REPORT OF WORKSHOP

2nd MICROTHERM WORKSHOP AND TUTORIAL ALBUQUERQUE CONVENTION CENTER

D. Cahill, G. Chen, M. S. Dresselhaus, K. E. Goodson, C.-M. Ho, J. Longtin, A. Majumdar, L. Phinney, R. Pohl, C. L. Tien, and C. Wong

Workshop Organizers: G. Chen, C. C. Wong, A. Majumdar, and C. L. Tien

PROGRAM

Tutorial, June 13, 1998

2:00–3:00 p.m. Registration and Refreshment

3:00–4:00 p.m. "Scanning Thermal Microscopy," A. Majumdar, University of California, Berkeley

4:00–5:00 p.m. "Micro-Electro-Mechanical-Systems," C. J. Kim, University of California, Los Angeles

5:00–6:00 p.m. "Micro-Flow Science and MEMS for Flow Control," C.-M. Ho, University of California, Los Angeles

6:00–7:00 p.m. "Thermophysics of Solid State Devices," G. Chen, University of California, Los Angeles

Workshop, June 14, 1998

7:20–8:10 a.m. Registration and Continental Breakfast

8:15–8:45 a.m. Keynote Lecture: "Low Dimensional Thermoelectrics," *M. S. Dresselhaus*, Massachusetts Institute of Technology

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*Invited paper.

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Session A: Thermal-Electric Solid State Devices (Chairs: D. G. Cahill and M. S. Dresselhaus)

8:45–9:00 a.m. *"Thermionic Emission Cooling in Single Barrier and Superlattice Heterostructures," *A. Shakouri*, C. LaBounty, P. Abraham, and J. E. Bowers, University of California, Santa Barbara

9:00–9:15 a.m. *"Thermal Conductance and Heat Capacity at the Quantum Limit," *K. Schwab*, California Institute of Technology

9:15–9:30 a.m. "Novel Passivation and IC Thermal Design," M. N. Touzelbaev, K. Kurabayashi, Y. S. Ju, and *K. E. Goodson*, Stanford University

9:30–9:45 a.m. "A Collective Impact Ionization Theory of Hot Current Filaments in Optically-Triggered Switches," *H. P. Hjalmarson*, F. J. Zutavern, G. M. Loubriel, Sandia National Laboratories; and D. R. Wake, University of Illinois, Urbana

9:45–10:00 a.m. "Two-Wire 3ω Method for Anisotropic Thin Film Thermal Conductivity Measurement," S. Q. Zhou, *G. Chen*, D. J. Yao; and C. J. Kim, X. Y. Zheng, J. L. Liu, and K. L. Wang, University of California, Los Angeles

10:00–10:20 a.m. Break

Session B: Micro and Nanostructures (Chairs: K. E. Goodson and R. O. Pohl)

10:20–10:35 a.m. *"Studying Disorder in Thin Films using Thermal Phonons," *R. O. Pohl*, Cornell University

10:35–10:50 a.m. *"Thermal Conductivity of Wear-Resistant Coatings," *D. Cahill* and A. J. Bullen, University of Illinois, Urbana; Torjbörn I. Selinder and S. Coromant, Stockholm, Sweden; and A. von Keudell, Max-Planck-Institut für Plasmaphysik

10:50–11:05 a.m. "Thermal Characteristics of Microtubes," *F.-C. Chou*, J. R. Lukes, and C.-L. Tien, University of California, Berkeley

11:05–11:20 a.m. "Microscale Thermal Relaxation in Silica Aerogels," *F. T. Conroy*, S. C. Davis, and P. M. Norris, University of Virginia, Charlottesville

11:20–11:35 a.m. *"Diamond and Polycrystalline Diamond for MEMS Applications: Atomic Level Simulations and Analysis of Experiments on Friction and Wear Processes," *T. Cagin*, J. Che, M. N. Gardos, and W. A. Goddard, California Institute of Technology

11:35–11:50 a.m. "Molecular Dynamics Simulation of Thermal Transport in Solids," *J. R. Lukes*, F.-C. Chou, and C.-L. Tien, University of California, Berkeley

11:50–12:05 p.m. "Hyperbolic Temperature Profiles for Micro-Scale Heating Elements," *C.-P. Jen*, and C.-C. Chieng, National Tsing Hua University, Hsinchu, Taiwan

12:05–1:15 p.m. Buffet Lunch

*Invited paper.

Session C: Microfluidics, Devices, and Systems (Chairs: J. P. Longtin and C.-M. Ho)

1:15–1:30 p.m. *"Study of Flow in a Micro Channel Suspended in Vacuum," S. Wu, Caltech, and J. Mai, University of California, Los Angeles; Y. Zohar, Hong Kong University of Science & Technology; Y. C. Tai, California Institute of Technology; and *C.-M. Ho*, University of California, Los Angeles

1:30–1:45 p.m. *"Cooling of Small-Scale Microelectronic Components with Synthetic Jet Actuators," *W. Z. Black*, A. Glezer, J. G. Hartley, M. B. Gillespie, and G. Russell, Georgia Institute of Technology

1:45–2:00 p.m. "Micro Pumping: A Technology Review," *S. Dessiatoun*, M. M. Ohadi, I. Ivakhnemco, and A. Gidwani, University of Maryland

2:00–2:15 p.m. "Micropump Based on the Temperature Dependence of Liquid Viscosity," *S. Matsumoto*, A. Klein, and R. Maeda, AIST/MITI, Tsukuba, Ibaraki, Japan

2:15–2:30 p.m. "Feedback Control of Microstate to Control Macrostate Properties of Controllable Fluids," *J. R. Lloyd* and C. J. Radcliffe, Michigan State University

2:30–2:45 p.m. "Miniature Heat Pump Design," *C. B. Gu*, N. S. Ashraf, K. B. Sundaram, and L. C. Chow, University Central Florida

2:45–3:00 p.m. "Disjoining Pressure Effect on the Wetting Characteristics in a Capillary Tube," *H. B. Ma*, G. P. Peterson, Texas A & M University; and D. M. Pratt, Air Force Research Laboratory Wright-Patterson AFB

3:00–3:15 p.m. "Thermosyphons Employing Microfabricated Components," C. Ramaswamy, *Y. Joshy*, and W. Nakayama, University of Maryland; and W. Johnson, Laboratory for Physical Sciences, College Park, Maryland

3:15–3:30 p.m. "Spatially Resolved Measurements of Wall Heat Transfer and Visualization of a Single Bubble on a Downward Facing Heated Surface," T. D. Rule, J. N. Chung, Washington State University; and J. Kim and T. S. Kalkur, University of Denver

3:30–3:50 p.m. Coffee Break

Session D: Photon-Microstructure and Photon-Fluid Interactions (Chair: L. Phinney)

3:50–4.05 p.m. "Energy Characterization of Pulsed-Laser Ablated Titanium Plume by Spectroscopic Techniques," *S. S. Chu* and C. P. Grigoropoulos, University of California, Berkeley

4:05–4:20 p.m. "Laser Modification of Glass Microstructure," *T. D. Bennett*, University of California, Santa Barbara; and D. J. Krajnovich, Western Digital, Santa Clara, California

*Invited paper.

