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Elastic strain engineering of charge and thermal transport in semiconductor nanostructures: the role of heterogeneity

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ABSTRACT

A variety of emergent phenomena in mechanical behavior, heat conduction, and electronic charge transport arise in materials when length scales associated with the physical dimensions or intrinsic structure approach the nanoscale. For instance, defect ensemble interactions and poor mechanical strength give way to discrete plasticity and ultra high strength in elemental nanostructures; facile thermal transport gives way to abundant phonon scattering in nanomaterials; and electronic band structure becomes altered in quantum-confined systems. Despite novel structural and transport physics discovered in many inorganic nanostructures, the interconnections between these various fields to exploit further property enhancements have received only recent attention. In this discussion, we describe the combination of a large dynamic range of elastic strain available in nanostructures with unique transport physics to enable tunable functional response via elastic strain engineering. In particular, the effect of strain heterogeneity on thermal and charge transport will be addressed by way of two examples on Si nanostructures. First, we report experimental measurements of the effect of tensile stress on thermal conductivity of an individual suspended Si nanowire using in situ Raman piezothermography. Our results show that, whereas phononic transport in undoped Si nanowires is only marginally affected by uniform elastic tensile strain, point defects introduced via ion bombardment that disrupt the pristine lattice reduces the thermal conductivity by over 70%. The second example furthers the study of inhomogeneous strains by showing tunable electrical conductivity and Seebeck coefficients in strained silicon nanomeshes with architected porosity. Using batch fabrication of freestanding nanomesh films from silicon-on-insulator wafers, we present a unique platform for exploring the effects of both changes in nanomesh geometry and strain state on charge transport. Experimental results are analyzed by combining analytical models for electron mobility in uniformly stressed silicon with finite element analysis of strained silicon nanomeshes. Our results show that the nonuniform and multiaxial strain fields defined by the nanomesh geometry give rise to spatially varying band shifts and warping, which in aggregate accelerate electron transport along directions of high stress. This allows for global electrical conductivity and Seebeck enhancements beyond those of homogenous samples under equivalent far-field stresses, ultimately increasing thermoelectric power factor over unstrained samples.