule heating effects.

When different three-layer solids are placed in a uniform static electric field and are being charged either positive or negative as the PD is varied from 1.00 V to 10.00 V in a step of 1 V each, the effect of electrostatic field on the thermal diffusivity of metal is investigated. At both positive and negative static charge on the sample, ten different temperature signal readings are obtained as the potential difference of the DC power source is varied. In this way, the free electrons in the conductor are made to move either towards or away from the temperature signal detection point respectively and hence the effect of the flow of free electrons in an open circuitry is established. It is found out that free electrons flowing both normal and parallel to thermal dissipation path in a metal affect its thermal diffusivity significantly. When electrons flow towards the thermal dissipation path due to electrostatic repulsion, the thermal diffusivity value of the metal is observed to increase and when the direction of electrons flow and thermal dissipation path due to electrostatic attraction are opposite one another, the thermal diffusivity value for the sample decreases.

The last phenomenon is understood to be the results of the fact that electrons in a metal behave like a collection of gas particles, 'Fermi-Gas' such that they move about through the metal unhindered and unaffected by the potentials of the ion core and hence remained un scattered for quite a long time. Within the limit of the room temperature at which the experiment is carried out, scattering of electrons in the metal by phonons is negligible. Similarly, for metals free from point defects, impurity and imperfections scattering by point defects and crystal imperfection is also ruled out. Hence, the applied potential difference accelerates the electrons towards or away from the temperature probe. When the electrons move towards the probe the thermal diffusivity value for the metal increases, and decrease when the electrons flow in the opposite direction. We also note that all these happened with no additional heat in the solid as the phenomenon occur in an open circuitry such that the Joule heating effects of flowing electrons are eliminated.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doctor Falsafah

KESAN MEDAN ELEKTRIK KE ATAS RESAPAN TERMA KONDUKTOR DIDALAM KONFIGURASI PEPEJAL TIGA-LAPISAN

Oleh

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March, 2015

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Satu model analitikal telah dibangunkan dengan menyelesaikan persamaan resapan haba untuk mendapatkan sifat-sifat terma filem nipis daripada isyarat termanya. Penyelesaian matematik yang novel ini adalah teras untuk menentukan resepan terma konduktor dalam konfigurasi tiga-lapis secara eksperimen dengan menggunakan Teknik Gelombang Terma Menumpu. Ia dapat dilakukan dengan mengungkapkan penyelesaian yang berkaitan Laplace hiperbolik bagi persamaan yang diturunkan dalam bentuk eksponential negatif. Pengembangan siri Binomial kemudian digunakan untuk meringkaskan penyelesaian dan dari sini jadual penukaran Lapalce, menggantikan teknik songsangan kamiran yang rumit, digunakan untuk memperolehi profil suhu temporal untuk sampel pepejal tiga-lapis dalam domain masa dan ruang nyata. Kemudian persamaan tersebut diplot menggunakan perisian Mathematica dan kejituannya diperiksa dengan melakukan analisis kepekaan ke atas parameter fizikal yang terkandung dalam persamaan yang diturunkan.

Dengan menggunakan Teknik Gelombang Terma Menumpu, tiga set eksperimen berasingan telah dijalankan ke atas sampel yang disediakan. Set pertama eksperimen yang terdiri dari empat sampel tiga-lapis dilakukan untuk menguji teori matematik dan untuk penentukuran peralatan dan skema pengukuran. Hasil yang diperolehi dari siri eksperimen ini menunjukkan model matematik dan skema pengukuran yang ditetapkan untuk penilaian resapan terma sampel tersebut adalah jitu dalam lingkungan ralat 5%.