4:20–4:35 p.m. "Temperature-Dependent Absorptance of $YBa_2Cu_3O_{7-\delta}$ Films in the Far Infrared," A. R. Kumar and *Z. M. Zhang*, University of Florida, Gainesville; and V. A. Boychev and D. B. Tanner, University of Florida, Gainesville

4:35–4:50 p.m. "High-Precision, Laser-Based Concentration Measurement of Binary Liquid Mixtures," *J. P. Longtin* and C.-H. Fan, State University of New York, Stony Brook

4:50–5:05 p.m. "Response of Micromachined Cantilivers to High Intensity Radiation," *L. M. Phinney*, University of Illinois, Urbana

5:05–5:20 p.m. *"Micro-Optomechanical Uncooled Infrared Camera," O. Kwon, M. Mao, T. Perazzo, and *A. Majumdar*, University of California, Berkeley; J. Varesi and P. Norton, Santa Barbara Research Center, Goleta, California

5:20–6:00 p.m. Open Forum

REPORT

The goal of this workshop and tutorial was to provide a cross-disciplinary forum for discussion, education, and presentation of the latest results in the rapidly developing area of microscale thermophysical engineering. It was co-funded by the Division of Chemical and Transport Systems of the National Science Foundation, the Division of Engineering of the Basic Energy Sciences in the U.S. Department of Energy, and Sandia National Laboratory. A one-day workshop was held on Sunday, 14 June 1998, in the Convention Center at Albuquerque, New Mexico. Preceding the workshop, on 13 June, four one-hour tutorial sessions were held to cover the fundamentals of the following active research areas: scanning thermal microscopy, thermophysics of solid-state devices, micro-electro-mechanical-systems; and micro-flow science and MEMS for flow control. As shown in the program, the workshop consisted of 28 presentations, which were divided into four sessions: thermal-electric solid state devices; micro- and nanostructures; microfluidics, devices, and systems; photon-microstructure and photon-fluid interactions. A keynote paper on low-dimensional thermoelectrics was presented by Professor Mildred S. Dresselhaus, Institute Professor at the Massachusetts Institute of Technology. The tutorial and the workshop were attended by approximately 40 and 80 participants, respectively, including people from academia (faculty and graduate students), industry, and national laboratories. A brief description of the highlights of the tutorial and workshop is provided here.

Tutorial

The tutorial session began with a review of the fundamentals and applications of scanning thermal microscope (SThM) by Arun Majumdar. Topics covered included the principles of various scanning probe microscope, fabrication of thermal probes for SThM, applications, and finished with a discussion of the heat transfer mechanisms between the tip and the sample. In the second tutorial, on

*Invited paper.

MEMS, C. J. Kim reviewed the basic microfabrication techniques, including bulk machining, surface machining, LIGA, and other nonconventional micromachining techniques, and gave examples of various micromachined devices. The third tutorial was given by C.-M. Ho on micro-fluid science and MEMS for flow control. This tutorial covered basic principles behind the control of macro fluidic systems with MEMS, and fundamental science issues related to the fluid flow at microscale. Applications examples of MEMS-based fluid devices to aeroplane control and biotechnology were illustrated. G. Chen concluded the tutorial sessions with a one-hour discussion of the thermophysics of solid-state devices. Fundamental concepts in solid-state physics about electrons and phonons were introduced, followed by a discussion of some examples of various size effects on electron and phonon transport in micro- and nanostructures. Applications of microscale heat transfer in microelectronics, thermoelectrics, and thermionics were illustrated.

The feedback we received from the tutorial participants was overwhelmingly positive, as noted in the attached summary of the survey results. All the feedback we received indicated that the tutorial was useful and should be included in future such workshops. After analyzing the comments, we think future tutorial topics could be more focused.

Workshop

The workshop began with a keynote speech by Professor Mildred S. Dresselhaus on low-dimensional thermoelectrics. The principles of increasing thermoelectric energy conversion efficiency through quantum size effects on electrons and classical size effects on phonons were elucidated. Proof-of-concept experimental results in quantum-well systems were reviewed, and recent developments on the fabrication and characterization of quantum wires for thermoelectric applications were presented. Professor Dresselhaus' work on low-dimensional thermoelectrics has generated tremendous interest in the thermoelectrics community, and she stressed that thermoelectrics is a highly multidisciplinary field, in that understanding micro- and nanoscale heat transfer is essential for the success of low-dimensional thermoelectrics.

Session A. Session A, on thermal-electric solid-state devices, began with a discussion of solid-state thermionics cooling by A. Shakouri. Shakouri described how electron transport at a heterojunction can be used to create technologically significant temperature drops and the possible application of these structures in the thermal management of optoelectronic devices. Cooling was demonstrated experimentally; reductions in lead and contact resistances will be needed to achieve the predicted cooling power. K. Schwab described the design of experiments that will be needed to achieve the quantum limit in low-temperature measurements of thermal conductance and heat capacity. The experimental system employs micromachined Si and SQUID noise thermometry. K. Goodson followed with an overview of recent results from his laboratory on thermal property measurement, novel dielectric materials, and thermal modeling of devices. Highly anisotropic thermal conduction has been discovered in polyimides, with important implications for the possibility of enhancing the thermal management of devices using this class of low-dielectric-constant insulators. H. Hjalmarso presented current theoretical ideas needed to explain the formation and propagation of current filaments in optically triggered GaAs switches. The electron-hole plasma reaches quasi-equilibrium at nanosecond time scales; the temperature of this plasma greatly exceeds the lattice temperature during the typical switching cycle of the device. Finally, G. Chen showed how the anisotropy of thermal conduction in a thin film can be studied using a two-wire version of the 3ω method. The thermal response of a wide metal line is dominated by the through thickness conduction, while a narrow metal line is also sensitive to the in-plane conductivity. For the Si/SiGe superlattice investigated, the ratio of in-plane to through-thickness conductivity is approximately 4.

Session B. R. O. Pohl started the session on micro- and nanostructures with a new method for studying imperfections in thin films using heat transport by thermal phonons in the frequency range of 5 to 100 GHz (50 to 1.0 K). It was tested through measurements of thermal oxide films on crystalline silicon. The phonon scattering was found to be equal to that in bulk a-SiO_2. This technique can also be applied to metal films. D. Cahill et al. reported measurements of the thermal conductivity of several industrially important thin film coatings of great hardness, which are being used as coatings on carbide cutting tools. They found that kappa-Al_2O_3 has a particularly small thermal conductivity, and thus appears to be especially useful as a thermal barrier. Cahill also discussed work in progress on amorphous carbon, and the prospects offered in particular by amorphous diamond. F.-C. Chou et al. examined the impact of interface scattering on thermal conduction in microtubes for practical heat transfer systems. For conduction normal to the tube walls, the critical tube radius is expected to be substantially larger than that predicted using macroscopic heat conduction theory. The authors also predicted substantial changes in the performance of pin fins and the effect of using hollow versus solid tubes. F. T. Conroy et al. studied acoustic transmission in silica aerogels using air-coupled ultrasonic transducers. They found that the relative reduction of acoustic velocity as a function of mean free path is identical for different gases at high pressures. The data were interpreted by comparing the acoustic frequency with the time scale for heat diffusion between the two phases in the aerogel. T. Cagin et al. discussed the importance of friction and wear for MEMS applications, and considered the advantages offered by diamond coatings. They presented a theoretical study of the atomic friction on diamond 100 surfaces, using a molecular dynamics method. They emphasized that this computational method can also be applied for arbitrary materials and surfaces. J. R. Lukes et al. performed classical molecular dynamics simulations of thermal conduction in solid argon using a Lennard-Jones potential function. They studied the variation of the heat transport rate with the dimensions of the sample. The predicted rates of heat flow differed substantially from those expected using both continuum and phonon transport theories. C. P. Jen and C. C. Chieng solved the hyperbolic heat conduction equation in three dimensions for microscale rectangular and circular heating elements using both Laplace and Fourier transform techniques. The predictions showed that the temperature distribution changes significantly with different shapes of heating elements for the same heat flux.

