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Editorial

Focus on thermoelectric effects in nanostructures

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Abstract
The field of nanoscale thermoelectrics began with a clear motivation for better performances of waste heat recovery processes by lowering the system dimensionality. Although this original inspiration still drives many recent developments, the field has also evolved to address fundamental questions on charge and energy transport across quantum conductors in the presence of both voltage and temperature differences. This 'focus on' collection provides new perspectives in the field and reports on the latest developments, both theoretically and experimentally.

We are pleased to present a collection of 23 research papers that discuss the latest developments in the field of thermoelectric effects in nanostructures. Thermoelectrics is devoted to cross effects that lead to the generation of electric current upon the application of thermal gradients (Seebeck effect) or the manipulation of heat flow using electric fields (Peltier effect). The interest in nanoscale thermoelectrics was triggered in the early 1990s by the pioneering works of Hicks and Dresselhaus [1], who envisaged a dramatic enhancement of the energy harvesting performance by means of tailored nanostructures with high power factors and low thermal conductivity. This proposal boosted the number of both articles and patents based on small systems. Two decades later, nanothermoelectrics has firmly established as a subfield in condensed matter physics in its own right. Specifically, this community addresses now also fundamental questions regarding charge and heat transport in nanoscale systems that lead to new, exciting physics, and that are the topic of this focus issue.

The search for better efficiencies is still an important issue. Fiedler and Kratzer [2] show that the figure of merit *ZT* gets larger in quantum dot superlattices. *ZT* increases are anticipated by Benenti *et al* [3] in two-dimensional electron gases with elastic collisions. Quasi-one dimensional systems are also good candidates to observe rising thermoelectric energy conversions, as indicated by Wang *et al* [4] for spatially structured nanowires. A different approach considers multiterminal nanoconductors. Jiang *et al* [5] propose a semiconductor junction with electron-boson coupling. Sothmann *et al* [6] predict large power outputs in quantum wells interconnected with a hot cavity. Mazza *et al* [7] find improved efficiencies at maximum power in three-terminal quantum thermal engines. Another possible route suggests time-reversal symmetry breaking fields. If the system's thermopower is asymmetric when an externally applied magnetic field reverses, the efficiencies become generally bounded, as Brandner and Seifert [8] demonstrate. Hence, a careful characterization of magnetic-fied asymmetries is relevant for the thermoelectric properties of a nanostructure. This is accomplished by Hwang *et al* [9] in the case of a quantum Hall antidot beyond linear response. The nonlinear linear regime of thermoelectric transport is an emerging topic with very few studies thus far. An experimental report is presented by Svensson *et al* [10]. They observe a strongly nonlinear thermovoltage in nanowires subjected to large heating bias. The effect is interesting because it involves a sign change of the thermocurrent, a quite unique feature without electric counterpart.

The field thus offers a large wealth of opportunities in fundamental condensed matter physics. The role that disorder plays in the thermopower *S* is theoretically described by Bosisio *et al* both for the elastic [11] and inelastic [12] regimes in nanowires. Narayan *et al* [13] experimentally detect density-dependent thermopower oscillations in two-dimensional gases, possibly related to disorder or electron-electron interactions. In fact, strong correlation phenomena are addressed within several contributions of this issue. Žitko *et al* [14] discuss the spin Seebeck effect—the generation of a spin voltage in response to an applied temperature difference—in the overscreened Kondo model and suggest that the spin thermopower can act as a useful tool that identifies Fermi liquid and non-Fermi liquid behaviors. Lim *et al* [15] extend the concept of spin thermopower to systems with orbital degrees of freedom, such as carbon nanotubes, and propose that the orbital thermopower can operate as a smoking gun signaling the transition between Kondo states with different symmetries. The idea of employing the Seebeck coefficient as a spectroscopic probe is reinforced by the findings of Leijnse [16], who points out that information on Majorana bound states can be extracted from *S*, and Tooski *et al* [17] , who investigate the large sensitivity of *S* to assisted hopping in interacting quantum dots.

Key to the promising functionalities of thermoelectric nanodevices is a solid understanding of heat transport. Bracht *et al* [18] analyze the thermal conductivity of silicon nanostructures. In molecular junctions, the heat dissipation exhibits an asymmetry that is precisely given by the Seebeck coefficient, as shown by Zotti *et al* [19] in connection with recent experiments. Molecular transistors represent the ultimate step in the miniaturization of thermoelectric devices. Dubi [20] discusses large fluctuations of *S* observed in these systems. The mutual influence of charge and heat and their fluctuations are investigated by Sánchez *et al* [21] in quantum dot thermoelectric engines. Spilla *et al* [22] prove that heat currents cause dephasing in superconducting qubits. An experimental account for the cooling properties of Peltier superconducting tunnel junctions is provided by Nguyen *et al* [23]. Lastly, the field also stimulates interdisciplinary approaches. The experiments of Gibbs *et al* [24] demonstrate that optical absorption can directly measure the electronic band structure of good thermoelectric materials.

We believe that the research presented in this collection represents an exciting snapshot of an ever growing field that will certainly bring fascinating surprises in the future. We would like to use this opportunity to thank all the contributing authors for their submissions and all the referees for the their hard work and insightful advice during the review process. We are also indebted to Carlo Beenakker, Tim Smith and Elena Belsole for their support in launching this focus issue and to Ceri-Wyn Thomas and Simon Buckmaster for their relentless editorial assistance. Last, but not least, we would like to dedicate this collection to the memory of Markus Büttiker for his deep physical insight and for his warm friendship.

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