Advanced Surface Engineering Division
Room: 104 - Session SE+SS-WeM

Surface Engineering for Thermal Management
Moderator: A.A. Voevodin, Air Force Research Laboratory, H. Barankova, Uppsala University, Sweden

8:20am **SE+SS-WeM2 Near-Field Radiation Heat Transfer**, *A. Mavrokefalos, P. Sambegoro, K. Esfarjani,* ***G. Chen***, Massachusetts Institute of Technology **INVITED**

Radiation heat transfer in nanostructures can differ significantly from that in macrostructures due to wave effects. Max Planck himself realized that the blackbody radiation law that now bears his name was limited to geometries much larger than wavelength of thermal radiation. Theory has predicted that thermal radiation heat transfer between two surfaces separated by tens of nanometers can exceed that of Planck's blackbody radiation law by several orders of magnitude. We have designed an experiment measuring near-field radiation heat transfer between a sphere and a flat plat using bi-layer atomic force microscope cantilevers as a heat flux and a temperature sensor. We demonstrated experimentally that near-field radiation heat transfer can exceed Planck's law prediction by four orders of magnitude, mediated by surface phonon polaritons. We will also show that existing fluctuating electrodynamics theory cannot predict experimental results in the extreme limit of small separation between two surfaces. Our experiments raise interesting question on the convergence of radiation heat transfer mechanism and interfacial heat conduction mechanism. Theoretical approaches bridging these two regimes will be discussed.

9:00am **SE+SS-WeM4 Atomic Level Temperature Measurements and Nearfield Thermal Energy Tunneling**, ***A.A. Voevodin***, *I. Altfeder, J. Hu, V. Varshney, A. Roy*, Air Force Research Laboratory

An atomic level thermometer was developed to study interfacial thermal conductivity using a scanning tunneling microscope with inelastic electron tunneling spectroscopy (STM-IETS), where inelastic peak broadening was used to measure temperature of the CO molecular group at the platinum probe apex, while Au substrate with (111) surface was cryogenically cooled. The experiments led to a discovery of vacuum phonon tunneling across nanometer contact gaps. This discovery showed that contact thermal transport can exceed by 10 orders of magnitude Planck's radiation Law for heat transfer in vacuum [1]. This indicated that there should be an alternative mechanism for thermal energy transfer, where near filed effects support energy tunneling across such small vacuum gaps. A hypothesis about mirror charge coupling at the interfaces was formulated and tested in the experiments with varied tip-sample temperature gradients. Based on these developments, the STM-IETS experimental approach was further extended to study interfaces made of the surfaces with different Debye temperatures. The second derivative of the tunneling current was used to obtain information on the interfacial thermal coupling and energy transfer. This paper reports on the experimental set-up for atomic scale thermometry, corresponding first principle calculation approaches for small gap interfacial thermal coupling, and discusses experimental and modeling results for different tip-surface combinations toward understanding near-field effects for thermal energy transfer.

1. "Vacuum phonon tunneling", I. Altfeder, A. A. Voevodin, A. K. Roy, Physical Review Letters, 105, 166101 (2010).

9:20am **SE+SS-WeM5 Two-Color Time-Domain Thermoreflectance with an Optical Parametric Oscillator**, ***J. Gengler***, Spectral Energies, LLC, *C. Muratore,* Air Force Research Laboratory, *S. Roy,* Spectral Energies, LLC, *J.R. Gord*, Air Force Research Laboratory

