Powerful and efficient energy harvesting with resonant-tunneling quantum dots

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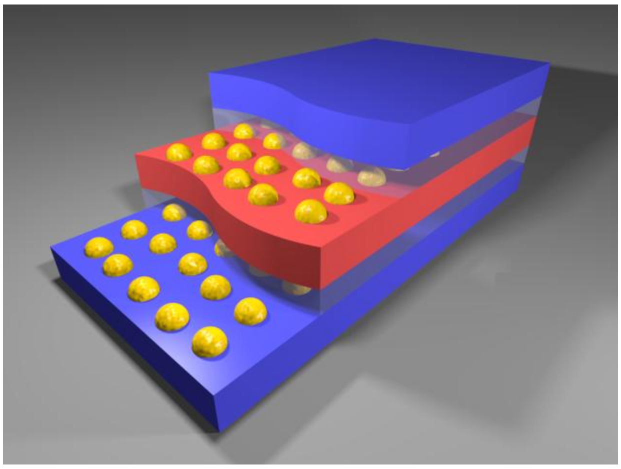
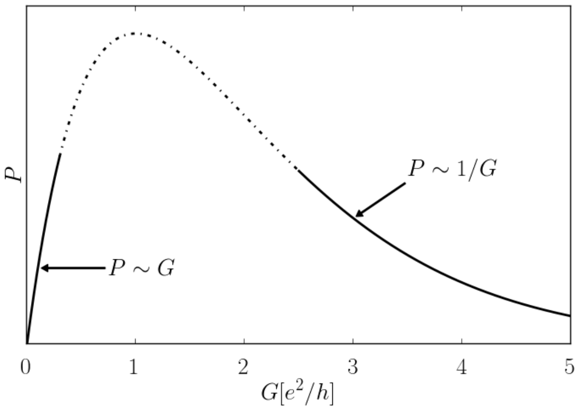
Abstract

The main purpose of energy harvesting is to collect energy from the ambient and to convert it into useful work. Of particular interest are thermoelectric energy harvesters. They can be applied, e.g., in computer chips where they convert waste heat back into electricity. One of the central goals of research in this field is to find highly efficient thermoelectrics. Mesoscopic solid-state physics can help to achieve this goal.

Quantum dots - nanometer-sized, artificially made structures – in the Coulomb-blockade regime have been shown to be highly efficient heat- to charge-current converters that can even reach Carnot efficiency [1]. Unfortunately, they deliver only very little power since transport occurs via tunneling of single electrons. Chaotic cavities connected to reservoirs via many open transport channels have been shown to yield currents that are two orders of magnitude larger [2]. However, the resulting power is comparable to devices in the Coulomb-blockade regime and decreases as number of channels is increased.
This suggests that systems with a single open transport channel are the optimal candidates for powerful and efficient thermoelectric setups. A paradigmatic realization of such a single-channel conductor is given by resonant tunneling through a quantum dot.

Here, we consider a setup consisting of a central cavity in thermal equilibrium with a heat source. It is connected to two cold electronic reservoirs via quantum dots with a single resonant level. Transport through the system can be described via scattering matrix theory. In the limit of small level width, we can





Left: Power P of a quantum-dot energy harvester as a function of the contact conductance G. In the Coulomb-blockade regime, power grows linearly with the conductance. For large conductances, the power decays as 1/G.

Right: Sketch of a parallelized heat engine based on self-assembled quantum dots. Top and bottom electrode (blue) are connected via quantum dots (yellow) embedded in an insulating matrix (transparent) to a central hot cavity (red).

solve the system analytically. We find that heat and charge currents are proportional to each other. Furthermore, the device can reach Carnot efficiency, i.e., it acts as an optimal converter. In addition, we provide a numerical analysis for arbitrary system parameters. Optimizing level position and width to maximize the output power, we find that the maximal power is given by $P=0.4\ (k\Delta T)^2/h$. For a temperature difference of $\Delta T=1$ K, the device thus delivers 0.1 fW of power.

In order to scale up the output power, one can put many such heat engines in parallel. A practical way to realize this parallelization is shown below. A large central cavity is sandwiched between two layers of self-assembled quantum dots. Transport between the cavity and two cold, external electrodes is only possible via the quantum dots. Interestingly, the layered structure can help to reduce phononic leakage heat currents that would otherwise reduce the device efficiency. Furthermore, we find this proposal to be robust with respect to fluctuations of dot properties.

References

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