Session C. The Microfluidics, Devices, and Systems session addressed topics relating to fluid flow and heat transfer on the microscale. Topics included both gas and liquid systems for electronics cooling, micropumps and tubes, miniature heat pumps, surface-tension studies and systems, phase change, and novel techniques for altering fluid properties. The session started with a paper by C.-M. Ho and his group on a micron-scale flow measurement system designed to measure viscous heating effects for gas flows in very small channels, and under high driving pressures. The internal flow channel dimensions were approximately 20 × 2 × 4,400 μm. The free-standing channel can withstand up to 600 psig, and was suspended above 80-μm cavities. The channel was instrumented with integral temperature sensors, and a vacuum was applied to accurately measure the channel temperature due to viscous heating. The second paper, by W. Z. Black and co-workers, involved a novel small-scale synthetic jet actuator. The device generates a directed air stream by electrically forcing a small diaphragm to oscillate inside an enclosed cavity with a small exit hole. The air stream can be used to cool microelectronic components effectively, e.g., the CPU in a notebook computer. Important parameters include jet oscillation frequency and strength, and the distance from the surface to be cooled. The results show a significant increase in local cooling compared with natural convection. S. Dessiatoun presented an overview of current micropumping technology. The presentation discussed several important applications of micropumps, including integrated small-scale cooling systems for electronics and satellites, micro hydraulic actuators, and medical dosage control and administration., Several different pumping topologies were discussed, including thermally, chemically, and electrically actuated pumping mechanisms. An interesting micro pumping technique that utilizes the temperature-dependent viscosity of fluids to control fluid flow was presented by S. Matsumoto. Fluid enters and leaves a small pumping chamber through narrow slits that have an embedded heater. Liquids have a lower viscosity when heated, thus to “open” the valve the heater is actuated to increase the temperature of the liquid passing through the slit. To reduce flow, the heat is turned off, and the liquid cools, resulting in increased viscosity, and more resistance to flow. A novel technique for controlling fluid properties on the microscale has been developed by J. R. Lloyd and co-workers. They placed micron-sized particles in a dielectric liquid and applied an electric field that allows control of the organizational state of the fluid, which, in turn, affects thermophysical properties such as viscosity, thermal conductivity, and radiative transmittance. Furthermore, these properties can be altered in real time. L. Chou and his colleagues performed a feasibility study of a meso-scale heat pump. The projected dimensions of the heat pump are 10 cm in diameter and 1 cm in thickness. The high axial force developed between the compressor-integrated rotor and the underlying disk stator can generate high driving torque, which enables the compressor to achieve 300,000 rpm, while consuming only 2 W. The robust and efficient design of the compressor-actuation assembly is the major challenge. H. B. Ma and his co-workers investigated the disjoining pressure effect on the wetting characteristics in a capillary tube. The increase in contact angle is the primary reason for the decrease in the wicking height formed by a wetting liquid in a vertical heated capillary tube. Their mathematical model was compared with previously obtained experimental data. The findings have applications ranging from electronic thermal control to distillation columns. Y. Joshi and his colleagues explored the cooling of electronic components by thermosyphons. A two-phase thermosyphon circulates working fluid from the evaporator through tubes to the condenser. The evaporator is made of porous copper microstructures consisting of cross-linked rectangular channels, 300 μm wide and 550 μm deep. Silicon microstructures with large micropores per unit area have also been used. Heat fluxes up to 22 W/m^2 have been obtained. The objective of work by T. B. Rule and his colleagues is to obtain space-resolved heat transfer variations underneath a single bubble growing on a heated surface facing downward. Ninety-six serpentine platinum resistance heaters with a nominal resistance of 1,000 Ω each were fabricated on a quartz substrate using a lithographic process. Each heater is maintained at a constant temperature by an electronic feedback control circuit. Stationary bubbles of decreasing size were obtained with increased subcooling.

Session D. Photon-Microstructure and Photon-Fluid Interactions. The final session of the workshop consisted of six papers in the area of light-material interactions. The interaction of photons with titanium, glass, high-temperature superconducting films, liquid mixtures, and micromachined structures were all discussed. The focus of the papers in this session was on the physical phenomena occurring during such interactions and how these phenomena can be applied. Laser texturing, infrared detection, concentration measurement in fluid mixtures, and laser processing are among the applications that benefit from the results of the research presented in this session. S. S. Chu began the session by describing the results of experimental and numerical investigations into laser ablation of titanium. Their group used a KrF laser at fluences from 3 to 8 J/cm^2 and varied the background gas composition and pressure. Their studies revealed that the ablated species were extremely energetic and provide insight into the quality of deposited films formed using pulsed laser deposition (PLD). T. Bennett then presented work on laser texturing of glass disks. Laser texturing of metal computer disks is standard industry practice now, and companies desire the technology to similarly create controlled topology on glass disks. Bennett and Krajnovich's results showed how a fictive temperature map could be used to relate the thermal history of the glass to the resulting microstructure. The third presentation was by Z. Zhang and co-workers on the temperature variation of the spectral absorptance of high-temperature superconducting films at wavelengths from 100 to 1,000 μm. They found a significant difference in the absorptance depending on whether the radiation was incident on the film or substrate side of the sample for $YBa_2Cu_3O_{7-\delta}$ (YBCO) films deposited on silicon substrates. J. Longtin described the measurement of concentration in binary liquid mixtures using a laser-based technique, which resolved very small changes in concentration, on the order of 0.01%, by measuring changes in the index of refraction and relating them to the concentration. Ways of using same technique for very precise temperature measurement were discussed following the talk. L. Phinney gave the next presentation, concerning the vibrational response of micromachined polycrystalline cantilevers exposed to high-intensity radiation. The maximum deflection of the beams depended linearly on laser fluence, on the length squared, and on the inverse of the beam thickness squared. The implications on the recovery of stiction-failed microcantilevers were described. A. Majumdar concluded the session by presenting work on the development of a microoptomechanical infrared camber for use at room temperature. The design employs arrays of bimaterial cantilevers, which bend due to a mismatch in thermal expansion, to sense the incoming radiation, and an optical readout method to detect the cantilever deflections and project an image on a display. The design of an uncooled infrared camber is an exciting use of micromachining technology and will result in significant cost and weight reductions.

