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EDITORIAL

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Special issue: Nanotechnology in energy

Nanostructured materials exhibit exotic properties for thermal transport and storage as well as light absorption. The aim of this special issue is to provide a small collection from a large field of nanotechnology related to energy applications. Nano/microscale heat and mass transfer plays an important role in emerging energy systems and thermal management. When the characteristic geometries become sufficiently small, thermal transport properties are strongly dependent on the dimensions and morphology. Unique thermal transport properties can be achieved with nanostructures and nanocomposite materials. One of the examples of tailoring the electrical and thermal properties based on nanostructures is in thermoelectric systems for power generation and energy conversion. Several papers presented here deal with the theoretical and experimental study of thermal transport in nanostructured materials and composites. In a noncontact setup, electricity can be generated by harvesting photons emitted by a high-temperature thermal source in a thermophotovoltaic (TPV) device. Since the chemical potential of a semiconductor in a p-n junction depends on the radiation equilibrium condition, in principle, there are additional noncontact power generation and refrigeration devices called radiative thermoelectric energy converters. Heat transfer can be greatly enhanced with boiling, yet there exists a transition temperature where boiling heat flux reduces due to the Leidenfrost effect. By engineering micro/nanostructured surfaces, the Leidenfrost state can be suppressed and the heat transfer enhancement can be achieved at much higher surface temperatures. Tip-based vibrational spectroscopy is an emerging and versatile technique for characterization of molecular and thermal properties with nanoscale resolution. Micro/nanostructures can greatly tailor the spectral and directional radiative properties for devices that harvest solar energy or radiation from a thermal emitter for waste heat recovery. A summary of each article is provided in the following.

1. Tervo et al. reviewed the state-of-the-art near-field radiative energy converters that can generate electric power or perform refrigeration tasks by exchange photons. Besides TPV devices, thermoradiative power generators and electroluminescent refrigerators have drawn much attention in recent years. These devices contain no moving parts and do not require chemical reactions. When operating in the near-field regime at separation distances much smaller than the characteristic wavelengths, the power output or refrigeration capacity of these devices may be greatly enhanced. This article covers the fundamentals of near-field thermal radiation, photon entropy, and nonequilibrium effects in semiconductor diodes that underpin device operation. Furthermore, challenges and opportunities for progress in this area are identified.

2. Talari et al. presented a comprehensive survey about the Leidenfrost drops on micro/nanostructured surfaces with an emphasis on how to increase the Leidenfrost temperature. Very large heat transfer coefficients and high heat flux can be achieved via boiling, which is very important for cooling applications including nuclear reactors. However, when a liquid is brought to contact with a solid surface that is at temperatures sufficiently higher than the saturation temperature, a vapor film can form between the liquid drop and the solid. The liquid drop is levitated above the surface,

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resulting in a reduced heat transfer coefficient due to the low thermal conductivity of the vapor. The Leidenfrost state represents a poor heat transfer regime. It is desirable to elevate the temperature, called the Leidenfrost point or Leidenfrost temperature, when the Leidenfront state starts to occur. This review focuses on the effect of micro/nanoengineered structures on the suppression of the Leidenfrost state. The fundamental physics and underlying theoretical background are also provided. The approach based on multiscale hierarchical surfaces that combine the advantages of both length scales is also discussed.

3. Jarzembski et al. provided a review of the integration of atomic force microscopy (AFM) with vibrational spectroscopy for nanoscale materials characterization. The interaction of electrons or individual functional groups in molecules with the illuminated visible or infrared light leads to changes of thermal response, optical absorption and scattering, as well as atomic force interactions. An AFM tip can be used to probe the signal with a high spatial resolution and superb sensitivity. Recent developments suggest that this method can break the diffraction limit and may become a critical technique for characterizing novel energy materials. The basic background, various configurations, and recent advancements are outlined, along with an outlook on the future research directions in tip-based vibrational nanospectroscopy.

4. Liu et al. gave an overview of the thermal transport properties for organic-inorganic composites, which have important applications for high-power thermoelectric materials for power generation and refrigeration, thermal interfaces in microelectronics thermal management, thermal insulation in aerospace, etc. Usually, the composites are made of a polymer matrix filled with a conducting material such as carbon nanotubes, graphene or BN platelets, metal nanowires or particles, ceramic particles or clusters, The physical mechanisms and recent theoretical and experimental progress are discussed, along with the factors affecting the thermal conductivity of organic-inorganic composites.

