DE-FG03-92ER14287
Final Report

Scholarly Publications (1997-98) of Chang-Lin Tien

DOE/ER/14287-T3

Books

1. C.L. Tien (Editor), Annual Review of Heat Transfer, Vol. 8, 318 pp., Begell House, New York (1997).
2. C.L. Tien, A. Majumdar, and F.M. Gerner (Editors), Microscale Energy Transport, 385 pp., Taylor & Francis, Washington, DC (1998).

Refereed Papers

1. J.P. Longtin and C.L. Tien, "Efficient Laser Heating of Transparent Liquids Using Multiphoton Absorption," International Journal of Heat and Mass Transfer, 40, 951-959 (1997).
2. A. Yabe, S. Terakado, J. P. Longtin, M. C. Hipwell, and C. L. Tien, "Thermoelectric Characteristics of Microscale Thin-Film Thermocouples," Microscale Thermophysical Engineering, 1, 53-60 (1997).
3. G. Chen, *et al.*, "Report of Workshop: Thermophysical Phenomena in Microscale Sensors, Devices, and Structures," Microscale Thermophysical Engineering, 1, 267-274 (1997).
4. A. Majumdar and C.L. Tien, "Micro Power Devices", Microscale Thermophysical Engineering, 2, 67-69 (1998).
5. M.C. Hipwell, C. L. Tien, X. L. Mao, and R. E. Russo, "Picosecond Differential Transmission Measurements on Porous Silicon," Microscale Thermophysical Engineering, 2, 87-99 (1998).
6. L. M. Phinney and C. L. Tien, "Recovery Mechanisms for Stiction-Failed Microcantilevers Using Short-Pulsed Lasers," Proceedings of the 11th International Heat Transfer Conference, 5, 145-150 (1998).
7. X.G. Liang, J.R. Lukes, and C.L. Tien, "Anisotropic Thermal Conductance in Thin Layers of Disordered Packed Spheres," Proceedings of the 11th International Heat Transfer Conference, 7, 33-38 (1998).
8. M. C. Hipwell, C. L. Tien, X. L. Mao, and R. E. Russo, "The Dual Beam Picosecond Continuum Technique for Measurement of Short Time-Scale Transmission Spectra," to appear in Experimental Heat Transfer.
9. M. C. Hipwell, and C. L. Tien, "Short Time-Scale Radiative Transfer in Light-Emitting Porous Silicon," to appear in International Journal of Heat and Mass Transfer.
10. Phinney, L. M., Fushinobu, K, and C. L. Tien, "Subpicosecond Laser Processing of Polycrystalline Silicon Microstructures," to appear in Microscale Thermophysical Engineering.

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11. C.L. Tien, J.R. Lukes, and F.C. Chou, "Molecular Dynamics Simulation on Thermal Transport in Solids," to appear in Microscale Thermophysical Engineering.
12. L. M. Phinney and C. L. Tien, "Electronic Desorption of Surface Species Using Short-Pulse Lasers," to appear in Journal of Heat Transfer.
13. F.C. Chou, J.R. Lukes, and C.L. Tien, "Heat Transfer Enhancement by Fins in the Microscale Regime," submitted to Journal of Heat Transfer.
14. J.R. Lukes, X.G. Liang, and C.L. Tien, "Molecular Dynamics Study of Solid Thin-Film Thermal Conductivity," submitted to Journal of Heat Transfer.

Introduction

The general objective of the current research program is to achieve a better understanding of the fundamental mechanisms of thermal radiation and heat conduction in microscale structures commonly encountered in engineering applications. Specifically, the program includes both experimental and analytical investigations of radiative heat transfer in microstructures, conductive heat transfer in micro devices, and short-pulse laser material interactions. Future work is planned to apply the knowledge of microscale heat transfer gained in this project to developing thermal insulating aerogel materials, thermal design schemes for quantum well lasers, and short-pulse laser micro-fabrication techniques.

Research Progress

Three major research activities have been scheduled and are currently in progress: (1) heat transfer in micro length scales, (2) heat transfer in micro devices, and (3) heat transfer in micro time scales. The specific scientific and technical issues being addressed are partially coherent radiative properties of thin films, nonlinear radiation interactions with materials, thermal properties and design of quantum well lasers, and laser heating mechanisms in the femtosecond and picosecond regimes.