In the open forum, presided over by A. Majumdar, there was heated discussion on the education of microscale heat transfer. It was a consensus that this is a critical issue and a special session should be devoted to this topic at the next such workshop. In a comparison of this microtherm workshop with other MEMS conferences, C.-M. Ho remarked that this was a unique workshop and the only place where microscale heat transfer and fluid sciences were discussed seriously.

ABSTRACTS

Low Dimensional Thermoelectricity

M. S. Dresselhaus

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Interest in thermoelectric materials has recently been revived as an active research field, in part due to the recent demonstration of enhancement in the thermoelectric figure of merit of a two-dimensional PbTe quantum well system, relative to its three-dimensional (3D) bulk counterpart. Calculations suggest that the thermoelectric performance of any 3D material should show an enhanced thermoelectric figure of merit, when prepared as a 2D multi-quantum well superlattice, utilizing the enhanced density of states at the onset of each electronic subband, and the increased scattering of vibrational waves at the boundary between the quantum well and the adjacent barrier of the superlattice. Low dimensionality also allows certain materials such as bismuth, which are poor thermoelectrics in 3D, to become good thermoelectrics. Recent work on 1D bismuth nano-wires is also discussed with regard to potential thermoelectric applications.

Thermionic Emission Cooling in Single Barrier and Superlattice Heterostructures

A. Shakouri, C. LaBounty, P. Abraham, and J. E. Bowers

Department of Electrical and Computer Engineering, University of California, Santa Barbara, California, USA

Conventional thermoelectric cooling materials are optimized by changing their bulk properties: electrical conductivity, thermal conductivity, and Seebeck coefficient. Thermionic emission current in heterostructure can be used to make solid-state evaporative coolers by selective emission of hot electrons over a barrier layer. In the latter case, there is an extra degree of freedom in the device design by considering interface and junction properties. Theoretical and experimental results about nonisothermal thermionic emission in single barrier and superlattice heterostructures are presented. Cooling on the order of a degree over a 1-μm-thick InGaAsP barrier and InGaAs/InGaAsP superlattice structure is reported.

Thermal Conductance and Heat Capacity at the Quantum Limit

*K. Schwab**

Condensed Matter Physics, Department of Physics, California Institute of Technology, Pasadena, California, USA

We are fabricating monocrystalline suspended semiconductor devices at length scales where one or more dimension is smaller than the dominant phonon wavelength at temperatures from 10 to 500 mK. In this size and temperature regime we expect to demonstrate thermal conductance and heat capacity measurements at the quantum limit. I present our recent efforts and results toward this end. It has recently been predicted that thermal conductance through ballistic phonon "channels" should approach a universal value at these temperatures: $K = \pi^2 k_b^2 T/3h$. This phenomenon is analogous to electronic conductance quantization, although some fundamental differences arise due to the bosonic versus fermionic nature of the excitations involved. We are utilizing dc SQUID-based thermometry techniques that yield minimal back action; we anticipate that these will ultimately enable heat capacity measurements on these nanofabricated devices with an energy sensitivity at the level of individual phonons. Such sensitivity should reveal new, exotic phenomena reflecting the quantum statistics of the phonons, such as phonon bunching, anticorrelated electron-phonon scattering, and the observation of the phonon-by-phonon decay of energy within an isolated, nanoscale thermal reservoir.

Novel Passivation and IC Thermal Design

M. N. Touzelbaev, K. Kurabayashi, P. G. Sverdrup, Y. S. Ju, and K. E. Goodson

Department of Mechanical Engineering, Stanford University, Stanford, California, USA

The semiconductor industry is incorporating a broad variety of novel dielectric materials into modern circuits, which replace conventional oxide passivation and promise improvements in performance and reliability. Novel materials include polymers, inorganic spin-on glasses, and porous oxides, which reduce interconnect delay for GHz logic, as well as diamond and diamond-like carbon layers, which improve conduction cooling and breakdown characteristics for smart power. Since the thermal properties of these materials are strongly anisotropic, nonhomogeneous, and process-dependent, the industry is seeking tools for their characterization and models that aid with thermal design.

This talk summarizes techniques and data that we are transferring to the IC industry, which determine the heat capacity and components of thermal conductivity tensor in novel passive layers. The measurements combine laser or Joule heating and optical thermometry at frequencies up to 100 kHz to minimize the experimental uncertainty. The data are used to improve and verify recent models for the anisotropy of thin-film polymers and diamond. We also report measurements and predictions of the temperature distributions in circuit structures with

*In collaboration with C.-W. Fon, E. Henriksen, J. M. Worlock, and M. L. Roukes.

Thermal Conductivity of Wear-Resistant Coatings

D. G. Cahill and A. J. Bullen
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T. I. Selinder
Sandvik Coromant, Stockholm, Sweden

A. von Keudell
Max-Planck-Institut für Plasmaphysik, München, Germany

We discuss our recent experiments on the thermal conductivity of two industrially important thin-film materials with high hardness: alumina and amorphous hydrogenated carbon. Alumina coatings are applied to carbide cutting tools to increase the performance and durability of the cutting edge. Chemical vapor deposition (CVD) α-Al_2O_3 coatings, 13 μ-thick, have a thermal conductivity comparable to single-crystal sapphire at $T > 300$ K. The relatively small thermal conductivity of κ-AI_2O_3 coatings suggests that this metastable phase of alumina can be applied as a thermal barrier for cutting tools. Hard carbon coatings are widely used as protective thin films; the hardness and hydrogen content are known to be highly sensitive to ion bombardment energy during plasma-enhanced CVD. The thermal conductivity of hard a-C : H is a fact of ~ 4 larger than that of polymeric a-C : H, but significantly smaller than theoretical expectations for “amorphous diamond.”

Thermal Characteristics of Microtubes

F.-C. Chou,* J. R. Lukes, and C.-L. Tien
Department of Mechanical Engineering, University of California, Berkeley, California, USA

The current literature contains many theoretical and experimental studies of thermal characteristics of thin films, but very few of them have paid attention to the thermal characteristics of microtubes. Hoffman [1] reported that microtubes could be made from practically any materials, and tubes larger than 1 μm in diameter could be made with any cross-sectional shape desired. Microtubes and microtube composites will provide the opportunity to miniaturize (even to the nanoscale) devices, such as micro-refrigerators, injectors, micro heat exchangers for micro cooling or heating, etc. The present study analyzes how the size effect on the thermal conductivity of insulation materials or microtube wall affects the thermal characteristics of microtubes. This paper covers three issues. The first one is on the critical radius of microtubes. The critical radius is significantly larger than that determined by macroscale results. The thermal resistance even slightly increases

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with the increase of thickness of insulation materials or tube wall before the critical radius is reached for $r_i = R_i/\lambda > 0.8$. The variable R_i is the inner radius of the tube, and λ is the mean free path of the heat carrier for the bulk material. The second issue considered is how to minimize the outer surface temperature T_0 in problems of heating fluids in microtubes or cooling micro hot spots by flowing fluids through microtubes. The heat input rate and bulk mean temperature of fluid in the tubes are fixed. In the macroscale regime, the result is simple: the thicker the tube wall, the larger the thermal resistance, then the higher the outer surface temperature. The trend of thermal resistance across the microtubes wall for $r_i < 0.2$, however, is contrary to that in the macroscale regime; it decreases with the increase of tube wall thickness. The cause is that by thermal conductivity of the microtube wall increases when the thickness of the microtube wall increases. The third section considers using a microtube as the hollow pin fin. Compared with a solid pin fin, a hollow pin fin has a larger moment of inertia for the same weight. The issue is how the size effect on the microtube thermal conductivity affects the performance of a hollow pin fin compared to a solid pin fin. The present abstract takes the case of tube wall thickness $t = 0.1 r_i$ as an example: the hollow pin fin will have more than four times larger moment of inertia than a solid pin fin with a same weight. The heat transfer rate ratio Q_h/Q_s, in which the subscripts h and s denote hollow and solid pin fins, respectively, shows a local minimum with a value below 1.0 around $t/k = 0.1$. This result is caused by the difference of mean free path between the thin wall tube and solid cylinder.

