NANOENERGY LETTERS

Powerful and efficient energy harvesting with resonant-tunneling quantum dots

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Abstract—**We consider a nanoscale heat engine based on resonant tunneling through quantum dot that act as energy filters. By coupling two quantum dots in series with a hot cavity, electrons have to gain a prescribed amount of energy in order to enter from one lead and leave to the other thereby performing work against an external bias. Despite our simple physical model, the heat engine turns out to be highly efficient and powerful. Finally, we demonstrate the possibility to scale up the power by putting many such heat engines in parallel in a self-assembled quantum dot structure.**

I. INTRODUCTION

Energy harvesters take energy from the environment and convert it into useful work. A particularly interesting class of energy harvesters is given by thermoelectric devices. These systems harvest heat, e.g., from a hot computer chip and convert it back into electricity. A key challenge of material research is to find thermoelectric materials with a high conversion efficiency. Unfortunately, decades of research in this area have only shown slow progress. Mesoscopic solid-state physics can help to overcome these problems of current thermoelectric devices.

Recently, quantum dots - nanometer-sized, artificially made structures - in the Coulomb-blockade regime have been shown to act as highly efficient heat-to-current converters [1]. Unfortunately, the resulting powers that they deliver are small since transport through these dots is based on the tunneling of single electrons.
Chaotic cavities that are connected to reservoirs via many open transport channels have been shown to deliver much larger currents, yet their power is comparable to those of dots in the Coulomb-blockade regime and decreases as the number of open channels is increased [2].

This suggests that transport through a single conductance channel is a very promising candidate for an efficient and powerful thermoelectric energy harvester, cf. Fig. 1. Therefore, in the following, we consider resonant tunneling through quantum dots which is a paradigmatic realization of a single transport channel [3].

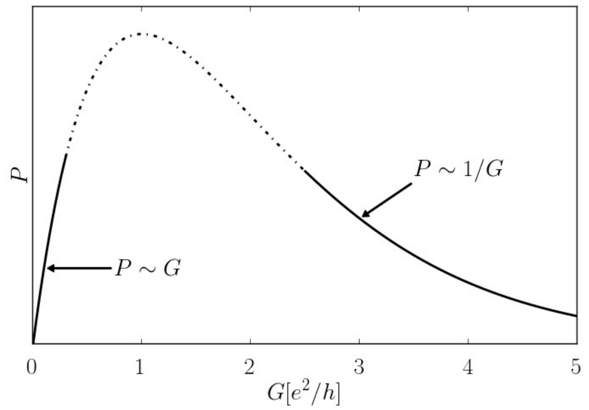

Fig. 1. Power P of a quantum-dot energy harvester as a function of the contact conductance G. In the Coulomb-blockade regime, power grows linearly with the conductance. For large contact conductances, power decreases as $1/G$.

II. SETUP

We consider a central cavity which is connected to two electronic reservoirs via quantum dots. Each reservoir r=L,R is described by a Fermi function $f_r(E) = \{\exp[(E-\mu_r)/k_\mathrm{B}T_R] + 1\}^{-1}$ with temperature T_R and chemical potential μ_r. The quantum dots each host a single level of width γ and energy $E_{L,R}$. The cavity is coupled to a heat source with temperature T_C that injects a heat current J into the cavity to keep it in thermal equilibrium with the heat source. We assume that electron-electron and electron-phonon interactions within the cavity are strong enough that the cavity is completely characterized by a Fermi distribution function $f_C(E) = \{\exp[(E-\mu_C)/k_\mathrm{B}T_C] + 1\}^{-1}$ with temperature T_C and chemical potential μ_C.

The latter two quantities are determined by the convervation of charge, $I_L + I_R = 0$, and energy, $J_L + J_R + J = 0$. Here, $I_{L/R}$ and $J_{L/R}$ denote the charge and heat current flowing from the cavity into the left/right reservoirs. They are given by the standard scattering theory expressions $I_r = (2e/h)\int dET_r(E)[f_r(E) - f_C(E)]$, $J_r = (2/h)\int dEET_r(E)[f_r(E) - f_C(E)]$. Here, $T_r(E) = \gamma^2/[(E-E_r)^2 + \gamma^2]$ denotes the

Lorentzian transmission of the quantum dots levels. While the expressions for the currents in general can be evaluated only numerically, in the limit of small level width, an analytical treatment becomes possible.

III. RESULTS

In the limit of small level width, $\gamma \ll k_\mathrm{B}T_R, k_\mathrm{B}T_C$, the conservation laws yield a set of two algebraic equations. Solving these, we find that heat and charge current are proportional to each other, $I/J = e/|E_L - E_R|$. In consequence, the efficiency η which is defined as the ratio between the output power $P = I|\mu_L - \mu_R|/e$ and the input heat J becomes $\eta = |\mu_L - \mu_R|/(E_L - E_R)$. At the stopping voltage $\mu_\mathrm{stop} = \Delta E(1 - T_R/T_C)$ where heat and bias-driven current compensate each other the heat engine thus reaches the Carnot efficiency $\eta_C = 1 - T_R/T_C$, i.e., it functions as in ideal heat to charge current converter. As the device acts adiabatically at this operating point, it does not produce any power. The maximal output power is achieved when half the stopping voltage is applied. Analytically, we find the maximum power to be $P_\mathrm{max} = \gamma(E_L - E_R)^2\eta_C^2/(16hk_BT_R)$. The efficiency at maximum power is given by $\eta_C/2$ in agreement with general bounds from thermodynamics [4].

In the limit of arbitrary level width, the conservation laws have to be solved numerically. Optimizing the full solution to maximize the output power, we find that the optimal parameters are given by $E_R = 6k_\mathrm{B}T$ and $\gamma = k_\mathrm{B}T$. The resulting maximal power is given by $P_\mathrm{max} \sim 0.4(k_\mathrm{B}\Delta T)^2/h$, i.e., it only depends on the temperature difference but not on the average temperature. For a temperature difference of $\Delta T = 1$ K this amounts to a power of 0.1 pW.

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 in Fig. 2. 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.

We finally remark that our proposal is robust with respect to fluctuation of the dot properties. Assuming a Gaussian distribution of level positions, we find that a scattering of 10% reduces the output power to 90% of its maximal value.

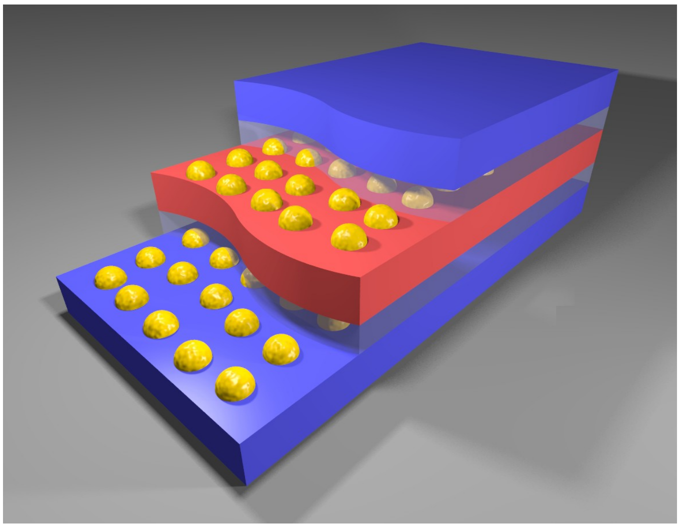

Fig. 2. Sketch of a parallelized heat engine based on self-assembled quantum dots. Top and bottom electrode (blue) are connected via quantum dots (yellow) embedded in an insulating matrix (transparent) to a central hot cavity (red).

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