Springer Theses

Recognizing Outstanding Ph.D. Research

For further volumes:
http://www.springer.com/series/8790

Aims and Scope

The series "Springer Theses" brings together a selection of the very best Ph.D. theses from around the world and across the physical sciences. Nominated and endorsed by two recognized specialists, each published volume has been selected for its scientific excellence and the high impact of its contents for the pertinent field of research. For greater accessibility to non-specialists, the published versions include an extended introduction, as well as a foreword by the student's supervisor explaining the special relevance of the work for the field. As a whole, the series will provide a valuable resource both for newcomers to the research fields described, and for other scientists seeking detailed background information on special questions. Finally, it provides an accredited documentation of the valuable contributions made by today's younger generation of scientists.

Theses are accepted into the series by invited nomination only and must fulfill all of the following criteria

- They must be written in good English.
- The topic should fall within the confines of Chemistry, Physics, Earth Sciences, Engineering and related interdisciplinary fields such as Materials, Nanoscience, Chemical Engineering, Complex Systems and Biophysics.
- The work reported in the thesis must represent a significant scientific advance.
- If the thesis includes previously published material, permission to reproduce this must be gained from the respective copyright holder.
- They must have been examined and passed during the 12 months prior to nomination.
- Each thesis should include a foreword by the supervisor outlining the significance of its content.
- The theses should have a clearly defined structure including an introduction accessible to scientists not expert in that particular field.

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

Springer

Author
Dr. Hai-Dong Wang
Department of Engineering Mechanics
School of Aerospace
Tsinghua University
Beijing
People's Republic of China

Supervisor
Prof. Zeng-Yuan Guo
Department of Engineering Mechanics
School of Aerospace
Tsinghua University
Beijing
People's Republic of China

ISSN 2190-5053 ISSN 2190-5061 (electronic)
ISBN 978-3-642-53976-3 ISBN 978-3-642-53977-0 (eBook)
DOI 10.1007/978-3-642-53977-0
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013957708

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Parts of this thesis have been published in the following journal articles

SCI Papers:

1. Wang H D, Liu J H, Zhang X and Takahashi Koji, Breakdown of Wiedemann–Franz law in individual suspended polycrystalline gold nanofilms down to 3 K. International Journal of Heat and Mass Transfer, 2013, in press.
2. Wang H D, Liu J H, Guo Z Y, Zhang X, Zhang R F, Wei F and Li T Y, Thermal transport across the interface between a suspended single-wall carbon nanotube and air. Nanoscale and Microscale Thermophysical Engineering, 2013, 17: 349365.
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.
4. Wang H D, Liu J H, Zhang X, Guo Z Y and Takahashi K. Non-Fourier heat conduction study for steady states in metallic nanofilms. Chinese Science Bulletin, 2012, 57(24): 3239−3243.
5. Wang H D, Cao B Y and Guo Z Y. Non-Fourier heat conduction in carbon nanotubes. Journal of Heat Transfer-ASME, 2012, 134, 051004.
6. Wang H D, Ma W G, Guo Z Y, Zhang X and Wang W. Measurement of electron–phonon coupling factor and interfacial thermal resistance of metallic nano-films using transient thermoreflectance technique. Chinese Physics B, 2011, 20(4), 040701.
7. Wang H D, Ma W G, Zhang X, Wang W and Guo Z Y. Theoretical and experimental study on the heat transport in metallic nanofilms heated by ultra-short pulsed laser. International Journal of Heat and Mass Transfer, 2011, 54(4): 967−974.
8. Wang H D, Liu J H, Zhang X, Guo Z Y and Takahashi K. Experimental study on the influences of grain boundary scattering on the charge and heat transport in gold and platinum nanofilms. Heat and Mass Transfer, 2011, 47(8): 893−898.
9. Wang H D and Guo Z Y. Thermon gas as the thermal energy carrier in gas and metals. Chinese Science Bulletin, 2010, 55(29): 3350−3355.
10. Wang H D, Cao B Y and Guo Z Y. Heat flow choking in carbon nanotubes. International Journal of Heat and Mass Transfer, 2010, 53(9−10): 1796−1800.
11. Wang H D, Ma W G, Zhang X and Wang W. Measurement of the thermal wave in metal films using femtosecond laser thermoreflectance system (in Chinese). ACTA PHYS SIN-CH ED, 2010, 59(6): 3856−3862.
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.
17. Ma W G, Wang H D, Zhang X and Takahashi Koji. Different effects of grain boundary scattering on charge and heat transport in polycrystalline platinum and gold nanofilms. Chinese Physics B, 2009, 18(5): 2035−2040.