REFERENCES

1. W. P. Hoffmann, The Application of Microtubes to Microstructures and Microfabricated Systems, Proc. Symp. on Microstructures and Microfabricated Systems held at the 185th Meeting of the Electrochemical Society, San Francisco, pp. 1–9, 1994.

Microscale Thermal Relaxation in Silica Aerogels

J. F. T. Conroy, B. Hosticka, S. C. Davis, and P. M. Norris

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The acoustic transmission velocity in silica aerogel was measured as a function of the gas type and pressure in the aerogel pores. This was done with air-coupled ultrasonic transducers configured for differential pulse transit time measurements. At high pressures, the fractional reduction of acoustic velocity as a function of mean free path is identical in different gasses.

The data can be interpreted in light of the thermal relaxation of the acoustic pulse. The microscale temperature oscillations of the gas and solid phases of the aerogel due to the acoustic pulse will not be identical if the heat transfer between the two phases is slow compared to the period of the acoustic oscillation. The energy transferred from the gas to the solid phase is lost and thus reduces the amplitude and velocity of the acoustic wave in the gas phase. The gas type and pressure provide adequate independent variables for probing these effects in aerogels.

Diamond and Polycrystalline Diamond for MEMS Applications: Atomic Level Simulations and Analysis of Experiments on Friction and Wear Processes

T. Cagin, J. Che, M. N. Gardos, and W. A. Goddard

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To date most MEMS devices have been based on silicon. This is due to the technological knowhow accummulated on manipulating, machining, and manufacturing of silicon. However, very few devices involve moving parts. This is because of the rapid wear arising from high friction in these silicon-based systems.

Recent tribometric experiments carried out by Gardos show that this rapid wear is caused by a variety of factors, related to both the surface chemistry and the cohesive energy density of silicon and diamond. In particular, the 1.8-times strength of the C—C bond in diamond as opposed to the Si—Si bond in the bulk translates into more than 10^4 times difference in wear rates, even though the difference in flexural strength is only 20 times, in hardness 10 times, and in fracture toughness 5 times. It has been shown that the wear rates of silicon and PCD are controlled by high friction-induced surface cracking, and the friction is controlled by the number of dangling, reconstructed, or adsorbate-passivated surface bonds. Therefore, theoretical and tribological characterization of Si and PCD surfaces is essential prior to device fabrication to assure reliable MEMS operation under various atmospheric environments, especially at elevated temperatures.

As part of rational design and manufacturing of MEMS devices, theory and simulation could play an important role. Predicting materials properties such as friction, wear, and thermal conductivity is of critical importance for materials and components to be used in MEMS. In this talk, we present theoretical studies of frictional process on diamond surfaces using a steady-state molecular dynamics method. We studied the atomic friction on diamond 100 surface using an extended bond order-dependent potential for hydrocarbon systems [1]. Unlike traditional empirical potentials, bond order potentials can simulate bond breaking and formation processes. Therefore, they are a natural choice with which to study surface dynamics under friction and wear. In order to calculate the material properties correctly, we have developed a consistent approach to incorporate nonbond interactions into bond order potentials. Besides the development of fundamental theory, we have also created an easy-to-use software under Cerius2 environment that can calculate atomic friction coefficient for an arbitrary system.

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Molecular Dynamics Simulation of Thermal Transport in Solids

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Novel nanometer-scale solid-phase materials such as buckyballs and buckytubes, highly nanoporous and ultrathin films, and quantum wires and dots are becoming increasingly important in modern technology. Thin solid films currently are key components in integrated-circuit transistors, quantum-well lasers, and microelectromechanical systems (MEMS). The favorable optical, thermophysical, mechanical, and/or electrical properties exhibited by quantum dots, quantum wires, porous thin films, and buckytubes may play a critical role in many future applications such as theramoelectric materials and optical computing devices. Operating temperatures have a significant impact on device and material performance in the above applications. For example, heating adversely affects the operation of vertical-cavity surface-emitting lasers and edge-emitting lasers, and temperature strongly influences the optical properties of semiconductor materials. For the best design of devices and novel materials in temperature-sensitive applications, an understanding of thermal transport is of paramount importance. The molecular dynamics computational technique will be an important tool for the analysis of thermal transport in such applications. Molecular dynamics (MD) is a computational method that simulates the real behavior of materials and calculates physical properties of these materials by simultaneously solving the equations of motion for a system of atoms interacting with a given potential. The MD method is especially suited to study the thermophysical properties of complex microstructures such as doped and nanoporous thin films, and materials with voids, cracks, dislocations, or other elaborate geometries. This work shows that molecular dynamics is a viable tool for calculating the thermal conductivity of solid thin films and, more generally, demonstrates the potential of molecular dynamics for ascertaining microscale thermophysical properties.

Hyperbolic Temperature Profiles for Micro-Scale Heating Elements

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Many pulsed heating processes of the order of material thermal characteristic time have been employed in microtechnology. This work investigates analytically non-Fourier effects on transient temperature distribution by a heat source of a micro-scale heated, rectangular plate by solving the three-dimensional hyperbolic heat conduction equations. The traditional Fourier heat conduction model implies an infinite speed of thermal signal and assumes that a local change of temperature will cause an instantaneous response in the temperature at each point of the material. It has been reported [1] that non-Fourier effects are dominating if the

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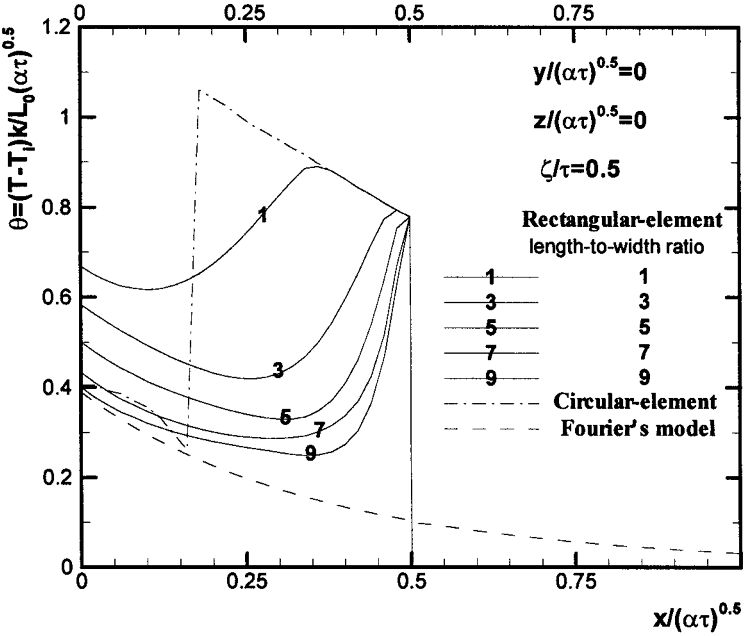

y/(ατ)^0.5=0
z/(ατ)^0.5=0
ζ/τ=0.5
Rectangular-element
length-to-width ratio
1
3
5
7
9
Circular-element
Fourier's model
θ=(T-T_i)k/L_0(ατ)^0.5
x/(ατ)^0.5
0
0.25
0.5
0.75
0.2
0.4
0.6
0.8
1
1.2

