A solid-state solar-powered heat transfer device

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A solar-powered solid-state heat transfer device capable of operating in either a refrigeration or a heat-pump mode is proposed. The device's operation is based on the combined utilization of the photovoltaic and Peltier effects.

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I. INTRODUCTION

Interest in solar-energy utilization has increased dramatically in recent years. Most of the interest has focused on the problem of the conversion of solar energy into electrical energy[1] and the associated problems of energy storage. In this paper we attack a slightly different problem—that of heat transfer. We propose a solid-state solar-powered heat transfer device which is capable of operating in either a refrigeration or a heat-pump mode.

The device is based upon two physical effects: the photovoltaic effect and the Peltier effect.[2] An electrical current is generated at an illuminated semiconductor junction by virtue of the photovoltaic effect and is circulated through a set of Peltier junctions, with the result that a net heat transfer is established between one side of the device and the other. Depending on the design parameter, either heating or cooling is achieved.

Before discussing the detailed construction and operation of the device, let us analyze what limitations, if any, are imposed by the second law of thermodynamics. Consider the diagram illustrated in Fig. 1. The upper and lower rectangles depict two thermal reservoirs at temperatures T_1 and T_2, respectively, where $T_1 > T_2$. The left-hand circle symbolizes the photovoltaic junction and the right-hand circle represents the Peltier junctions. Let E be the solar energy delivered to the device in some time interval. A fraction f of this energy is converted into electrical energy and is delivered to the Peltier junctions. Let Q_1 denote the heat delivered to the high-temperature reservoir and Q_2 the heat extracted from the low-temperature reservoir. From the first law of thermodynamics

$$Q_1 = fE + Q_2. \tag{1}$$

For the sake of definiteness, let us study the case where the device is to act as a refrigerator. The heat extracted from the lower reservoir must exceed the heat delivered to it, i.e.,

$$(1 - f)E < Q_2. \tag{2}$$

The coefficient of performance for the Peltier junctions, acting as a refrigerator, is the heat extracted divided by the energy input

$$W = Q_2/fE. \tag{3}$$

An upper limit on this coefficient is imposed by the Carnot relation for a reversible refrigerator[3]

$$W < T_2/(T_1 - T_2). \tag{4}$$

Combining the above relations leads to

$$f > 1 - T_2/T_1. \tag{5}$$

Thus, given two temperatures, T_1 and T_2, refrigeration is possible provided the conversion efficiency exceeds the value given by the right-hand side of Eq. (5). Alternatively, for a given efficiency and reservoir temperature T_1, there exists a maximum temperature differential that may be established

$$\Delta T = \max(T_1 - T_2) = f T_1. \tag{6}$$

Thus we conclude that the device is not in conflict with

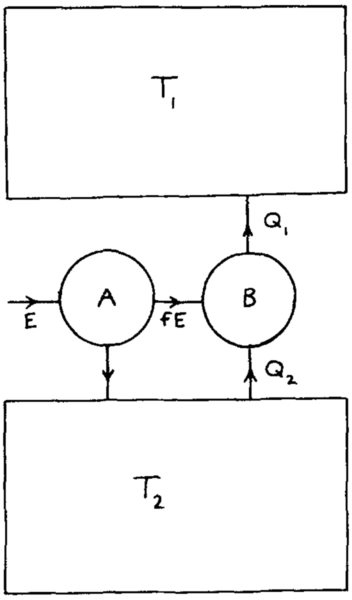

FIG. 1. Schematic thermodynamic diagram depicting the flows of energy. The upper rectangle denotes a thermal reservoir at temperature T_1 and the lower rectangle symbolizes a reservoir at temperature T_2. The circle labeled A represents a photovoltaic junction and the circle labeled B represents a set of Peltier junctions.

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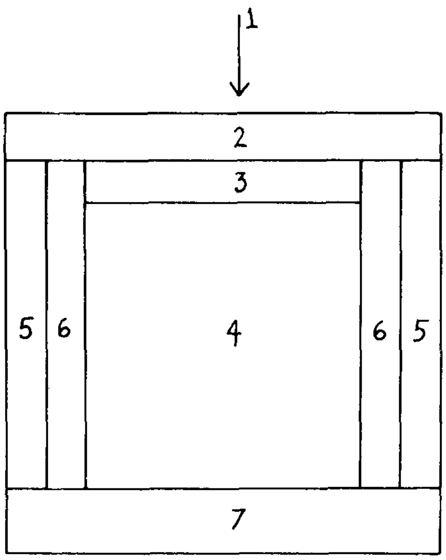