Set eksperimen kedua dilakukan untuk sampel pepejal tiga-lapis berbeza apabila arus terus dilalukan menerusi sampel. Hasil yang diperolehi menunjukkan nilai re-

sapan terma bagi kerajang logam dalam pepejal tiga-lapis bertambah dengan beza keupayaan merentasi kerajang. Didapati juga suhu kerajang logam meningkat sedikit hasil daripada kesan pemanasan Joule. Dalam siri ketiga eksperimen pepejal tiga-lapis berkenaan ditempatkan dalam medan elektrik statik dan dengan demikian tercas sama ada positif atau negatif sewaktu beza keupayaan berubah dari 1.00 V ke 10.00 V dengan setiap kenaikan 1 V, kesan medan elektrostatik ini telah dikaji. Pada kedua-dua keadaan sampel tercas positif dan negatif, 10 bacaan isyarat suhu berbeza telah diperolehi sebaik beza keupayaan DC diubah. Dengan cara ini, elektron bebas dalam konduktor digerak masing-masing sama ada ke arah atau menjauhi titik pengesan isyarat suhu dan dengan ini kesan elektron bebas mengalir kedua-duanya normal atau selari terhadap laluan susutan terma dalam sekeping logam memberi kesan yang signifikan kepada resapan termanya. Apabila elektron mengalir ke arah laluan susutan terma disebabkan tolakan elektrostatik, nilai resapan terma logam didapati bertambah dan apabila laluan susutan terma melawan arah elektron mengalir disebabkan tarikan elektrostatik, nilai resapan terma sampel berkurangan.

Fenomena terakhir ini dapat difahami sebagai natijah bahawa elektron dalam logam pada kenyataannya merupakan sekumpulan zarah-zarah gas, 'Gas-Fermi' sehingga mereka bergerak menerusi logam tanpa halangan dan tidak terkesan oleh keupayaan teras ion dan dengan demikian kekal tidak tersebar untuk masa yang agak panjang. Dalam lingkungan suhu bilik yang mana eksperimen dijalankan, penyebaran elektron oleh fonon adalah boleh diabaikan. Demikian juga, untuk logam yang bebas dari cacat titik, bendasing dan ketaksempurnaan penyebaran oleh titik cacat dan ketaksempurnaan hablur adalah boleh dinafikan. Dengan ini, beza keupayaan yang dikenakan memecut elektron ke arah atau menjauhi penduga suhu. Apabila elektron bergerak ke arah penduga nilai resapan terma bagi logam bertambah, dan berkurangan apabila elektron mengalir dalam arah berlawanan. Kami juga mendapati kesemua ini berlaku tanpa penambahan haba dalam pepejal kerana fenomena berlaku dalan keadaan litar terbuka sehingga kesan pemanasan Joule kepada elektron yang mengalir dapat dihapuskan.

ACKNOWLEDGEMENTS

In the name of Allah the most Gracious the most merciful. I will like to begin by first thanking Allah the most merciful and most knowledgeable for making it possible for me to accomplish this task in my life time.

Special thanks and gratitudes go to my late parents for their role in seeing to my upbringing and education when they were alive. Theirs is a love,commitment, sacrifice, will and strength I'm yet to find its similarity. I pray that Allah rewards them abundantly, forgive their mistakes and shortcomings and makes Jannatul-firdaus their final abode.

Special thanks and mention must to be made of the chairman of my supervisory committee in person of Prof. (Dr.) Mohd. Maarof Bin Hj Abd Moksin for his tireless efforts and commitments from the start and completion of this work. His constructive criticism, comments, suggestions and advice are actually what make this work focused and successful. The whole idea behind the work is owed to his resourcefulness. I pray that Allah will continue to increase his vast knowledge, forgive his shortcomings and rewards him with His best of rewards here and in the hereafter.

Other members of my research supervisory committee including Prof. (Dr.) Azmi Bin Zakaria, Prof. (Dr.) Zainal Abidin Bin Talib (the Dean, Faculty of Science) and Associate Prof. (Dr.) Jumiah Bint Hassan are equally appreciated for their supervisory role, comments, commitments and advice throughout this work.

For Prof. (Dr.) Azmi Bin Zakaria I actually have no enough words to describe his believe, understanding and commitments in the execution and success of this work and particularly his acceptance to continue as the chairman of the supervisory committee when Prof. (Dr.) Mohd. Maarof Bin Hj Abd Moksin retired from the services of the Univerisity before my graduation. May Allah continue to increase his vast knowledge, forgive his shortcomings and rewards him with His best of rewards here and hereafter.

To my immediate and larger family I say a very big thank you for your patience, understanding and reasoning with self throughout this work. Your believe, good wishes, patience and prayers have really helped me especially during the difficult times of this research. May Allah continue to strengthen us in love, understanding and patience to one another.