Study of Flow in a Micro Channel Suspended in Vacuum

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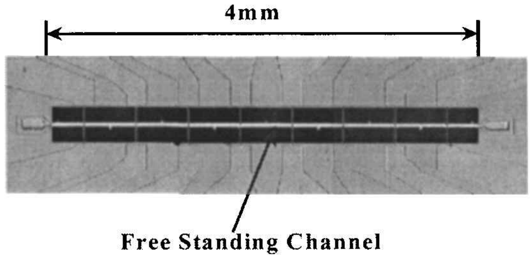
Micromachining is a rapidly emerging technology, which enables the fabrication of micron-scaled fluidic devices. Micro channels may be used in a variety of applications, such as for cooling of electronic circuits, transport of gases in micro chromatography, and micro fluidic control. In order to design and fabricate such micro devices effectively, the physical laws governing fluid flow in small conduits needs to be understood. Such a flow may differ from its macroscopic counterpart. The Knudsen number effect for a gas flow or surface force effects for a liquid flow may not be negligible because of the small length scale.

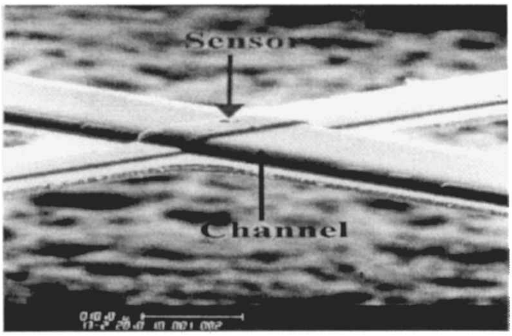
In this study, a freestanding micro channel (Figure 1*a*), with integrated temperature sensors (Figure 1*b*), has been developed for studying flow under high viscous dissipation. These micro channels are approximately 20 μm × 2 μm × 4,400 μm, and are suspended above 80-μm-deep cavities, bulk micromachined using a BrF_3 dry-etch technique. The free-standing channel was suspended in vacuum in order to examine the viscous heating effect. The thickness of the channel wall is only 1 μm. However, it can stand inlet pressure up to 600 psig.

In recent years, micro channel flow has attracted considerable attention for many possible biomedical applications. Pfahler et al. [1] estimated experimentally the friction factor for gas and liquid flow in small channels. Arkilic et al. [2] considered the effect of compressibility in a microchannel flow. Detailed studies were conducted by Pong et al. [3] and Shih et al. [4], who measured not only the overall pressure drop and flow rate, but also the pressure distribution along the microchannel. However, they were only able to obtain data for relatively low inlet pressures [5]. They showed that surface slip due to Knudsen number effect has been observed. If the density change due to the viscous dissipation is also included, the flow rate can be accurately determined.

Theoretical studies addressing compressible, viscous, steady laminar flow in small uniform conduits are limited. Prud'homme et al. [6] calculated the mass flow rate of gas through a long tube for an ideal gas. Van den Berg [7] presented a



(*a*)



(*b*)

Figure 1. (*a*) Top view of a free-standing micro channel. (*b*) SEM of a free-standing channel with a temperature sensor embedded onto the top wall.

detailed study using perturbation methods to calculate the mass flow rate of a gas through a cylindrical capillary. They clearly identified the effects of compressibility, acceleration, and the velocity profile.

We present experimental studies of gas and liquid flow through a micro channel under high inlet pressures. We compare the results with an analytical model developed for capillary flow that accounts for slip and compressibility as well as corrections for flow acceleration and the velocity profile. In this experiment, preliminary tests also have been performed to obtain the streamwise temperature distribution by using the integrated temperature sensors along the channel.

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Micro Pumping: A Technology Review

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Micro electromechanical devices (MEMS) are in increasing demand in a number of fields, including microelectronics, automotive technology, and biomedicine. The integration of MEMS with common micro electric circuits in micro systems yields a wide range of potential applications. Recent developments in integrated circuit (IC) technology yield circuits of much higher density, which has renewed concern about heat dissipation. Now that entire computers can be made in a single chip, heat dissipation for devices of this scale can no longer be solved by simply adding additional fans or specialized passive heat sinks. MEMS technology—in particular, micro pumps—can solve this problem of cooling chips that fit into microelectronic systems without adding vibration and without significant increases in weight or power consumption. The rapidly expanding telecommunications industry demands an increasing a number of small satellites for signal processing and conversion stations. For satellite programs, much of the cost is associated with the launch, which in turn is dependent on the weight of the system. Here again, MEMS technology finds a natural and effective application in the development of micro and nano satellites. Micro pumps and mechanical actuators are essential elements of future micro systems. They will be needed for integrated cooling devices, for pumping and portioning minute quantities of fluids, and, more recently, for micro hydraulic actuators. Applications for such devices include medical dosage-control implants, fuel injection, and microscopic fluid or gas sampling. Micro pumps come in two types—with and without mechanical moving parts. Miniaturization of systems with moving parts is limited by both friction and adhesion. However, in micro-fabricated systems using pumps without mechanical elements, fluid driving forces can be generated thermally (convection or boiling pumps), chemically (osmotic pumps), electrically (electro-convective pumps), by surface tension (capillary pumps), or with pumps utilizing acoustic pressure gradients.

This paper addresses advances in micro pumping technology, reviews several types of micro pumps and their corresponding actuation principles, and evaluates potential applications for the technology.

Micropump Based on the Temperature Dependence of Liquid Viscosity

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A micropump based on a novel flow rectification principle is developed. The proposed pump consists of a chamber with a diaphragm actuated by a piezoelectric element, and a pair of "dynamic valves," the function of which can be controlled thermally, without mechanically movable parts. A dynamic valve generates flow resistance, which is dependent on the direction of flow, yielding a net amount of flow as a result of reciprocating motion of the fluid. Our valve is based on the strong temperature dependence of the viscosity of the working liquid. The flow rectification is achieved by heating and cooling the liquid in the valve channel, synchronously to the alternation of the flow direction caused by the diaphragm vibration. The direction of flow rectification is determined by the signal sequence given to the piezoelectric element and the heaters, allowing a bi-directional operation. In order to attain a practical pumping efficiency, it is necessary to find the appropriate valve geometry and the signal sequence. The main difficulty exists in the realization of a sufficiently large temperature difference between two dynamic valves, alternating as rapid as the diaphragm motion.

