Advanced Surface Engineering
Room: Cimmaron - Session SE-TuA

Surface Engineering for Thermal Management
Moderator: A.A. Voevodin, Air Force Research Laboratory

2:00pm **SE-TuA1 Nanometer-Scale and Interfacial Thermal Transport and Thermal Properties Characterization**, ***W.P. King***, University of Illinois at Urbana-Champaign **INVITED**

This talk discusses recent work on measurements of nanometer-scale and interfacial heat transfer as well as measurements of nanometer-scale thermophysical properties of solid materials. The research combines atomic force microscope (AFM)- based measurements, nanometer-scale thermal processing, and nanometer-scale infrared spectroscopy.

In the first research thrust, an AFM cantilever probe can be used to measure thermomechanical expansions with spatial resolution smaller than 10 nm and out-of-plane displacements as small as 3 pm. Such displacements correspond to about 10 mK temperature changes. We use this technique to measure temperature distributions in graphene and carbon nanotube devices. It is possible to make a quantitative measurement of temperature rise in carbon nanoelectronic devices that are one atom thick.

In the second research thrust, we use AFM cantilever probes with integrated heaters. When the AFM tip is in contact with a solid substrate, the tip-substrate contact is an ultrasmall hotspot with a diameter as small as 1 nm. This tip can be used to measure nanometer-scale temperature-dependent mechanical, chemical, and electronic properties of surfaces.

2:40pm **SE-TuA3 Determination of Thermal Accommodation Coefficients from Heat Transfer Measurements Between Parallel Plates**, ***W.M. Trott***, *J.R. Torczynski, M.A. Gallis, D.J. Rader, J.N. Castañeda*, Sandia National Laboratories

Thermal accommodation coefficients have been derived for a variety of gas-surface combinations using an experimental apparatus developed to measure the pressure dependence of the conductive heat flux between parallel plates at unequal temperature separated by a gas-filled gap. The heat flux is inferred from temperature-difference measurements across the plates in a configuration where the plate temperatures are set with two carefully controlled thermal baths. Temperature-controlled shrouds provide for environmental isolation of the opposing test plates. Since the measured temperature differences in these experiments are very small (typically 0.3^{o} C or less over the entire pressure range), high-precision thermistors are used to acquire the requisite temperature data. High-precision components have also been utilized on the other control and measurement subsystems in this apparatus, including system pressure, gas flow rate, plate alignment, and plate positions. The apparatus also includes the capability for *in situ* plasma cleaning of the installed test plates. Measured heat-flux results are used in a formula based on Direct Simulation Monte Carlo (DSMC) code calculations to determine the thermal accommodation coefficients. Thermal accommodation coefficients have been determined for three different gases (argon, nitrogen, helium) in contact with various surfaces. Materials include metals and alloys such as aluminum, gold, platinum, and 304 stainless steel. A number of materials important to fabrication of Micro Electro Mechanical Systems (MEMS) devices have also been examined. For most surfaces, coefficient values are near 0.95, 0.85, and 0.45 for argon, nitrogen, and helium, respectively. Only slight differences in accommodation as a function of surface roughness have been seen. Surface contamination appears to have a more significant effect: argon plasma treatment has been observed to reduce thermal accommodation by as much as 0.10 for helium. Mixtures of argon and helium have also been examined, and the results have been compared to DSMC simulations incorporating thermal-accommodation values from single-species experiments. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

3:00pm **SE-TuA4 The Nanoscale Surface Modification of the Wettablity on Enhancements of Two Phase Change Heat Transfer Coefficient and Critical Heat**, ***C.H. Li***, The University of Toledo, *G.P.B. Peterson*, Georgia Institute of Technology

Nanoscale surface modification has been an emerging technology for many engineering applications; particularly it could enable the two phase change heat transfer of an order of magnitude higher performance compared to the untreated smooth surface. Moreover, a micro scale surface structure modification will enhance the liquid replenishment by separating the vapor and liquid flow paths. By integrating those two surface modification methods, the critical heat flux and heat transfer coefficient of two phase change heat transfer have been significantly improve.

4:00pm **SE-TuA7 Surface Engineering for Thermoelectric Energy Conversion**, ***D.S. Dudis***, *M. Check, J. Ferguson*, Air Force Research Laboratory **INVITED**

Thermoelectric energy conversion encompasses both the conversion of thermal energy to electricity (energy harvesting and power generation), as well as the conversion of electrical energy to thermal energy (refrigeration and heat pumping). Since 1993 a renaissance has taken place in quest for better thermoelectric materials offering improved thermoelectric energy conversion efficiencies. An obstacle to achieving improved thermoelectric properties is to increase the electrical conductivity to thermal conductivity ratio (σ /κ), while not negatively impacting thermopower (Seebeck coefficient). Surface engineering has proven particularly important in this quest, as the transport of thermal energy across boundaries is intimately tied to surface effects. This talk will review recent progress in thermoelectric materials research and highlight some challenges tied to surface and materials engineering.