To my best friends and co-researcher here in Malaysia, Shahril Husin I want to say thank you so much for the friendship, understanding and help throughout this work and my stay here in Malaysia. As we belong to the same research group and carried

out similar experiments, Shahril put me through all the soft and hard- wares needed for this work. To friends and family members back in Nigeria I say thank you all for your love, prayers and understanding throughout this programme. I also wish to appreciate my friend Sirajo Lawan Bichi for his extraordinary input in the mathematical analysis of this work and his friendly gesture toward self and family during the course of my studies. Mention must also be made of such friends and collegues including but not limited to Dr. Sabo Wada Dutse, Salahu Hamza Muhammed, DR. Eng. Bashir Ahmed D/Zomo, Shamsu Abubakar, Alhassan Shu'aibu, Yusuf Zuntu, and many more that time and space will not allow self to put down. Thank you all

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

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LIST OF ABBREVIATIONS

AC	Alternating Current
d	Thickness of Layer/Material
DE	Differential Equation
DC	Direct Current
e	Electronic Charge
E	Electric Field Strength
F	Force Field
I	Current
k	Thermal Conductivity
m	Mass
ODE	Ordinary Differential Equation
P	Power
PD	Potential Difference
PDE	Partial Differential Equation
q	Quantity of Camera Heating Energy
r	Radius of Camera Flash Heating Ring
R	Radius of Sample
s	Laplace Parameter
t	Time
t_0	Characteristic Rise Time
T	Temperature
V	Velocity
α	Thermal Diffusivity
β	Small-Value Negative Integer
τ	Pulse Duration
ρ	Density

CHAPTER 1

INTRODUCTION

Recent advances in science and technology bring about sophistication in electronics, photonics, sensors, photovoltaic and associated devices. These advances are made possible not only as a result of miniaturization or scaling down of transistors and associated components but also due to the fact that corresponding advances have been made in efficient heat removal from these systems. With less efficient heat removal techniques from these devices, sudden breakdown and or malfunction are bound to occur.

The use of layered materials in the efficient removal of heat from appliances is as imperative as the advances themselves. The Thermal Interface Materials (TIMs) for example used to remove heat from electronics and photonics devices is basically a multilayer device placed between the heat source and heat sink. Essential part of these TIMs is a metal or any thermal conducting material containing free electrons and or phonons that carries the generated and unwanted thermal energy for dissipation. In a situation where electrons are involved and also since most of these appliances work with applied Potential Difference (PD), the thermal diffusivity value of the metals conducting heat energy will change as a result of a change in the number and or velocity of the metals' free electrons. When the direction of flow of conducting electrons in a metal due to applied electric field coincides with the direction of heat dissipation path, or when more of the conducting electrons are made to flow in that direction, thermal diffusivity value of the metal is envisage to be enhanced. On the other hand, when the applied electric field makes conducting electron to flow in a path completely opposite to that of heat dissipation or when few electrons are made to flow in that direction, the metal's thermal diffusivity will likely be reduced greatly.

This work therefore, aims at using an extended version of Converging Thermal Wave (CTW) technique initially developed by Cielo and his co-workers to evaluate the possible change in the value of the thermal diffusivity of a metal in a three-layer device as the device carries Direct Current (DC) supply in both open and closed circuitries. The present chapter therefore gives a short and brief introduction of the topics and basic concepts to be covered in this thesis which include: thermal conductivity, thermal diffusivity, relationship between them and other thermo-physical quantities and classification of thermal conductivity into types and dimensions. Some highlights on the significance of experimental determination of thermal diffusivity are also given in this chapter. The general overview of the requirements for the experimental analysis of thermal diffusivity such as the heating source, the sample and sample holder, as well as the temperature probe is also briefly discussed. The chapter ends with the statement of our research problem, research objectives and an outline of our research scope.