Conventional single-color laser pump-probe methods for measuring thermal properties are limited by sample requirements that arise from considerations of surface roughness and compatible thermoreflectance transducers. Here we describe a new experimental arrangement for performing two-color time-domain thermoreflectance (TDTR). The technique is a variation of traditional pump-probe spectroscopy that is based on a femtosecond Ti:sapphire oscillator of fixed wavelength and an optical parametric oscillator (OPO), with the goal being to create an independently tunable probe wavelength. This method offers two advantages: 1) spectral filtering of diffusely scattered pump light (to prevent it from reaching the detector), and 2) generation of thermoreflectance signal from different metal thin films. The wavelength tunability of the system allows enhancement of TDTR signal generation for multiple thermoreflectance transducer materials. This wavelength-adjustable feature, in turn, facilitates direct measurement of the thermal transport properties of various thin films and substrates, which would be difficult with single-color femtosecond pump-probe systems. Demonstrated results include optimization of the probe wavelength for different metals, measurement of metal-graphite interfacial conductances on relatively rough samples, and two orders-of-magnitude calibration of thermal conductivity measurements using copper as a thermoreflectance transducer.

9:40am **SE+SS-WeM6 Low-Friction V-alloyed ZrO_2 Thin Films with Temperature Homogenization Functions for High Temperature Sliding Interfaces**, *O. Jantschner, C. Walter,* ***C. Mitterer***, University of Leoben, Austria, *C. Muratore, A.A. Voevodin*, Air Force Research Laboratory

The effect of vanadium on reactively magnetron-sputtered zirconia coatings was investigated with respect to its structural and mechanical properties as well as its thermal management abilities for high temperature sliding interfaces. ZrO_2 coatings with different V-content (0, 2.2, 5.8 and 17.4 at%) were co-sputtered from Zr and V targets using an Ar/O_2 discharge. The X-ray diffraction pattern of the as-deposited coatings show a change in crystal structure from monoclinic (0-2.2 at% V) to cubic/tetragonal (5.8 at% V) and finally X-ray amorphous structure at even higher V content (17.4 at% V). Hardness and Young's modulus were evaluated by nanoindentation showing a decrease beyond 2.2 at% V from 17.4 to 7.5 GPa and from 230 to 150 GPa, respectively. The tribological investigations by ball-on-disc tests against alumina balls were carried out at three different temperature levels (25, 600 and 800°C). Additional in-situ Raman analyses have been done to study the formation of tribolayers in the sliding contact. At 25°C, the coefficient of friction (COF) is about 0.2 for low V contents (≤ 2.2 at%). For higher V contents, the COF increases up to 0.5 and higher. At 600°C, the COF measured was between 0.4 and 0.8. At the even higher temperature of 800°C, the COF decreased to below 0.2 for V contents of 17.4 at%, where a self-lubricating film was formed in the sliding contact. Differential scanning calorimetry (DSC) measurements of virgin powder samples showed a characteristic exothermic peak at ~600°C which is due to the formation of a stoichiometric ZrV_2O_7 phase. This phase was found to decompose at ~800°C by an endothermic reaction in ZrO_2 and V_2O_5. The re-runs of the DSC measurements indicated melting of V_2O_5 at 670°C.

In summary, alloying of V to ZrO_2 coatings has on the one hand been proven to result in self-lubricious properties at temperatures above 700°C. On the other hand, the endothermic reactions needed for formation of the self-lubricious phase have the potential to reduce high local temperatures in the sliding contact, enabling thermal management abilities of these coatings.

10:40am **SE+SS-WeM9 Thermal Characterization of Metal/Carbon Interfaces: Comparison of Metallized Nanotubes and Graphite**, *C. Muratore, S. Shenogin,* ***A. Waite***, *A. Reed, J. Gengler, T. Smith, J. Hu, J. Bultman, A.A. Voevodin*, Air Force Research Laboratory

