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

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Hai-Dong Wang

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

Doctoral Thesis accepted by
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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.
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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.
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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.

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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.
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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} $\mathrm{Wm^{-2}}$. 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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