1.1 Conduction of Heat in Solids

Sadik (1985) defines heat as the form of energy that crosses the boundary of a thermodynamic system by virtue of a temperature difference existing between the system and its surrounding, (Sadik, 1985). Heat is therefore understood as energy in transition and the potential that drives it along a certain path and or direction is the temperature gradient. Although heat transfer happens to be a very complex phenomenon in relation to processes through which it occurs, however three modes of heat transfer mechanisms have been observed as basic. These are conduction, convection and radiation. Temperature distribution in a medium is generally controlled by the combined effects of these modes of heat transfer. It is not therefore very easy to entirely isolate one mode of heat transfer from interactions with other modes. However, since in solids convection is altogether absent at working temperature of the present work while radiation is very negligible, (Carlslaw and Jaeger, 1959), only conduction, as the basic heat transfer mechanism in solids will be considered in this work.

Conduction of heat in solids is a microscopic phenomenon where more energetic particles of a substance transfer their energies to their less energetic neighbours. This energy transfer process in solids occurs by lattice vibrations (phonons) and or by motion of free electrons. Transfer of heat by phonons in non-metallic substances dominates that by free electrons in solids whereas electrons contributions dominate thermal conduction in metals, (Balandin, 2011).

1.1.1 Conduction of Heat in Metals

Since there is abundance of free electrons in metals, electronic contribution to thermal conduction dominates; with phonons contributing only about 1 - 2% of the total thermal conduction. This explains why all metallic substances are good electrical as well as good thermal conductors. The fact that free electrons are more numerous, free, light and interact with one another less often as a result of shielding and Pauli exclusion principle makes solids composed of electrons to conduct thermal energy better than solid composed of any other conducting quasi particle. The only possible exception to this is the pattern of thermal conduction in the recently discovered carbon-based materials where thermal conduction is extremely high, and yet brought about mostly by phonons contributions to thermal conduction.

Due to the similarity between the thermal and electrical conduction in metals, a relation based on experimental facts exists between the two phenomena. The Weidemann-Franz law gives this relationship and is stated as, the ratio of thermal and electrical conductivities is the same for all pure metals at the same temperature and is directly proportional to the absolute temperature of the metal. The constant of proportionality here is called the Lorentz number and is constant for all pure metals. Any effect which inhibits the flow of free electrons in a metal reduces both thermal and electrical conduction. Hence thermal conduction in pure metals is impeded by: rise in temperature of the metal, presence of impurities, mechanical forming and reduction in the density of the metal.

1.1.2 Conduction of Heat in Metallic Alloys

Electrons are also the majority carriers of thermal energy in this class of materials owing to their large concentrations. Their motion which was hitherto free in pure metals is however impeded by scattering with the introduced foreign atoms. Since the free electrons can not move as free and as quickly as in pure metals, their contribution to thermal conduction is greatly reduced. The thermal conductivity of pure copper near room temperature, for example, is 401 W/mK, presence of traces of arsenic reduces the value to 142 W/mK, (Thirumaleshwar, 2006). Unlike pure metals however, the thermal conductivity of alloys increases with temperature.

1.1.3 Conduction of Heat in Non Metallic Solids

These are the class of solid materials with less free conducting electrons. They are therefore generally bad conductors of both heat and electric current. Thermal conduction in these materials is carried mostly by lattice vibrations (phonons), as such conduction increases with increase in temperature. The contribution of electrons to thermal conduction here is very small as very few of them can break free from the potentials of the ion core holding them rigid. Other factors which can affect thermal conduction of these class of materials include density and moisture contents.

1.1.4 Conduction of Heat in Carbon-Based Materials

These are the class of materials with less free conducting electrons like all non metallic solids and hence supposed to behave in a similar manner. Yet, carbon-based materials show a remarkable departure from other non-metallic materials as far as thermal conduction is concerned. The thermal conductivity of graphite, for example, is reported to be as high as 2000 W/mK, (Yan et al., 2012) and between 4840 W/mK to 5300 W/mK for single-layer graphene at room temperature (Balandin et al., 2008). This high thermal conductivity is the sole contributions of phonons and is explained by the strong covalent sp^2 bonding resulting in efficient heat transfer by lattice vibrations in these materials, (Balandin, 2011).

1.2 Photothermal Analysis

Solids can be heated by absorbing optical radiation which produces a thermal change in the state of the solids. This process often called photothermal spectroscopy involves absorption of modulated light energy and its subsequent liberation from the solid. The liberated thermal energy usually contains information about the absorbed energy as well as details in respect to the thermal properties of the solid. The fraction of the absorbed thermal energy not only causes a change in temperature of the material but also changes in other properties of the solid such as density and pressure. Figure 1.1 shows the basic processes involved in Photothermal spectroscopy and the three thermodynamic parameters which change as a result of optical absorption by the solids.