FIG. 2. A cross-sectional view of the proposed device. Light (1) passes through a metallic mesh (2), through a thin layer of semiconductor (3), and illuminates the photovoltaic junction [the interface between (3) and (4)]. On the sides is a semiconducting shaft (5). At the bottom is a metallic base (7). A thermal and electrical insulator (6) separates the semiconductor columns.

the Clausius statement of the second law of thermodynamics: that no machine operating in a closed cycle can have the net effect of driving heat from a cold reservoir to a hot reservoir. The proposed device is not a closed system but rather is an open system in which energy is continuously derived from the sunlight. Due to the fact that sunlight possesses an intrinsic entropy, a slight lower value for ΔT should be defined. We neglect this refinement here, however.[4]

II. THE PROPOSED DEVICE

A cross-sectional view of the proposed device is presented in Fig. 2. Light (1) impinges on the top of the device, passes through a metallic mesh (2) and through a semiconducting layer (3) onto a semiconducting substrate (4) whose conductivity type is different from the layer above it. At the sides of the aforementioned semiconductors is a region of thermal and electrical insulating material (6). On the other side of this insulating material is semiconducting material (5) whose impurity doping density is different than in (4). At the base of the device is a metallic layer (7).

By way of example, consider the case where one semiconductor (3) is of n type, another (4) is of p type with doping density denoted by N_A, and the third semiconductor (5) is of p type with doping density denoted by N'_A. The photocurrent that is generated at the interface between regions (3) and (4) circulates through the inner p-type semiconductor (4), through the metallic base (7), up through the outer p-type semiconductor (5), through the metallic mesh (2), and back through the n-type semiconductor (3). In regions (4) and (5) the majority carriers are holes. In addition to carrying electrical charge, these carriers transport thermal energy. The amount of thermal energy crossing a unit area in a unit time J_Q is proportional to the electrical current density J_E,

$$J_Q = PJ_E, \tag{7}$$

where the constant of proportionality P is the Peltier coefficient. Its value depends on the impurity doping density. If the doping densities are arranged properly, more heat may be transported by the carriers upward through (5) than are transported downward through (4). This is the physical origin of the Peltier effects that occur at the junctions between regions (4) and (7) and between regions (5) and (7).

In addition to the above thermal flows, there exists a thermal flow associated with the phonons of semiconductors (3)–(5). Material (6) is chosen to have suffficiently low thermal conductivity so its contribution to the heat flux may be neglected.

Let the cross-sectional area in a direction perpendicular to the symmetry axis of Fig. (2) be denoted by A_i, $i = 2,...,7$. Let the height of the various regions be denoted by H_i, $i = 2,...,7$. Let K_i, $i = 2,...,7$, denote the lattice thermal conductivities of the various materials. Let T_1 be the temperature of the metal mesh (2) and T_2 be the temperature of the metal base (7). Assume $T_1 > T_2$. The net heat current flowing up through region (5) is

$$I_{Q_5} = P'I_E - \frac{K_5A_5}{H_5}(T_1 - T_2). \tag{8}$$

The net heat current flowing down through the lower part of region (4) is

$$I_{Q_4} = PI_E + \frac{K_4A_4}{H_4}(T_{34} - T_2), \tag{9}$$

where I_E is the electrical current through the outer semiconductor, P and P' are the Peltier coefficients for regions (4) and (5), respectively, and T_{34} is the temperature at the (3)–(4) interface. Assume H_3 is considerably less than H_4 so, to some approximation,

$$T_{34} \approx T_1. \tag{10}$$

The net heat current upward through the device is

$$I_Q = (P' - P)I_E - \left(\frac{K_4A_4}{H_4} + \frac{K_5A_5}{H_5}\right)(T_1 - T_2). \tag{11}$$

For refrigeration of the base to occur, we must have

$$I_Q > 0. \tag{12}$$

This can only occur is P' is sufficiently larger than P.

While one may design the device employing empirical values for P and P', we may simply relate them to semiconductor parameters for the case of extrinsic nondegenerate doping. Then

$$P = \frac{kT}{e}\left[\lambda - \ln\left(\frac{N_A}{N_v}\right)\right], \quad 2 < \lambda < 4, \tag{13}$$

where T is some average temperature, approximately equal to T_2, k is Boltzmann's constant, e is the magnitude of the electron's charge, N_A is the doping density and N_v is given by

$$N_v = \int d\epsilon\, D_v(\epsilon) \exp(-\beta|\epsilon|), \tag{14}$$

where $D_v(\epsilon)$ is the valence band density of states. N_v repre-

TABLE I. Tabulation of the optimized function of Eq. (29).

uzv	y/v	f_0
0.05	10.7	0.791
0.10	8.2	0.580
0.20	6.5	0.409
0.50	5.1	0.242
1.00	4.4	0.154
2.00	3.9	0.095

sents the density at which degeneracy effects become important.