EI Papers:

1. Wang H D and Guo Z Y. Thermomass two step model and general heat conduction law for metals (in Chinese). Journal of Engineering Thermophysics, 2013, 34(4): 738−741.
2. Wang H D, Ma W G, Guo Z Y, Zhang X and Wang W. Experimental study of ultra-fast heat conduction process in metals using femtosecond laser thermal reflection method (in Chinese). Journal of Engineering Thermophysics, 2011, 32(3): 465−468.
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.
4. Liu J H, Wang H D, Ma W G, Zhang X and Guo Z Y, Experimental study of thermal and electrical properties of gold nanofilms at ultra low temperature (in Chinese). Journal of Engineering Thermophysics, 2012, 33(11): 1944−1946.
5. Ma W G, Wang H D, Zhang X and Wang W. Electron–phonon coupling in thin gold films (in Chinese). CIESC Journal, 2011, 62(S1): 48−53.
6. Ma W G, Wang H D, Zhang X and Guo Z Y. Experimental study of electron–phonon coupling factor of copper thin film (in Chinese). Journal of Engineering Thermophysics, 2010, 31(3): 499−502.
7. Ma W G, Wang H D, Cao B Y and Zhang X. Experimental study of thermal and electrical properties of gold nanofilms (in Chinese). Journal of Engineering Thermophysics, 2009, 30(11): 1907−1909.

International Conference Papers:

1. Wang H D, Cao B Y, Zhang X and Guo Z Y. Experimental proof of energy-mass duality of heat. In: Proceedings of 3rd International Forum on Heat Transfer (IFHT2012). November 13−15, 2012, Nagasaki, Japan.
2. Wang H D, Ma W G, Zhang X and Wang W. Use of genetic algorithms for the simultaneous estimation of electron–phonon coupling factor and interfacial thermal resistance of metallic thin films. In: Proceedings of 9th Asian Thermophysical Properties Conference (ATPC 2010). October 19−22, 2010, Beijing, China.
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 thermoreflectance 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 8.1×10^5 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 2×10^{10} 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

Acknowledgments

I would like to express my appreciation and thanks to my supervisor, Prof. Zeng-Yuan Guo, and to Prof. Xing Zhang who has guided and helped me with my experimental work from the very beginning. It has been a great honor for me to be a student of these two great professors in the past several years. They have guided me into this exciting frontier thermal science field and taught me how to think and work as a skilled researcher. I appreciate all their ideas, encouragement, and constructive comments that help me to accomplish my Ph.D. research at Tsinghua University.

I would also like to thank all the members in our research group, Wei-Gang Ma, Jin-Hui Liu, Qin-Yi Li, Yu-Dong Hu, Jian-Li Wang, Xue-Tao Cheng, Wei-Ming Song, Zhi-Qiang Zhou, Sheng-Hong Ju, and Yuan-Wei Li. Their brilliant insights and collaboration have been of great help to me. Their warmness and kind sharing made our laboratory a great family.

I would like to thank Prof. Koji Takahashi, Prof. Hiroshi Takamatsu and Prof. Yasuyuki Takata at Kyushu University for their excellent nanofilm samples and kind suggestions for experiments and analyses. I would like to thank Prof. Kai-Li Jiang, Prof. Fei Wei, and their students, Tian-Yi Li, Ru-Fan Zhang and Huan-Huan Xie for providing us perfect carbon nanotube samples and kind discussions for experiments.

Finally, I would like to thank my wife and parents for their never-ending love and support for my research career.

This work is supported by the National Natural Science Foundation of China (Grant Nos. 51327001, 51136001, 51076080, 50730006 and 50976053), China Postdoctoral Science Foundation and Tsinghua University Initiative Scientific Research Program.

Contents