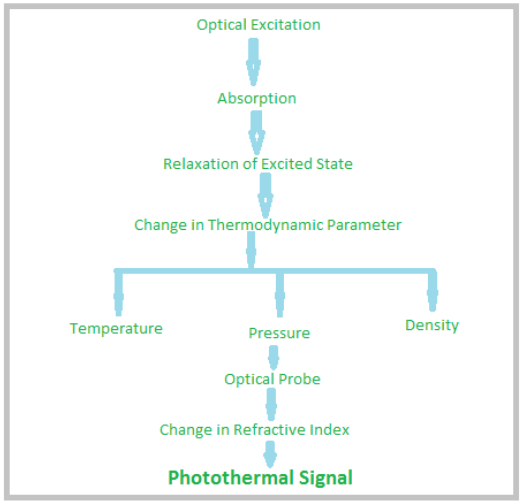

Figure 1.1: Processes involved in photothermal analysis

Each of these thermodynamic parameter is associated with some property/properties that can be measured from the interaction. If temperature is the thermodynamic property that changes as a result of the optical absorption, for example, this change can be measured in either of two ways. The temperature can be measured directly through a technique called calorimetric analysis using probes like thermocouples, thermistors, pyroelectric detection system, as done by majority of researchers in this field, (Parker et al., 1961), (Cielo et al., 1986), (Murphy et al., 2005), etc, or the temperature induced infrared emission can be measured through a process called photothermal transient radiometry as demonstrated by some researchers including (Vitkin et al., 1994), (Mandelis, 1991), (Imhof et al., 1998). Other measured properties and the detection techniques adopted for them are as summarised in Table 1.1.

Table 1.1: Common detection techniques used in photothermal spectroscopy

Thermodynamic Parameter	Measured Property	Detection Technique
Temperature	Temperature	Calorimetry
	Infrared Emission	Photothermal Radiometry
Pressure	Acoustic Waves	Photoacoustic Spectroscopy
Density	Refractive Index	Photothermal Lens
		Photothermal Interferometry
		Photothermal Deflection
		Photothermal Refraction
		Photothermal Diffraction
	Surface Deformation	Surface Deflection

1.3 Thermal Diffusivity and Thermal Conductivity

Thermal and electric fields coexist in electronics and photonics components and devices where electric field is needed and used to power the devices while thermal field is generated mostly by Joule heating. This generated thermal energy need to be removed from the devices for their proper functioning and most importantly to avoid breaking down of the devices. Since electrons are the major carriers of thermal energy in solids, their number, speed and direction will affect the amount of heat energy dissipated in a particular direction. The existence of both electric and temperature fields represents a closer approximation to the situation in any electronic device while in operation where problems associated with overheating are a major concern. As heat is therefore generated within current carrying materials, thermal diffusivity of the material may change from its known value depending on the magnitude and direction of the material's free electrons in relation to the direction of thermal dissipation in the material. To understand what really happens when electrons conduct heat in both the direction of heat dissipation path and in its completely opposite direction we need to understand some basics about heat conduction as enumerated below.

Whenever there is a temperature gradient within a body or when two or more bodies at different temperatures are brought in to thermal contact with one another, heat or thermal energy flows from the region of higher temperature to that at lower temperature. Apart from the temperature difference between the regions or bodies concerned, the most important intrinsic factor which determines the rate of thermal energy flow is a material property called thermal conductivity. Thermal conductivity may therefore be understood as that ability of a material which allows it to transport (conduct) heat from one point to the other. It is a direct microscopic exchange of kinetic energy of particles through the material boundary between two systems kept at different temperatures. At such instances heat flows from the region or material with highest temperature to that with lowest in accordance to the second law of thermodynamics, (Serway and Jewwet, 2010). At room temperature and fixed lower temperatures, electrons are the major carries of this heat energy in metals devoid of lattice imperfection and defects, whereas in carbon-based materials at the same temperature, phonons are the dominant carriers. Apart from conduction, convection and radiation are other known methods of transferring heat from one material to the other. However, in solids, convection is very negligible while radiation is all together absent hence, as far as heat transfer in solids is concerned, conduction processes are the leading methods.