This pump principle was verified with a prototype device fabricated by silicon-based micro machining. Experiments were performed using water as the working liquid. The frequency of the rectangular input signal was fixed to 50 Hz. The results showed that the flow rate is proportional to the duration and the power of the heating pulse. The maximum flow rate was limited by the increase of the minimum temperature in each cycle, and by the formation of vapor bubbles. The highest flow rate in a series of experiments was about 3 mL/min. The ability of bi-directional pumping was also confirmed.

Feedback Control of Microstate to Control Macrostate Properties of Controllable Fluids

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Controllable fluids are those fluids whose properties can be controlled through the application of an externally applied field. Any field may be used, including electric, magnetic, pressure, or other field types. Of particular interest in the present paper are those fluids whose properties are controlled by electric fields. These fluids are made of micron-sized dielectric particles suspended in a liquid of low dielectric constant and are called electrorheological fluids. Electrorheological fluids are used typically based upon control of fluids viscosity and stiffness. Recently our attention has been on thermal process control through control of thermal transport properties. Specifically, the radiative transmittance and the thermal conductivity have been of interest. The concept is to control the organizational state of the particle-laden electrorheological fluid and thus to control the mechanism of thermal energy transport.

Thermal property control can be accomplished through the following mechanism. When the fluid is exposed to the dielectric fields, chains of micron-sized particles will form into small or even micro chains. These chains provide for preferred pathways for thermal energy transport. Further, the directionality of the transport is controlled, since the particle chains follow the field lines. Thus it is possible to have the preferred path curve relative to the thermal field, if indeed we can create curved electric fields lines.

There are many possible applications, and the final section of paper discusses these.

Miniature Heat Pump Design

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The focus of the work is directed at the thermodynamic feasibility study of millimeter-scale heat pumps as cooling modules in layers of sheet. With sheet heat pumps configured in miniature devices, efficient local control of temperature is facilitated. The robust and efficient design of millimeter-scale compressor-actuation device constitutes the largest technical challenge in the fabrication of a high-throughput heat pump. The present research work on millimeter-scale heat pump incorporates powerful efficient actuation through a rotary-drive, high-throughput, variable capacitance, electrostatic disk motor (VCM) configured as stator and integrated rotor-centrifugal compressor assembly. Because of the high axial force developed between the compressor-integrated rotor and the underlying disk stator, higher driving torque is generated, which enables the integrated compressor to achieve rpm as high as 310,500 while consuming power of 2 W. The optimization of the motor dynamics to extract an optimal set of design parameters is provided and enables a sizable compression ratio of 3.7 : 1. For the feasibility study, a design layout of the structural components of the prototype millimeter-scale heat pump is performed. Apart from the high-performance actuation unit, the prototype device is equipped with a condenser plate and an evaporator plate with significant heat transfer capability. The above components fabricated on an integrated silicon wafer will ensure high sophistication and reliability in application. Lastly, a fabrication process sequence for the disk stator and integrated motor-compressor unit is enumerated for high mass reproducibility of the proposed miniatured heat pump. The overall dimension of heat pump is projected at 10 cm (dia.) × 1 cm (thick). The proposed heat pump device has potential utility in microcooling of refrigeration units, cooling for computer hardware chips, cooling of electronic chips for high-temperature operations, and cooling of miniature heat engines and turbines in energy systems.

Disjoining Pressure Effect on the Wetting Characteristics in a Capillary Tube

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A mathematical model capable of predicting the wicking height formed by a wetting liquid in a vertical heated capillary tube was developed. The model incorporates the disjoining pressure, fluid flow, and heat transfer in the thin-film region, and thermocapillary effects, and indicates that the meniscus radius of curvature at the vapor–liquid interface increases significantly with increasing heat flux, resulting in an increase in the contact angle due to the surface tension variation, disjoining pressure, and fluid flow in the evaporating thin film. The increase in the contact angle is the primary reason that a decrease in the wicking height in capillary tubes is typically observed when compared with the dynamic flow effect resulting from the frictional force occurring in the tube during dynamic flow conditions. In order to verify the model presented here, a comparison with previously obtained experimental data is made. The investigation presented in this paper provides a better understanding of the wetting phenomena occurring in the heated capillary tube and has applicability in a wide range of applications ranging from electronic thermal control to distillation columns.

Thermosyphons Employing Microfabricated Components

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Indirect liquid cooling using thermosyphons offers considerable promise for individual high-power electronic components. A typical two-phase thermosyphon consists of evaporator and condenser sections separated by connecting tubing. The working fluid of the thermosyphon circulates from the evaporator to the condenser within a closed loop. Thermosyphons can be made very compact with the use of microfabricated structures to promote heat dissipation. Three-dimensional porous copper microstructures consisting of cross-linked rectangular channels, 300 μm wide and 550 μm deep have been employed for fabricating the evaporator section of one such setup. Heat fluxes of 70 W/cm^2 with dielectric fluorinert FC-72 as the working fluid have been achieved for a temperature rise of 60°C at the heater surface.

There is not enough information in the literature on the effect of feature sizes of enhancement structures on boiling heat transfer performance. A linear increase in the heat dissipation capability with increase in the number of microstructures per square centimer has been demonstrated by Gebhart et al. [1]. The present study aims at studying the effect of reducing the channel sizes and thus increasing the number of micropores per square centimeter. Fabrication and testing of three-dimensional silicon microstructures similar to those in copper has been carried out. Several microfabrication techniques, e.g., wet etching, laser milling, and wafer dicing, have been explored to fabricate these structures. Joining techniques including epoxy bonding, eutectic bonding, and direct water bonding have been tried. One such tree-dimensional stack, which consists of channels 30 μm wide and 250 μm deep, fabricated using a wafer dicing saw and bonded with a conductive epoxy, has been tested in a compact thermosyphon. Heat fluxes up to 22 W/cm^2 have been obtained (with the same maximum temperature rise as for the copper structure). The lower performance of the silicon structure compared to the copper structure may be caused by the lower thermal conductivity of silicon, resulting in less effective spreading. Also, the channel sizes could be much smaller than an optimum value, which would depend on the surface tension and liquid–vapor interactions within the channel structures. To explore this further, copper structures with 75- and 125-μm channel sizes are currently being fabricated using wire electro-discharge machining. Structures with 30-μm channels are also being tried on a copper substrate.

Spatially Resolved Measurements of Wall Heat Transfer and Visualization of a Single Bubble on a Downward Facing Heated Surface

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The objective of this work is to measure space-resolved heat transfer variations underneath a single bubble growing on a heated surface facing downward. A microscale heater array along with a video camera were used to provide heat transfer measurements and photographic records of the bubble.

The heater array is constricted using VLSI techniques, and consists of 96 serpentine platinum resistance heaters on a quartz substrate. Each heater in the aray is 0.27×0.27 mm in size, and has a nominal resistance of 1,000 Ω. The heaters are arranged on a 10×10 grid. One great benefit of building the heaters on a quartz substrate is that photographs can be taken through the substrate. Electronic feedback loops are used to keep the temperature of each heater in the array at a specified value, and the variation in heater power required to do this is measured. The frequency response of a heater/circuit combination was measured to be 15 kHz, which is much faster than the frequencies associated with boiling. The boiling rig used in the test included a bellows to allow the test section pressure to be controlled, a stirrer to break up stratification within the test chamber, and a temperature controller and a series of Kapton heaters to control the bulk fluid temperature. A CCD video camera coupled to a microscope lens was used to image the bubbles during boiling video camera coupled to a microscope lens was used to image the bubbles during boiling at 30 frames/s. In order to minimize dissolved gas effects, the FC-72 liquid was degassed by repeatedly pulling a vacuum on the fluid. The final dissolved gas concentration in the liquid was measured to be less than 1.0×10^{-3} moles/mole.