Radiation-Microstructure Interactions. Radiative interactions with microstructures are important for the determination of the structure's properties. A general theory based on the coherence theory of light was established to describe the optical behavior of multi-layer thin films not only in the limiting geometric or wave optics cases, but also in the intermediate range, the partial coherent case. Experiments on the transmissivity of one and two-layer films conducted with an Infrared Spectrometer confirm the theoretical approach. Figure 1 is a regime map for film radiative properties. Absorption of radiation generates a thermal field in thin films, thus altering radiation

Figure 1 Regime map for film radiative properties

propagation and absorption through temperature-dependent optical properties. An analytical model combining both electromagnetic wave and heat conduction theories was constructed to characterize this strongly coupled nonlinear process. The results are useful for optical characterization of thin films, design and operation of optical bistability devices, and localized processing of film structures. Further experimental and theoretical investigations are in progress to characterize radiation interactions with oxide films, non planar microstructures, and highly scattering biological tissues. The information will be important for precision laser processing and imaging.

Thermal Characteristics of Quantum Well Lasers. Gallium arsenide (GaAs) based quantum well (QW) lasers represent a rapidly expanding area of research and development. A major problem in the design of better semiconducting lasers is heat dissipation. Thermal diffusivity is an important parameter for heat dissipation in QW lasers, and its value generally differs from that of the corresponding bulk materials due to the effects of microstructures, boundaries, and interfaces. A new measurement technique that determines the thermal diffusivity of thin films in both parallel and perpendicular directions has been developed. Experimental results show that the thermal diffusivity of the vertical-cavity surface-emitting laser structure is anisotropic and an order of magnitude smaller than that of the corresponding bulk media in the perpendicular direction. In addition, heat generation mechanisms in QW lasers were also studied and a new explanation for thermal damage of QW lasers is developed. Figure 2 shows the comparison of the new thermal-damage explanation with the conventional one. Further studies are in progress to implement these findings to the thermal design of QW lasers, including optimization of temperature distributions and structure dimensions. This effort will increase the reliability and output power of QW lasers.

Short-Pulse Laser-Material Interactions. Pulse durations in modern short-pulse lasers have been reduced from microseconds to femtoseconds, greatly increasing the time resolution of optical observations and the spatial controllability of laser processing.

Figure 2 Comparison of the new explanation with the conventional one

Due to the extremely high heat flux and short interaction times encountered in short-pulse laser applications, applicability of conventional thermal models is subject to question. A general macroscopic model based on microscopic electron-lattice interaction and electron transport was developed to describe short-pulse laser heating of metals. Femtosecond laser heating experiments were conducted for single and multi-layer metal films. The results show that laser heating of metals involves a two-step microscopic process: the radiation absorption by free electrons and the subsequent energy redistribution between electrons and the lattice. The conversion of laser energy to lattice energy is not instantaneous and does not occur at the location where it is absorbed. Microscopic energy deposition and transport must be considered for short-pulse laser-material interactions. Figure 3 summarizes different heat transfer mechanisms in different time regimes for laser heating of gold. The knowledge gained in this research program is useful for the thermal design of high-power laser components and for a better control of short-pulse laser micro fabrication as well as short-pulse diagnostics.