Most applications of carbon nanotubes require contact with more ordinary materials, such as metals or polymers. Unfortunately, the extraordinary thermo-electro-mechanical properties of nanotubes are often negated at the interface between the nanotubes and whatever they touch, resulting in a major shortfall between the measured and predicted performance of nanotube-based materials. One of the most troubling discrepancies in projected versus measured properties is found in thermal conductivity measurements of nanotube-containing composite materials. For example, a continuous network of thermally conductive nanotubes (or about 1 percent, by volume) within an organic matrix (k = 0.3 W m-1 K-1) should yield a 30-fold increase in thermal conductivity over the pure matrix phase alone, based on simple effective medium theory. Despite this potential increase, experimental results typically show an increase of only a factor of 2 at best in composites with nanotube additives. To better understand the nature of interfacial resistance in carbon nanotubes, modeling and experimental studies investigating engineered interfaces on highly oriented pyrolytic graphite (HOPG) samples were conducted. This substrate was selected as a practical 2-dimensioinal analog for nanotube sidewalls to facilitate modeling and experimentation. Molecular dynamics simulations of heat transfer through metal carbon interfaces were conducted, and measurements of thermal conductance at these interfaces were made by analysis of the two-color time domain thermoreflectance (TDTR) data from the samples. The TDTR analysis of the different metals on HOPG was made possible by having an optical parametric oscillator on the probe beam which allows for tuning the wavelength to match absorption bands for each metal studied. Comparison of simulation and experimental results between graphite and nanotubes is highlighted. Metal films were selected to identify effects of atomic mass, chemical interactions and mechanical properties. For example, metals known to exhibit in situ formation of an interfacial carbide layer when in contact with a carbon source and heated, such as titanium and boron, were investigated, and the effect of this carbide layer formation on interfacial conductance was examined. Graded and sharp interfaces were also considered with computational and experimental efforts.

11:00am **SE+SS-WeM10 The Experiment of Surface Tension Driven Flow with Various Parameters on JEM/ISS**, ***S. Yoda***, Japanese Aerospace Exploration Agency, *S. Matsumoto,* JAXA, Japan, *A. Komiya*, Tohoku University, Japan

The surface tension driven flow (Marangoni) experiments were carried out by using 50mm diam. with liquid bridge of Silicones oil under microgravity condition on Japanese Experiment Module on International Space Station. The parameters in these experiments were liquid bridge length being corresponded to aspect ratio which is defined as liquid length/liquid diam., and temperature difference between hot and cold disks which sustains the liquid bridge. The particles coated by gold to fit with the density of the liquid silicones were inserted into the liquid bridge. Observing the movement of the particles by three CCD camera, we can determine the flow behavior of Marangoni with different temperature as 3 dimension observation of the flow. Moreover, two ultrasonic transducers were attached in the cold disk to measure the particles velocity. The number of experiments done on JEM were more than 40 times with around 6 hr for all each experiment. The Marangoni number was changed with aspect ratio. The smaller aspect ratio around showed smaller critical Marangoni numbers, whereas the lager those were larger the numbers.

11:20am **SE+SS-WeM11 Enhanced Thermal Transport at Covalently Functionalized Carbon Nanotube Interfaces**, *S. Kaur,* Lawrence Berkeley National Lab, *N. Raravikar,* Intel Corporation, ***D.F. Ogletree***, Lawrence Berkeley National Lab

Thermal transport is restricted in systems including carbon nanotubes (CNT) due to high thermal interface resistance. We have substantially improved thermal transport at CNT-metal interfaces by functionalizing the contacting surfaces with amino-propyl silane to form covalent chemical bonds bridging the CNT-metal gap. This strategy was suggested by molecular dynamics calculations of Hu e*t al.* (1)

We have characterized the resulting interface using multi-frequency and multi-wavelength time-domain thermo-reflectance (TDTR) measurements, which are able to independently determine interface and bulk CNT contributions to thermal transport. TDTR analysis showed that thermal contacts were made between a functionalized Al surface and 4-5% of the CNTs in an array grown on silicon. The intrinsic CNT interface conductivity exceeded 300 MW/m^2-K, resulting in an effective thermal interface resistance of less than 0.8 mm^2-K/W. Successful interface functionalization was independently verified by mechanical adhesion testing, which showed a correlation between interface strength and thermal transport, as discussed by Prashar. (2).

(1) Ming Hu, Pawel Keblinski, Jian-Sheng Wang, Nachiket Raravikar, J. Appl. Phys. 104 083503 (2008).

(2) Ravi Prashar, Appl. Phys. Lett. 94 041905 (2009).

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