Data were obtained with the bulk liquid subcooled by 10°C and 20°C. Stationary bubbles of decreasing size were obtained with increased subcooling. Measurements of the heat transfer distribution on the surface were obtained, and are presented.

Energy Characterization of Pulsed-Laser Ablated Titanium Plume by Spectroscopic Techniques

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Pulsed laser deposition (PLD) of thin films has evolved into a well-recognized technique for a wide range of materials and in a variety of devices. There is a great interest in the energy characterization of the ablated plume because this is a key parameter in determining the quality of the deposited film. Spectroscopic techniques were employed in this experiment to quantify the energies of different species in the plume.

A titanium target was ablated by a KrF excimer laser with fluences varying from 3 to 8 J/cm^2 in nitrogen-, argon-, and helium-filled environments with pressures ranging from vacuum to 1 torr. The effects of laser fluence and background gas pressure on the kinetic energies of ablated species were found by temporally and spatially resolved emission spectroscopy. Temporarily and spectrally resolved imaging with gate width as short as 5 ns was employed to reveal the evolution of the ablated plume against the background gas. Plume splitting was observed for pressures greater than 50 mtorr. In addition, the plume interaction with a heated substrate was captured by imaging techniques.

Laser Modification of Glass Microstructure

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The goal of developing zone texture for glass substrates of computer disks motivates the study of laser-driven topography formation on silicate glasses. Results from an experimental study of CO_2 laser texture illustrate several fundamental characteristics of the process of topography or “bump” formation. To explain the experimental results, we introduce a “fictive temperature map” that relates microstructure of glass to its thermal history. In using this map, it is important to identify the transition temperature correctly, as a temperature for which the rate of change of microstructure is comparable to the rate of change of temperature. As such, the transition temperature can be altered by the time scale of the thermal cycle imposed by the laser pulse. This introduces the ability to control the degree to which the fictive temperature is elevated in the glass during laser texturing. Laser texture bumps are the product of a local elevation in fictive temperature in the heat-affected zone. Many key characteristics of glass laser texture can be explained in terms of the fictive temperature map. For example, at near-threshold pulse energies, the bump growth is sensitively dependent on the peak temperature of the thermal cycle. This is a result of the Arrhenius rate dependence of microstructural change on temperature. In contrast, if the peak surface temperature is much higher than the transition temperature, the bump growth depends predominately on how far the transition temperature isotherm is driven into the bulk of the glass. The fictive temperature map also facilitates explanations for the observed bump growth with multiple laser pulses, the effect of chemical strengthening, and the effect of annealing before and after laser texture.

High-Precision, Laser-Based Concentration Measurement of Binary Liquid Mixtures

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The precise measurement of concentration in liquids is important in fields such as semiconductor manufacturing, food manufacturing, analytic chemistry, waste inspection, and measurement of liquid diffusion coefficients. This work presents a noncontact, laser-based technique to measure the index of refraction of a binary mixture, which can be used, in turn, to determine the concentration of the mixture. The technique can resolve extremely small changes in concentration, on the order of 0.01% or one part in 10,000, while at the same time making such precise measurements over a large range of concentration values. The essential components in the system include a HeNe laser as the light source, a precision glass cuvette used as the liquid container and optical cell, and a very-high-resolution position-sensing diode and voltmeter. The experimental configuration is small, reliable, and inexpensive, and can be readily adapted for continuous flow measurement, making it suitable for real-time monitoring and control of liquid manufacturing processes. With minor modifications, the technique can be used to measure temperature variations in a pure liquid. Results are presented for several common alcohols and for two water-salt solutions, with very good agreement found between measured values and those reported in the literature.

Response of Micromachined Cantilivers to High Intensity Radiation

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Microelectromechanical systems (MEMS) are a rapidly developing technology with applications in the automotive, health care, aerospace, environmental sensing, and consumer products industries. Due to the planar nature of surface micromachining, one of the three main fabrication methods, MEMS devices produced using this technology are often slender and very compliant in one or more directions. An example of a compliant structure found in many MEMS designs is a singly or doubly clamped cantilever. High-intensity laser interactions with such microstructures can result in vibrational responses. Because of the particle nature of light, a radiation pressure from the change in phonon momentum at a surface is present on the microstructure surface. The radiation pressure imparted by the laser radiation can be on the scale needed to induce vibration in mechanical structure. This is important for applications such as the recovery of stiction-failed microstructures or laser processing of MEMS.

This paper focuses on analytical investigations of the mechanical response of micromachined cantilevers due to high-intensity laser radiation. The magnitude of the radiation pressure depends on the laser intensity, surface reflectivity, and material absorptivity. The mechanical response fo the cantilever is a function of the radiation pressure, Young's modulus, cantilever geometry, mass density, and load distribution. Investigations into microcantilever vibrations induced by high-intensity laser irradiation examine the effect of varying the laser operating conditions, beam geometry, and material properties of the beams. The necessary conditions for vibrations, which could affect microstructure recovery as well as be damaging to the structure, are determined. The impact on laser processing of MEMS structures is assessed.

Micro-optomechanical Uncooled Infrared Camera

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Detection of (IR) radiation, especially in the long-wavelength infrared (LWIR) range (8–14 μm wavelength) is a critical issue in several technologically important problems such as environmental monitoring, satellite imaging, and night-vision cameras. Photoconductive and photovoltaic detectors using materials as such as doped silicon and mercury cadmium telluride (HgCdTe) have been used in the past. However, to detect LWIR radiation, these detectors must be cooled down to cryogenic temperatures (typically below 80 K) in order to reduce thermal noise. This requires elaborate cooling system design, which increases cost and weight, besides posing reliability problems. There has recently been a major impetus toward developing uncooled infrared cameras. These are typically bolometric or pyroelectric, where the absorption of the radiation increases the device temperature, which in turn changes its electrical characteristics.

This paper presents a new micro-optomechanical infrared camera that operates at room temperature and that has a direct optical interface with the human eye or CCD camera. The focal plane array of this camera contains pixels made up of bi-material cantilever beams that bend in response to temperature rise due to mismatch in thermal expansion. The optical readout system simultaneously detects the deflection of all the cantilevers in the focal plane array and projects a visible image of the infrared scene. Since the output of each pixel is optical, it eliminates the need for interconnect fabrication, scanning electronics, and a visible display system that are required for electro-optic or bolometric cameras that produce electrical signals from each pixel. The major challenges in the initial development of this micro-optomechanical camera are (1) thermomechanical analysis for optimal cantilever design; (2) microfabrication of stress-free bi-material cantilever beams; (3) development of an optical readout system that can detect cantilever deflections with a resolution of 0.1 nm. This paper reports the progress in each of these topics.

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