Figure 3 Regime map for laser heating of gold

Referred Publications

1. G. Chen and C.L. Tien, "Partial Coherence Theory of Thin Film Radiative Properties," *Journal of Heat Transfer*, Vol. 114, pp. 636-643, 1992.
2. T.Q. Qiu and C.L. Tien, "Short-Pulse Laser Heating on Metals," *International Journal of Heat and Mass Transfer*, Vol. 35, pp. 719-725, 1992.
3. G. Chen and C.L. Tien, "Thermal Conductivities of Quantum Well Structures," *Journal of Thermophysics and Heat Transfer*, Vol. 7, pp. 311-318, 1993.
4. G. Chen and C.L. Tien, "Internal Reflection effects on Transient Photothermal Reflectance," *Journal of Applied Physics*, Vol. 73, pp. 3461-3466, 1993.
5. G. Chen and C.L. Tien, "Facet Heating of Quantum Well Lasers," *Journal of Applied Physics*, Vol. 74, pp. 2167-2174, 1993.
6. G. Chen and C.L. Tien, "Thermally-Induced Optical Nonlinearity During Transient Heating of Thin Films," *Journal of Applied Physics*, Vol. 73, pp. 3461-3466, 1993.
7. T.Q. Qiu and C.L. Tien, "Size Effects on Nonequilibrium Laser Heating of Metal Films," *Journal of Heat Transfer*, Vol. 115, pp. 842-847, 1993.
8. T.Q. Qiu and C.L. Tien, "Heat Transfer Mechanisms during Short-Pulse Laser Heating of Metals," *Journal of Heat Transfer*, Vol. 115, pp. 835-841, 1993.
9. K. Richter, G. Chen and C.L. Tien, "Partial Coherence Theory of Multilayer Thin-Film Optical Properties," *Optical Engineering*, Vol. 32, pp. 1897-1903, 1993.
10. C.L. Tien, T.Q. Qiu and P.M. Norris, "Microscale Thermal Phenomena in Contemporary Technology," to appear in *Journal of Thermal Science Engineering*, 1994.
11. J.P. Longtin, T.Q. Qiu and C.L. Tien, "Impact of Thermal Boundary Resistance on Laser Inclusion Damage," to appear in *Journal of Thermophysics and Heat Transfer*, 1994.
12. T.Q. Qiu, J.P. Longtin and C.L. Tien, "Characteristics of Radiation Absorption in Metallic Particles," to appear in *Journal of Heat Transfer*, 1994.
13. K. Richter, P.M. Norris and C.L. Tien, "Aerogels: Applications, Structure, and Heat Transfer Phenomena," to appear in *Annual Review of Heat Transfer*, Vol. VI, 1994.
14. P.M. Norris, G. Chen and C.L. Tien, "Size Effects on the Temperature Rise in Vertical-Cavity Surface-Emitting Laser Diodes," to appear in *International Journal of Heat and Mass Transfer*, 1994.
15. T.Q. Qiu and C.L. Tien, "Femtosecond Laser Heating of Multi-Layer Metals: Part I—Analysis," to appear in *International Journal of Heat and Mass Transfer*, 1994.
16. T.Q. Qiu, T. Juhasz, C.G. Suarez, W.E. Bron and C.L. Tien, "Femtosecond Laser Heating of Multi-Layer Metals: Part II—Experiment," to appear in *International Journal of Heat and Mass Transfer*, 1994.
17. T.Q. Qiu, C.P. Grigoropoulos and C.L. Tien, "A Novel Technique for Non-Contact and Microscale Temperature Measurements," to appear in *Experimental Heat Transfer*, 1994.
18. G. Chen and C.L. Tien, "Thermal Diffusivity Measurement of GaAs/AlGaAs Thin-Film Structures," to appear in *Journal of Heat Transfer*, 1994.
19. C.L. Tien and G. Chen, "Challenges in Microscale Radiative and Conductive Heat Transfer," to appear in *Journal of Heat Transfer*, 1994.

Unexpended Balance at End of Current Funding Period

The anticipated unexpended balance at the end of the current funding period is approximately \$11,700.

A budget for Year 3 follows on page 9.

Statement on Program Modifications

This research program follows the original proposal. There is and will be no significant modification of the program.

UCB Eng-9029
C-L Tien

Budget - Year 3
DOE Award DE-FG03-92ER14287
August 1, 1994 - July 31, 1995

	<u>Amt/time</u>	<u>Rate/mo*</u>	<u>Subtotal</u>	<u>Total</u>
Personnel				
C-L Tien, Principal Investigator	10% of cal. yr. effort		No Charge	
1.5 Grad. Student Researcher I	8 acad. yr. mos. @ 50%	\$2,072	\$12,930	
	4 summer mos. @ 100%	\$2,072	\$13,059	
TOTAL PERSONNEL				\$25,989
Employee Benefits				
Grad. Student	1.81%		\$470	
Grad. Student Health Insurance**	2.75%		\$715	
Grad. Stud. Partial Fee Remission**	12.77%		\$3,319	
Nonresident Tuition Remission, Fall '94, Spr. '95 for 1 GSR				
	\$4235/semester		\$8,470	
TOTAL EMPLOYEE BENEFITS				\$12,974
TOTAL PERSONNEL & BENEFITS				\$38,963
Travel				
2 East Coast RTs for contractors meetings:				
(2 x \$900 RT airfare; 3 days per diem @\$100/day)			\$2,400	
TOTAL TRAVEL				\$2,400
Other Direct Costs				
Materials and supplies; thermocouple wire; metal plates; piping			\$2,400	
Publication costs, page charges			\$836	
Xeroxing, communications, office supplies, etc.			\$433	
Clerical Services			\$2,252	
TOTAL OTHER DIRECT COSTS				\$5,921
TOTAL DIRECT COSTS				\$47,284
Indirect Costs	49.5% of Modified Total Direct Costs base of \$34,780			\$17,216
TOTAL AMOUNT REQUESTED - YEAR 3				\$64,500

*Current salary rates shown. Subtotals include a projected cost of living increase of 4.0% effective July 1, 1994.

**Graduate Student Health Insurance, Graduate Student Partial Fee Remission, & Nonresident Tuition Remission are not part of the indirect cost base.