Strong nonlinear thermoelectricity generation and close-to-Carnot efficient heat engines in Superconductor-Insulator-2D electron gas junctions

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The use of thermoelectricity in a cryogenic environment opens pathways for ultrasensitive passive detection and for control and cooling of quantum technology applications. We introduce the Superconductor-Insulator-2DEG junction [1] as a novel nonlinear thermoelectric element. We assess its potential via a fully nonlinear model where we consider the temperatures of both sides, T_S and T_{Sm}, and the conduction band edge of the 2DEG, E_c. Its band structure allows the formation of nonlinear thermoelectricity even for relatively small temperature gradients, enhancing the thermoelectric figures of merit. For $T_S > T_{Sm}$, we obtain a maximum Seebeck potential larger than the superconductor gap Δ_0, $V_S \sim 6.75\ \Delta_0$ in the $E_c = 0.03\ \Delta_0$ regime, and a maximum efficiency of $\eta = 0.92\ \eta_c$ when used as a heat engine, close to the Whitney limit for efficiency at maximum power in nonlinear quantum systems [2]. For the relevant case $\Delta_0 = 200\ \mu$eV and tunnel resistance $R_t = 1$ k Ω, we obtain a maximum Seebeck coefficient of ~ 1 mV/K, a maximum Peltier current of $I_0 \sim 20$ nA, and a maximum output power of 4 pW for $T_S - T_{Sm} \sim 0.9 T_c$, with $T_c = 1.3$ K. We discuss the causes and the implications for these large figures of merit, in particular, the impact of energy filtering on efficiency. In different regimes, the system also shows a large dV_S/dT_S and a bistability pattern, which show potential for detection and control applications, respectively. It also shows bidirectional cooling, being the first system to cool a superconductor via a tunnel junction without another superconductor.

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