An approximate expression for the electrical current may be obtained by taking H_3 comparable to the optical absorption length for semiconductor (3), and H_4 sufficiently small so that the current is not Ohmic limited. H_4 must be larger than the majority-carrier diffusion length L for semiconductor (4). Let g denote the number of electron-hole pairs generated per unit volume per unit time in the junction region. It is related to the incident optical flux I through the relation

$$g = qI/hfH_3, \tag{15}$$

where hf is the mean energy of an incident photon and q is the quantum efficiency for electron-hole production. Then

$$I_E = geLA_4. \tag{16}$$

Referring back to Eq. (6), refrigeration is possible provided $N_A/N_v > N'_A/N'_v$ and the temperature difference is less than

$$\Delta T = \frac{kT_2LA_4qI \ln(N_A N'_v/N'_A N_v)}{H_3hf(K_4A_4/H_4 + K_5A_5/H_5)}. \tag{17}$$

A more favorable (larger) estimate for the maximum temperature difference ΔT is obtained when the p-type semiconductor (4) is allowed to be in the degenerate region. Then, in the same order of approximation P is negligible and

$$\Delta T = \frac{kT_2LA_4qI\,[\lambda - \ln(N'_A/N'_v)]}{H_3hf(K_4A_4/H_4 + K_5A_5/H_5)}. \tag{17'}$$

A criterion for the device to be non-Ohmic is that the gap energy for semiconductor (4) be larger than the Ohmic voltage drop

$$E_g \gtrsim eRI_E, \tag{18}$$

where R is the electrical resistance of the circuit and is approximately

$$R = \frac{1}{e}\left(\frac{H_4}{N_A\, u_4 A_4} + \frac{H_5}{N'_A\, u_5 A_5}\right), \tag{19}$$

where u_4 and u_5 are the majority-carrier mobilities of semiconductors (4) and (5).

The condition that the semiconductor be nondegenerate is that

$$N_A \lesssim N_v. \tag{20}$$

If we combine Eqs. (17)–(20) we obtain an upper limit on the temperature differential

$$\Delta T = \frac{kN_vT_2E_g}{e}\frac{u_4}{K_4}f(u,v,x,y,z), \tag{21}$$

where we have let

$$f = \frac{\ln(Y/v)}{(1 + xyz)\,(1 + u/x)}, \tag{22}$$

and

$$u = K_5/K_4, \tag{23}$$

$$v = N_v/N'_v, \tag{24}$$

$$x = H_5A_4/H_4A_5, \tag{25}$$

$$y = N_A/N'_A, \tag{26}$$

$$z = u_4/u_5. \tag{27}$$

Maximization of f with respect to x occurs when

$$x = (u/yz)^{1/2}, \tag{28}$$

and then

$$f = \frac{\ln(y/v)}{[1 + (uyz)^{1/2}]^2}. \tag{29}$$

If we further optimize f with respect to the product uzv we may write Eq. (21) as

$$\Delta T = \frac{kN_vT_2E_gf_0}{e}\frac{u_4}{K_4}, \tag{30}$$

where f_0 is tabulated in Table I.

Now let us consider the operation of the device in the heat-pump mode. Referring back to Eq. (11), assume that the doping in the semiconductors is such that $P' < P$. Both terms on the right-hand side will now be negative, indicating a flow away from the illuminted side. The first term represents a current-induced flow of heat from hot to cold while the second term corresponds to the normal thermal conduction process. The first term accounts for the heat-pumping action.

The condition $P' < P$ may be achieved in two ways. If the semiconductors (4) and (5) are p type, then it is sufficient to have $N_A/N_v < N'_A/N'_v$. Alternatively, if semiconductor (5) is n type, the electrons will flow in a downward direction through (5) and so will the associated thermal flow. Thus, the doping density is not critical for the existence of the effect.

While we have analyzed the device primarily by way of a specific example [semiconductors (3)–(5) being of n,p, and p types respectively] it is clear that the roles of n and p may be interchanged. For refrigeration it would then be necessary for the donor densities to satisfy $N_D/N_C > N'_D/N'_C$. In the opposite case, i.e., when $N_D/N_C < N'_D/N'_C$, the device would function as a heat pump, as it would if semiconductor (5) were made of p-type material.

In summary, we have proposed an integrated solid-state structure which acts as a solar-powered heat transfer device. Depending on the exact design specifications, the device may act either as a refrigerator or a heat pump.

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