5. Qin and Hu presented a short review on the theoretical studies of thermal transport in monolayer phosphorene, a two-dimensional (2D) semiconductor with high carrier mobility and unique chemical and physical properties. The hinge-like structure makes the thermal transport inherently anisotropic in the two planar directions unlike other 2D materials. This review provides a fundamental insight into the thermal transport by considering resonant bonding in phosphorene. Progress and perspectives are also presented.

6. Chen et al. summarized recent progress in the design of thermoelectric materials with nanostructural engineering that yield high performance as measured by the figure of merit (ZT). Low-dimensional thermoelectric materials are extensively discussed. 1D materials, such as nanotubes and nanoribbons, 2D systems including graphene, silicene, germanene, as well as transition metal dichalcogenides are reviewed. Both theoretical and experimental studies are presented.

7. Yuruker et al. performed a system-level optimization method for on-chip thermoelectric coolers based on the Parento frontier curve, which indicates the existence of an optimal thickness and a corresponding optimal current that maximize the temperature reduction in order to remove a fix amount of heat flux. A case study is provided to demonstrate how to apply the optimization procedure in a given application.

8. Cheng et al. experimentally measured the thermal and electrical transport properties of palladium-based alloys (i.e., $Pd_{40}Ni_{10}Cu_{30}P_{20}$ and $Pd_{43}Ni_{10}Cu_{27}P_{20}$), which belong to a kind of material with high glass forming ability and can also be crystallized. It holds promise as a candidate of thermoelectric materials. Their results show that the thermal conductivity and electrical conductivity of crystallized palladium-based alloys are significantly higher but Seebeck coefficient is lower than their amorphous counterparts.

9. Xu et al. fabricated nanoporous $In_{0.1}Ga_{0.9}N$ films of various patterns and measured their cross-plane thermal conductivities using a time-domain thermoreflectance technique. These alloys have been suggested to have better electrical properties than conventional Si_xGe_{1-x} alloys and the purpose of introducing nanoporosity is to confine phonon transport and lower the thermal conductivities. The result of this study provides insights for ZT enhancement in alloys of nitrides and oxides.

10. Ji et al. used molecular dynamics (MD) simulation to theoretically study the nanoscale thermal transport between Si/Ge superlattices, focusing on the impact of the interface between Si and Ge on the cross-plane thermal conductivity reduction. Different types of interface structures are considered, including cone-shape and aperiodicity in order to guide the design of interface structures with reduced thermal conductivity for thermoelectric converters.

11. Xie et al. employed the concept of thermal reffusivity (which is the inverse of thermal diffusivity) to elucidate the underlying physics of phonon transport as well as defect scattering of electrons and phonons on the thermal transport theory. They also reported, for the first time, the difference between white hair and normal black hair from heat conduction perspective.

12. Fang et al. designed multilayered structures consisting of metal and dielectric films for solar radiation absorption with theoretical prediction and experimental demonstration. The design principles are based on Salisbury screens and Jaumann absorbers, which were originally invented during World War II to absorb radio frequency waves for radar applications. Admittance matching equations were used to find good initial structures, followed by optimization of the performance.

13. Won and Lee investigated the effect of scattering by nanoparticle suspension on the performance of a dielectric solar collector. The Monte Carlo method is used to numerically solve the radiative transfer equations considering volume scattering in the nanofluids. It is shown that when the absorption coefficient is small, multiple scattering can increase the mean optical path where the photon bundles travel inside the collector channels.

14. Chen et al. developed a photonic crystal structure as an energy saving glass. Submicron polystyrene spheres were used to tune the photonic bandgaps. By taking advantage of the dual photonic layers with different photonic bandgaps, the infrared transmittance of the glass window can be suppressed that will prevent heat from entering the building.

15. Ni et al. theoretically investigated light trapping in an ultrathin TPV cell with a metamaterial structure for narrow-band resonance absorption. The effects of Fabry-Perot resonance, surface plasmon polariton (SPP), and magnetic-polaritons (MPs) on the absorption characteristics are elucidated. The local power absorption distribution is also calculated.

We hope the readers can find valuable information from this collection of review articles and research papers on nanoscale thermal transport and thermal properties of nanostructured materials for energy applications. It is expected that this collection will have a lasting impact on much broader research efforts in thermal transport properties and light-matter interactions at the nano/microscales for future energy devices and systems, enabled by nanoscience and nanotechnologies. Special thanks are owed to Ms. Dongping HUANG at the Frontiers in Energy Editorial Office for her tireless efforts in making this special issue possible.

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