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# Three-terminal heat engine and refrigerator based on superlattices

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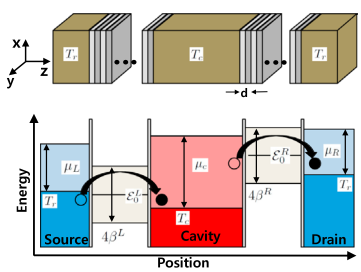
## HIGHLIGHTS

- Introduces thermoelectric device based on the mini-band structure of superlattices.
- Heat engine mode delivers a large power output compared to similar devices.
- Analysis of coefficient of performance of the refrigerator in nonlinear regime.
- Explicit treatment of phonon transport through the device.

## GRAPHICAL ABSTRACT

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## ABSTRACT

We propose a three-terminal heat engine based on semiconductor superlattices for energy harvesting. The periodicity of the superlattice structure creates an energy miniband, giving an energy window for allowed electron transport. We find that this device delivers a large power, nearly twice than the heat engine based on quantum wells, with a small reduction of efficiency. This engine also works as a refrigerator in a different regime of the system's parameters. The thermoelectric performance of the refrigerator is analyzed, including the cooling power and coefficient of performance in the optimized condition. We also calculate phonon heat current through the system and explore the reduction of phonon heat current compared to the bulk material. The direct phonon heat current is negligible at low temperatures, but dominates over the electronic at room temperature and we discuss ways to reduce it.


## 1. Introduction

There has been increasing interest in developing high efficiency, high power thermoelectric devices, constructed from the bottom-up using nanoscale designs. The primary applications driving interest in this area are energy-harvesting, the collection and conversion of waste heat to electrical power, produced from sources ranging from hand-held electronics to industrial sources of heat, and refrigeration, actively cooling a spatial region via electrons to evacuate heat out of an area. The use of nanoscale architecture instead of bulk materials is motivated by the low figure of merit - or poor thermoelectric conversion efficiency - of bulk materials, whereas conduction through nanoscale electronics can reach Carnot efficiency.

One way to produce high thermodynamic efficiency in the

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conversion of heat to power is the use of structures with sharp spectral features, such as quantum dots [1–3]. The use of quantum dots in thermoelectric transport has been extensively researched in the past several years [4–11]. See Refs. [12,13] for recent reviews of these and related activities. In particular, if the dot is transporting electrons via resonant tunneling, the quantum dot acts as an energy filter – permitting the "tight-coupling" of heat and charge transport which can lead to Carnot efficiency. Other structures from mesoscopic physics, including the quantum point contact and electron cavity [14], quantum wells [15,16], quantum Hall bar [17,18], superconducting leads [19], and Coulomb blockaded quantum dots(s) [20–24] have also been investigated for their multi-terminal thermoelectric properties. The late Prof. Markus Büttiker, for whom this special issue is in memory of, was highly influential in the theoretical development of these ideas, as can be seen in the above list of references.

Several experiments have begun exploring this physics. Prance et al. [25] performed experiments on a cavity connected to resonant tunneling quantum dots acting as an electronic refrigerator, based on the proposal of Edwards et al. [26]. They demonstrated that applying bias to the system results in cooling a large 6 $\mu m^2$ cavity from 280 mK to below 190 mK. Very recently, Roche et al. [27] and Hartmann et al. [28] showed rectification of electrical current of the nano Amp scale and power production on a pico Watt scale from a capacitively coupled source of fluctuations. This was based on the theoretical proposal of Sothmann et al. [14].

While a nanoscale thermoelectric generator can power nanoscale devices, it is of great interest to find practical ways to scale up these nanoengines. One way is to simply add them in electrical series while being able to couple to a common source of heat. In commercial thermoelectric generators, this is usually done by alternating the semiconductor type, of either p-type or n-type to be able to apply the heat difference in parallel because the heat and electrical transport are in opposite directions in a p-type semiconductor [29]. This permits the generated voltage to grow with the number of elements, while keeping the current fixed. Various other ways of scaling the devices have been proposed [30–33]. In Jordan et al., a layered structure was proposed by alternating layers of semiconductor and self-assembled quantum dots, so as to create a large-scale device where heat and electrical transport are separated, while keeping the high thermodynamic efficiency [9]. This is a parallel strategy of scaling, so the generated current grows with the number of dots, while the voltage difference is fixed. Sothmann et al. considered a technically simpler method of creating quantum wells that permit resonant tunneling [15]. The physics there is somewhat different because energy may be distributed into the transverse degrees of the electron motion. Nevertheless, reasonable thermodynamic efficiency was found, with increased power production.

