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Hai-Dong Wang

Theoretical and Experimental Studies on Non-Fourier Heat Conduction Based on Thermomass Theory

Doctoral Thesis accepted by
the Tsinghua University, Beijing, China

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3. Wang H D, Liu J H, Zhang X, Li T Y, Zhang R F and Wei F, Heat transfer between an individual carbon nanotube and gas environment in a wide Knudsen number regime. *Journal of Nanomaterials*, 2013, 181543.
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12. Zhang R F, Zhang Y Y, Zhang Q, Xie H H, Wang H D, Nie J Q, Wen Q and Wei F. Optical visualization of individual ultralong carbon nanotubes by chemical vapour deposition of titanium dioxide nanoparticles. *Nature Communications*, 2013, 4: 1727.

13. Liu J H, Wang H D, Ma W G, Zhang X and Song Y. Simultaneous measurement of thermal conductivity and thermal contact resistance of individual carbon fibers using Raman spectroscopy. *Review of Scientific Instruments*, 2013, 84: 044901.
14. Ma W G, Wang H D, Zhang X and Wang W. Theoretical and experimental study of femtosecond pulse laser heating on thin metal film (in Chinese). *ACTA PHYS SIN-CH ED*, 2011, 60(6): 064401.
15. Ma W G, Wang H D, Zhang X and Wang W. Study of the electron–phonon relaxation in thin metal films using transient thermoreflectance technique. *International Journal of Thermophysics*, 2011, DOI: 10.1007/s10765-011-1063-2.
16. Ma W G, Wang H D, Zhang X and Wang W. Experiment study of the size effects on electron–phonon relaxation and electrical resistivity of polycrystalline thin gold films. *Journal of Applied Physics*, 2010, 108: 064308.
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3. Wang H D, Cao B Y and Guo Z Y, Motion of thermomass in metals—state equation for thermomass in electron gas (in Chinese). *Journal of Engineering Thermophysics*, 2010, 31(5): 817–820.
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3. Wang H D, Ma W G, Zhang X and Wang W. Mass nature of heat and its applications iv: thermal wave and periodic temperature oscillation in metallic films heated by ultra-short pulsed lasers. In: Proceedings of 14th International Heat Transfer Conference (IHTC 2010). August 8–13, 2010, Washington DC, America.
4. Wang H D, Ma W G, Zhang X and Guo Z Y. Measurement of the thermal wave in metal films using femtosecond laser thermoreflectance system. In: Proceedings of 9th Kyoto-Seoul National-Tsinghua University Thermal Engineering Conference. October 21–23, 2009, Kyoto, Japan.
5. Wang H D, Cao B Y and Guo Z Y. Non-Fourier heat conduction in carbon nanotubes. In: Proceedings of 2nd Micro/Nanoscale Heat & Mass Transfer International Conference (MNHMT 2009). December 18–21, 2009, Shanghai, China.
6. Ma W G, Wang H D, Zhang X, et al. A novel relationship between thermal and electrical conductivities in polycrystalline metallic nanofilms. In: Proceedings of the 20th International Symposium on Transport Phenomena. July 7–10, 2009, Victoria B C., Canada.

Supervisor's Foreword

Recent rapid developments of ultra-fast laser technique and ultra-high heat flux micro-processors have imposed great challenges to classical thermophysical sciences. The fundamental theory of heat conduction Fourier's law is no longer valid for these extreme conditions. In recent years, great efforts have been made to study non-Fourier heat conduction, but the experimental data available are still limited because the non-Fourier phenomena only occur at very low temperatures or ultra-short time scales. Also, the present non-Fourier heat conduction models are only phenomenological ones depending on empirical parameters. Lacking a thorough understanding of the macroscale physical mechanisms, microscopic theory is difficult to use for practical applications. No theoretical models have yet been developed that fully explain non-Fourier heat conduction. This thesis analyzes non-Fourier heat conduction based on the first principles to develop a general heat conduction law. The theory is validated by comparisons with experimental results.

