Recent Developments in Nanoscale Thermoelectric Materials and Device Technology

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Thermoelectric semiconductor materials and devices can enable a wide array of applications from solid state cooling of electronics and compact air-conditioning systems, to waste-heat harvesting in many scenarios such as automotive exhaust and industrial plants. The two major difficulties limiting the widespread use of thermoelectric technology have been achieving a sufficiently high materials figure of merit (ZT) and converting enhanced materials' ZT into superior device performance by overcoming various device electrical and thermal losses. These limitations have curtailed the widespread use of semiconductor thermoelectric devices since their original development in 1950's, even though they offer several other advantages including reliability, noise-free operation, and green technology. Nanoscale materials based on superlattices, nano-dots, nano-wires and bulk materials with second phases or nano-inclusions have become dominant approaches to enhance the ZT in thermoelectric materials since 2001 (*Nature* 413, 597 (2001)) and they have been further validated recently (*Nature* 451, 163 (2008), *Nature* 451, 168 (2008) and *Science* 320, 634 (2008)). Almost all of the recent successful efforts in ZT improvement – in a marked departure from the state-of-the-art of the 1950's to up until 2000 – have been a result of the significant reduction in lattice thermal conductivity through phonon scattering in nanostructures, without affecting the electrical transport of electrons or holes, by so-called *phonon-blocking electron-transmitting structures*. Our progress in materials ZT along with other efforts from the labs in the US and around the world will be described. Studies on the phonon-transport using femto-second optical and acoustic phonon property measurements have provided further understanding of the physics behind thermal conductivity reduction in superlattices. Careful band offset measurements have been carried out to understand and model carrier transport across interfaces in several superlattice systems. Motivated by the success with engineered nanoscale thermoelectric superlattices, laboratories in the world, including us, are developing bulk nano-materials with significantly higher ZT and with better heat-to-electric conversion efficiencies. More recently, we have been studying thermoelectric characteristics of ultra-thin Bi_2Te_3 films in the range of a few nanometers to hundreds of nanometers, grown on electrically-insulating GaAs substrates. The films at the thinner dimensions show ultra-high electrical conductivity, yet show sufficiently large Seebeck coefficient; this new concept in ultra-low-dimensional systems can also take advantage of the exciting physics of topological insulators. Characterization techniques for various material properties, and in particular thermal conductivity and ZT, will be described. Device development with advanced nanoscale superlattice thermoelectric materials, like hot-spot cooling of high performance electronics (*Nature Nanotechnology* 4, 235 (2009)) as well as energy harvesting for various applications will be presented and discussed.

Dr. Venkatasubramanian (Ph.D. Rensselaer, New York, 1988; B.S. Indian Institute of Technology, Madras, India, 1983; Electrical Engineering) is currently the Senior Research Director of the Center for Solid State Energetics at RTI International, where he directs innovative basic and applied research in thermoelectrics, photovoltaics and optoelectronic materials and devices for solid state energy conversion applications. Dr. Venkatasubramanian is the Founder of Nextreme Thermal Solutions, which is commercializing thin-film thermoelectric technology developed under his leadership with DARPA funding. He has over 115 publications, 15 patents, and 100 presentations in the area of thermoelectric materials and devices, photovoltaics, optoelectronics, and two book chapters (Semiconductors and Semimetals – Recent Trends in Thermoelectrics, Academic Press and Thermoelectrics - Micro to Nano, CRC Press). Dr. Venkatasubramanian initiated and developed a research program focused on demonstrating the fundamental advantages of atomically engineered superlattices and other nanoscale materials; this research resulted in the first major breakthrough in the field of thermoelectrics in 40 years (*Nature* 2001, *Nature Nanotechnology* 2009) that has led to many tens of laboratories around the world working on other nanoscale materials. Dr. Venkatasubramanian has received the R&D 100 Awards in 2002 and 2010 for thermoelectric innovations, the Margaret Knox Excellence Award for research at RTI and Rensselaer's Allen B. Dumont Prize for research achievements. Dr. Venkatasubramanian was elected Fellow of the IEEE for contributions to nanoscale thermoelectrics for thermal management of electronics and energy harvesting. Dr. Venkatasubramanian serves as an Editor of the IEEE Transactions on Electron Devices. Dr. Venkatasubramanian has organized several symposia and edited proceedings in thermoelectrics, energy harvesting and nanoscale thermal transport for the American Physical Society, Materials Research Society, IEEE and other professional societies.