4:40pm **SE-TuA9 Thermal Conductance of Pt/VO$_2$/Pt Heterointerfaces**, ***D.-W. Oh***, *D.G. Cahill*, University of Illinois at Urbana-Champaign

The metal-insulator-transition (MIT) of VO$_2$ at ≈68°C allows us to systematically explore heat transport at interfaces between metals and correlated-electron systems. We use time domain thermoreflectance (TDTR) to measure interfacial thermal conductance of Pt/VO$_2$/Pt structures. Pt/VO$_2$/Pt layers are deposited by reactive dc sputtering on sapphire substrates. High throughput measurements of dependence of the conductance on the VO$_2$ thickness *h* are enabled by creating a lateral thickness gradient, $0<h<30$ nm, across the width of the sample. The thermal conductance of Pt/VO$_2$/Pt structures with $h<10$ nm was found to be large (~800 MW m^{-2} K^{-1}), implying that the VO$_2$ layer is not planar. The thermal conductance of thicker VO$_2$, $h>10$ nm, was ~200 MW m^{-2} K^{-1}. We have not yet been able to resolve a difference in the thermal conductance between the metal and insulator phases of VO$_2$; the upper limit on the change in conductance at the metal-to-insulator transition is ~40 MW m^{-2} K^{-1}. This conductance implies that the specific electrical resistance of an interface between metallic VO$_2$ and Pt is >2´10^{-8} W cm^{2}.

5:00pm **SE-TuA10 Synthesis and Thermoelectric Properties of RuO$_2$ Nanorods**, ***D. Music***, *F.H.-U. Basse*, RWTH Aachen University, Germany, *J.J. Gengler, A.A. Voevodin,* Air Force Research Laboratory*, J.M. Schneider*, RWTH Aachen University, Germany

We have explored the effect of the O/Ru ratio on the morphology and the Seebeck coefficient of RuO$_2$ nanorods (space group *P*4$_2$/*mnm*) synthesized by reactive sputtering. At an O/Ru ratio of 1.69, a faceted surface is observed, while nanorod formation occurs at O/Ru ratios of 2.03 and 2.24. Using classical molecular dynamics with the potential parameters derived in this work, we show that volatile species enable nanorod formation. Based on *ab initio* calculations, two effects of the nanorod formation on the Seebeck coefficient are observed: (i) increase due to additional states in the vicinity of the Fermi level and (ii) decrease due to oxygen point defects (volatile species). These two competing effects give rise to a moderate increase of the Seebeck coefficient upon nanorod formation.

5:20pm **SE-TuA11 Thermal Conductivity Measurements of RuO$_x$ Thin Films**, ***J.J. Gengler***, *A.A. Voevodin,* Air Force Research Laboratory, *D. Music, F.H.-U. Basse, J.M. Schneider*, RWTH Aachen University, Germany

Thermal conductivity trends in RuO$_x$ thin films of varying stoichiometry were characterized with a time-domain thermoreflectance (TDTR) technique. At an O/Ru ratio of x = 1.69, a faceted film surface is observed with a measured thermal conductivity value of 28.8 ± 0.8 W m^{-1} K^{-1}. With an O/Ru ratio of x = 2.24, nanorod formation occurs. These films were grown by a reactive magnetron sputtering technique with nonrotating substrates oriented 20^{0} normal to the Ru target. Such material synthesis conditions resulted in a gradient sample structure at the onset of nanorod formation. As a result, the RuO$_{2.24}$ samples exhibited gradually changing surface roughness (rms of 12 nm – 200 nm) and thermal conductivity values (22 W m^{-1} K^{-1} – 5 W m^{-1} K^{-1}), respectively. The thermal conductivity of the thin film samples studied here are all well below that of single crystal RuO$_2$ with tetragonal rutile structure (50 W m^{-1} K^{-1} [1]). The samples also have an inverse relationship of thermal conductivity with Seebeck coefficient [2], which is desirable for improving the figure of merit for thermoelectric performance.

References

[1] Ferizovic D, Hussey LK, Huang Y-S, Munoz M. Determination of the room temperature thermal conductivity of RuO_2 by the photothermal deflection technique. Appl Phys Lett 2009;94:131913.

[2] Music D, Basse F H-U, Habdorf R, Schneider JM. Synthesis and thermoelectric properties of RuO_2 nanorods. J Appl Phys, submitted for review.

5:40pm **SE-TuA12 Heat Transport at Water Interfaces in the Proximity of Micro- and Nano-Structured Surfaces**, ***S.A. Putnam***, *J.G. Jones*, Wright Patterson Air Force Base

Breakthroughs in many of today's advanced technologies depend on the ability to reliably dissipate enormous amounts of thermal energy (heat) from very small areas. The most demanding applications are managed with nucleate boiling-based cooling schemes (e.g. spray cooling, heat pipes, thermosyphons, flow boiling, and jet impingement), where the cooling effectiveness is dictated by both the cooling configuration and the coolant itself. Surface features can also play a crucial role in boiling/cooling processes because they can, for example, i) increase the total wettable surface area, 2) control the bubble nucleation dynamics at the surface (e.g. vapor bubble release rate and size), and iii) change the effective surface energy (i.e., the intrinsic driving mechanism for wetting the hot surface with a coolant). Here we present our studies on thermal transport at liquid interfaces, focusing on 1) our recent experimental data and corresponding numerical simulations of water microdroplets evaporating, wetting, and bouncing on micro- and nano-structured surfaces and 2) our time-domain thermoreflectance (TDTR) experiments for the interfacial thermal conductance (G) of evaporating water microdroplets on aluminum thin-films as a function of surface temperature.

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