The higher the thermal conductivity of a material, the better the material conducts heat, and vice versa. Consequently, in pure metals at room temperature, the higher the number of free electrons drifting in the direction of heat dissipation path, the better the metal conduct heat in that direction, and vice-versa. At fixed temperatures, thermal conductivity of a material is constant; otherwise it changes with a change in temperature of the substance (Carlslaw and Jaeger, 1959). The S.I. unit of thermal conductivity is the Watt per metre Kelvin (W/mK) and its dimension is given as M L $T^{-3}\theta^{-1}$.

1.4 Classification of Thermal Conductivity

Thermal conduction in solids may be classified into types and dimensionality as explained in the next subsections.

1.4.1 Types of Heat Conduction

Conduction of heat in solids may generally be categorized into transient or steady state. Transient state conduction is that in which the rate of heat transfer changes continuously with time and hence, the transfer rate is time dependent whereas, steady-state heat conduction is that in which the heat transfer rate does not change with time and hence the transfer rate can be said to be time independent. All natural conduction transfer processes begin as transient and then steadily approach steady state over time until equilibrium is attained.

1.4.2 Dimensionality of Heat Conduction

Depending on the magnitude of heat transfer rate in different directions of a solid, heat transfer can take place in one of the following dimensions: one-dimension, two-dimensions or three-dimensions. In one-dimensional heat transfer, the transfer rate is more assertive and dominant in one direction than the others. Temperature distribution, T is characterized by only one spatial component and the heat flux q characterized by one dimensional component. One-dimensional heat transfer can happen in all classes of materials depending on the material's geometry, the level of accuracy desired, (Yunus and Afshin, 2011) and the direction of the vector normal to isothermal surface drawn on the material. Examples of physical systems in which the transfer rate is approximately one-dimensional include: the hot metal plate of a pressing iron, electrical resistance wire, a cast iron steam pipe, etc. The Fourier's law of heat conduction in one-dimension for example, x-direction, through isotropic material is written as (Thirumaleshwar, 2006);

$$\frac{\partial q}{\partial t} = -kA\frac{\partial T}{\partial x} \tag{1.1}$$

Here q = thermal energy, t = time, k = thermal conductivity, A = material's cross sectional area and T = temperature.

In two-dimensional heat transfer, the transfer rate is approximated to take place more along two directions than the other remaining direction. Hence temperature distribution, T is characterized by two spatial components and the heat flux q is also characterized by two dimensional components; for example T_x, T_y and q_x, q_y for heat transfer along the x and y directions respectively. The Fourier's law of heat conduction in the two-dimensions mentioned above and through isotropic material is written as, (Carlslaw and Jaeger, 1959),

$$\frac{\partial^2 q_x}{\partial t^2}+\frac{\partial^2 q_y}{\partial t^2}=-kA(\frac{\partial T_x}{\partial x}+\frac{\partial T_y}{\partial y}) \tag{1.2}$$

In most general case, heat transfer problem is three-dimensional, i.e. that in which the heat conduction takes place through all the three principal directions (x, y, z in Cartesian coordinates). Here the temperature distribution is characterized by three different spatial components T_x, T_y, T_z while the heat flux term is characterized by three different components q_x, q_y, q_z. The three-dimensional heat conduction equation for a transient conduction in which no heat is generated is given as (Ozisik, 1993);

$$\frac{\partial^2 T_x}{\partial x^2}+\frac{\partial^2 T_y}{\partial y^2}+\frac{\partial^2 T_z}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1.3}$$

1.5 Thermal Diffusivity

Closely related to thermal conductivity is a quantity called thermal diffusivity which specifies how fast a material conduct heat. The higher the thermal diffusivity value of a material the faster the material conducts heat and vice versa. Like thermal conductivity, thermal diffusivity is also a function of material's temperature apart from other physical quantities. Its S.I. unit is $\mathrm{m^2s^{-1}}$ while its dimension is $\mathrm{L^2T^{-1}}$. Thermal diffusivity is mathematically related to thermal conductivity by the following relation;

$$k=\alpha\rho C \tag{1.4}$$

Here k = thermal conductivity, α = thermal diffusivity, ρ = density and C = specific heat capacity.
As a consequence of Equation (1.4) above, thermal diffusivity α is written as;

$$\alpha=\frac{k}{\rho C} \tag{1.5}$$

As the denominator to Equation (1.5) above is equivalent to the volumetric heat capacity of a material, thermal diffusivity can be thought to be a measure of the ratio of the total amount of heat conducted away by the material to that retained in it. Thermal diffusivity will also change when the direction of flow of metals' conducting electrons changes with that of the heat dissipation direction.