The main content and conclusions are:

1. Thermomass theory is used to analyze non-Fourier heat conduction. Thermomass is the relativistic mass of heat and the heat flux is known as the directional flow of thermomass along a temperature gradient. Newtonian mechanics is used to establish the thermomass motion equation, which is actually the general heat conduction equation. The thermomass theory gives a full understanding of non-Fourier heat conduction as the consequence of the non-negligible thermomass inertia effect. Furthermore, thermomass theory predicts the occurrence of non-Fourier heat conduction even for the steady case for the first time.
2. A femtosecond laser thermorefectance system has been established to detect the ultra-fast heat transfer between electrons and phonons in metallic nanofilms. A temperature wave was observed with a propagation speed of about $8.1 \times 10^5 \text{ ms}^{-1}$. The temperature wave is distinguished from the thermal wave with the temperature wave being the heat diffusion for periodic boundary conditions, while the thermal wave is actually the hyperbolic wave propagation.
3. A low temperature direct current measurement system has been established to study steady state non-Fourier heat conduction. The measured average temperature of the gold nanofilm was notably higher than the temperature predicted by Fourier's law, with the temperature difference increasing as the heating power increased or the environmental temperature decreased. The maximum

temperature difference reached 23 K at an environmental temperature of 3 K when the heat flux exceeded $2 \times 10^{10} \text{ Wm}^{-2}$. In this case, the thermomass inertia is non-negligible which causes the deviation from Fourier's law. The good agreement between the predictions of the general heat conduction law and the experimental data validates the thermomass theory.

4. The electrical and thermal conductivities of several gold nanofilms were measured from 3 K to 300 K. The measured conductivities are much less than the corresponding bulk conductivities, showing a significant size effect. The electron-grain boundary scattering is shown to be the dominant factor for this size effect. The Wiedemann–Franz law is found to fail at low temperatures because of the inelastic electron scattering (Raman electron scattering). A new theoretical model that takes inelastic electron scattering into account agrees well with the experimental data.

Beijing, October 2013

Zeng-Yuan Guo

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Contents

1	Introduction	1
1.1	Present Study on Non-Fourier Heat Conduction	1
1.2	Present Theoretical Models	3
1.2.1	C-V Model	3
1.2.2	Hyperbolic Two-Step Model	4
1.2.3	Parabolic Two-Step Model	5
1.2.4	Phonon Kinetic Model	5
1.2.5	Dual-Phase Lag Model	6
1.3	Present Experimental Study of Heat Conduction in Metallic Nanofilms	7
1.3.1	Experimental Study in Unsteady States	7
1.3.2	Experimental Study in Steady States	11
1.4	Conclusions	14
	References	15
2	Thermomass Theory for Non-Fourier Heat Conduction	21
2.1	Definition of Thermomass and the State Equation of Thermon Gas	21
2.1.1	Definition of Thermomass and Thermon Gas	21
2.1.2	State Equation of Thermon Gas in Ideal Gas	24
2.1.3	State Equation of Thermon Gas in Dielectrics	25
2.1.4	State Equation of Thermon Gas in Metals	26
2.1.5	Unified State Equation of Thermon Gas	29
2.2	Non-Fourier Heat Conduction Equation in Unsteady States	30
2.2.1	Governing Equation of Motion of Thermon Gas	30
2.2.2	General Heat Conduction Equation	31
2.2.3	Two-Step Thermomass Model for Metals	33
2.2.4	Numerical Simulation Examples	34
2.3	Non-Fourier Heat Conduction Equation in Steady States	42
2.4	Heat Flow Choking Phenomenon	44
2.5	Conclusions	52
	References	53

3	Experimental Investigation of Thermal Wave and Temperature Wave	55
3.1	Principles of Femtosecond Laser Thermoreflectance System.	55
3.1.1	Experimental Principle.	55
3.1.2	Experimental Setup.	58
3.2	Thermal Wave and Temperature Wave in Metallic Nanofilms	62
3.3	Measurement of Temperature Wave in Metallic Nanofilms	66
3.4	Electron–Phonon Coupling Factor and Interfacial Thermal Resistance	69
3.5	Conclusions	79
	References	80
4	Experimental Proof of Steady-State Non-Fourier Heat Conduction	83
4.1	Electrical and Thermal Conductivities of Metallic Nanofilms	83
4.1.1	Direct Current Heating Experiment of Metallic Nanofilms	83
4.1.2	Electrical Conductivity	89
4.1.3	Thermal Conductivity	93
4.1.4	Break Down of Wiedemann–Franz Law at Low Temperatures.	97
4.2	Experimental Proof of Steady Non-Fourier Heat Conduction	101
4.2.1	Experimental Principle.	101
4.2.2	Experimental Result and Analysis.	101
4.3	Conclusions	108
	References	109
5	Conclusions	111