One of the outstanding challenges to creating high-efficiency thermoelectric devices is phonon transport. Phonons give a way for the hot and cold side of the device to exchange energy directly, without converting it to power via the electrons. Therefore, any possible way to reduce the phonon transport while still allowing electron transport will aid in the overall thermodynamic efficiency. Interface-based devices, such as described above can help with this, because the interface helps to reflect the phonons [34–41]. Ideally, there will be additional material layers that act as thermal insulators.

The purpose of the present paper is to build on these accomplishments and make an analysis of a thermoelectric device based on semiconductor super-lattices. These structures are fabricated by making a periodic layered structure of alternating materials, such as GaAs/AlGaAs. The effect on the electronic transport is to form a series of mini-bands of allowed and forbidden energies where conduction electrons can transport [42–45]. This structure can be considered as a generalization of the resonant tunneling quantum wells. The mini-band gives a top-hat profile of variable width for the energy-filtering. Such a top-hat profile has been argued by Whitney to offer the highest efficiency for a given power extraction [46]. However, we note the transverse degrees of freedom make the system somewhat different. At a small band width, our system will be similar to a quantum well, but can be extended to allow a fixed width longitudinal energy window. We make a first-principles analysis of the heat and charge transport in a three-terminal geometry, where two terminals carry charge, and

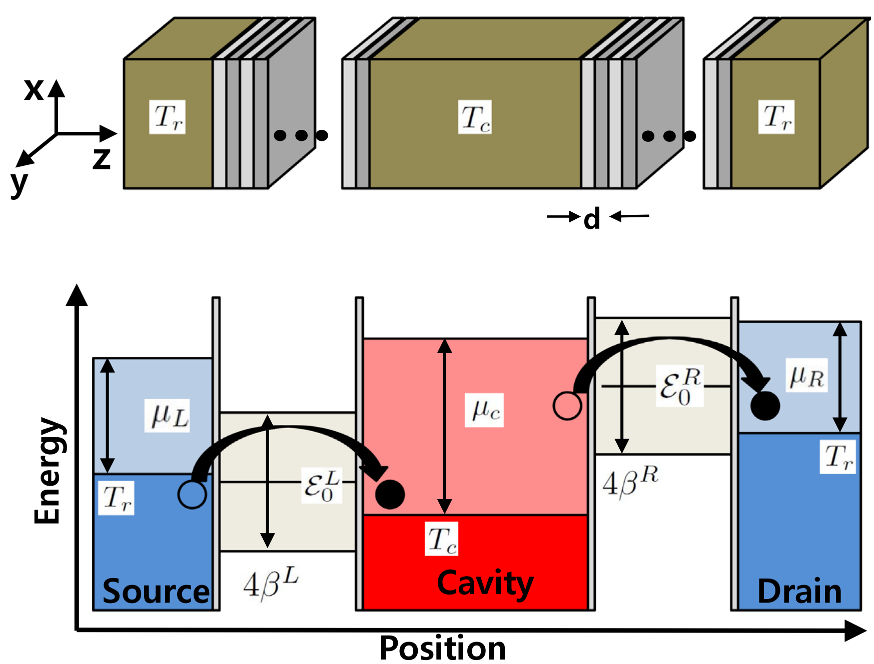


**Fig. 1.** (Top) Schematic of the superlattice heat engine. A hot cavity at temperature $T_c$ is coupled via superlattices to cold electronic reservoirs at temperature $T_r$. (Bottom) The periodic structure of the superlattices form the miniband centered at $\mathcal{E}_0^{L/R}$ with the width $4\beta^{L/R}$ when we apply the bias voltage $\mu_R - \mu_L = eV$. The gray shading area shows the energy miniband where the electrons can transport between regions. The shadings in the source, cavity, and drain regions indicate thermal smearing.