In the study of heat conduction in solids, thermal diffusivity is by far more important not only because of its mathematical relevance as given by Equations (1.4) and (1.5) above but, also because, it is more easier to determine experimentally than thermal conductivity or even other thermo-physical quantities. Some other advantages of experimental determination of thermal diffusivity include:

1. All thermal diffusivity experiments are transient in nature hence, less time is required to perform experiment.

2. They are much more accurate than thermal conductivity values.

3. Its determination makes the evaluation of other thermo-physical quantities easier.

4. Thermal diffusivity experiments make use of small samples sizes with different geometry

5. They are usually non-contact and less prone to errors

1.6 General Overview of Thermal Diffusivity Measurement

All experimental determination of thermal diffusivity of materials involves transient heating of a sample usually of small dimension but of almost any geometry. The essential features of these types of experiments involves the heating source, the heated sample, sample holder and temperature probe. These are briefly discussed in the subsections that follow.

1.6.1 The Heating Source

This is the source of thermal energy which initiates the heating of the sample. It is usually either a pulsed laser (coherent sources) or broad spectrum range sources (incoherent sources) used to induced initial temperature profile in the sample. Some of the coherent sources include: helium-neon gas, argon fluoride, Nd:YAG, argon ion, gallium arsenide, semiconductor diode array, etc. The incoherent sources on the other hand include: xenon-lamp, globar, nernst, and of recent camera flash, etc. Five types of sample heating used in photo-thermal method of thermal diffusivity experiments are as mentioned below (Park et al., 1995):

1. Large area surface heating.

2. Line heating.

3. Small spot heating

4. Grating heating and

5. Circular heating

In photo-thermal method of thermal diffusivity determination, the heating source is usually in a form of light source of high intensity. At the surface of the sample, and where the heating initiates, this light is converted to thermal energy and also causes other physical changes in and around the sample as shown in Figure 1.2, (Almond and Patel, 1996). Since after the first experiment in this series by Parker and his co-workers in 1966 (Parker et al., 1961), laser flash became the main source of heating in majority of transient thermal diffusivity experiments.

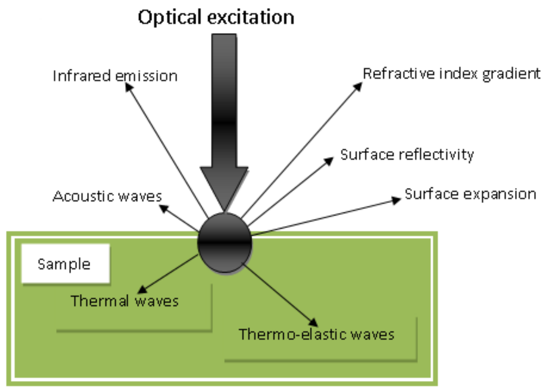

Figure 1.2: Photothermal phenomenon caused by sample illumination

The use of camera flash in place of laser as sample heating source in thermal diffusivity experiments is made possible due to the following reasons:

1. Camera flash is much cheaper to set up and maintain than laser flash apparatus.

2. It is much safer and easier to work with than the hazardous laser flash.

3. No much skill and or expertise is required to operate the camera flash set up.

4. It is small and portable and hence can be set up in almost all laboratories and can as well be moved about easily.

5. It can be operated with dry cell batteries and hence save a lot of trouble and energy in using electricity from the mains supply.

6. The fact that its width length is shorter than that of the laser flash affords the researcher a new but simpler mathematical method of evaluating the temporal temperature of the heated sample.

Generally, any other source of heating in the form of light may be used in as much as the converted thermal energy is just enough to initiates heating of the sample, high enough to be detected by the temperature probe and low enough so as not to produce any phase change in the sample.

1.6.2 The Sample and Sample Holder

Majority of the samples in transient thermal diffusivity experiments are some portion of solid, liquid or gas to be tested. The fluids are usually enclosed in a specially made container depending on its volume, type and weather the experiment is intended to be made for stationary or moving fluids. The solids on the other hand are most often small, thin and of almost any geometry. It is mounted on to a special surface called sample holder for the heating process.

Depending on the type of heating needed for the sample, different sample holders are made to hold the sample for the desired heating. The essential feature of all sample holders should be such that they held the sample fixed and rigid for the experiment, they neither block, absorb or reflect the light before its incident on the sample and also before it reaches the temperature probe, they should be appropriate to the type of heating required for the sample as explained in section 1.6.1 above.

1.6.3 The Temperature Probe

Thermal waves are detected using three general schemes: acoustic, optical and thermal, (Almond and Patel, 1996). Depending on whether the medium is solid or gas, acoustic detection techniques make use of either a piezoelectric transducer or a gas condenser microphone for the detection of thermoelastic waves in solid media or the detection of pressure variation in gas respectively. Optical methods of temperature probe makes use of probe beams and photo-detectors to monitor the variation in the optical properties of the heated sample or that of a fluid medium placed close to the heated sample. The last detection scheme listed above which is also employed in this work and majority of similar experimental works makes use of wide range of thermal detection apparatuses and appliances such as infrared detector, thermocouples, thermistor, pyroelectric transducers, etc., to detect thermal waves from the heated sample directly.

1.7 Research Question

In metals at room temperature, both phonons and electrons contribute to thermal conduction. The electrons' contribution however dominates with phonons contributing only about 1-2% of the total, (Balandin, 2011). In this class of materials therefore, and at the stated temperature and lower, electrons are the major carriers of heat and hence, their number, speed and direction of motion will affect the thermal conductivity and by extension thermal diffusivity of the material. The number, speed and direction of electrons may be affected by flowing or static electric field, whereas, temperature gradient is needed to initiate heat transfer process. The existence of both electric and temperature fields represents a closer approximation to the situation in any electronic device while in operation where problems associated with overheating are a major concern. As heat is therefore generated within current carrying materials, thermal diffusivity of the material may change from its known value depending on the magnitude and direction of the current in relation to the direction of thermal dissipation in the material. Current literature is however deficient on effect of flowing and static electric current on the thermal diffusivity of metals in three-layer solid configuration similar to thermal interface materials.

1.8 Research Objectives

The objectives of this research are as follows:

1. To derive and solve the two-dimensional unsteady-state heat conduction equation for a single-layer, two-layer and three-layer solid samples using the In-

tegral transform method so as to set up the basic theoretical scheme for the research work.

2. To fabricate different three-layer solid composites using different techniques and characterize same for use in the experimental determination of thermal diffusivity of a layer in the three-layer solid configuration.

3. To experimentally determine the thermal diffusivity of metal foils in three-layer solid configurations so as to calibrate the measuring scheme and apparatus.

4. To experimentally determine the effect of direct electric current passing across metal foils on the thermal diffusivity of the foils in three-layer solid configurations.

5. To experimentally determine the effect of static electric fields on the thermal diffusivity of metal foils in three-layer solid configurations.

1.9 Research Scope

This work aims at evaluating the effect of static and flowing direct electric current on the thermal diffusivity of metals occurring in three-layer solid composites. Unlike the flow of DC through a metal, it has been established that the flow of AC makes the sample's temperature profile non-parabolic and the volumetric power generated within the sample non-uniform, (Barletta and Zancini, 1995), (Abdel-Hamid, 1997), hence, this work will not focus on the effect of AC fields on the thermal diffusivity of the metal. Similarly, the work will concentrate more on the thermal diffusivity of three-layer solid samples under the influence of the fields mentioned above, as such single-layered and multi-layered solid samples with composite layers, $N \neq 3$ (N being the number of layers in the composite) will not be considered in this work. The work will only aimed at evaluating thermal diffusivity of the samples mentioned above; hence, no any other thermal property of the said three-layer solid composite will rigorously be evaluated in this work.

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