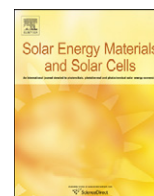




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Letter

Impact of the Peltier effect on concentrating photovoltaic cells

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ABSTRACT

Photovoltaic cells convert most of the absorbed photon energy to heat. Removal of the heat by thermal conduction creates a heat flux that is significant in concentrating photovoltaic (CPV) cells subject to high incident radiation flux. The Peltier effect interaction of this heat flux and the electrical current in the cell can either increase or decrease the temperature gradient within the cell. Here we show that the Peltier effect contributes to a measurable change in the temperature gradient in Ge-based CPV cells and therefore this effect should be considered in cell modelling. The effect may also have an impact on the temperature gradient of other photovoltaic cells and of other high power optoelectronic devices.

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1. Introduction

Photovoltaic cells convert some of the absorbed photon energy to electricity, but most of the energy is converted to heat [1]. The generated heat is removed by thermal conduction to the back plane of the cell, to minimize the increase in cell temperature that would lead to reduction in the conversion efficiency of the cell [2]. The heat flux to be removed can be significant in concentrating photovoltaic (CPV) cells, typically exposed to illumination fluxes 500–2000 times higher than natural sunlight [3]. While heat removal by standard thermal conduction (“Fourier’s Law”) is well known, another part of the heat transfer problem due to thermoelectric effects has so far been ignored.

The electrical current crossing the cell structure (Fig. 1) produces the Peltier effect, a thermoelectric phenomenon whereby some heat is transported as a thermoelectric interaction with the electrical current, in parallel to heat transport by the conventional Fourier mechanism. The thermoelectrically transported heat flux changes when crossing an interface between two materials having different values of the Seebeck coefficient, and this change is expressed as a surface heat source or sink for the Fourier heat transport [4]. The Peltier effect can therefore either increase or decrease the heat flux in certain sections of the cell, depending on the values of the Seebeck coefficient in the different layers in the cell. This effect and its impact within the cell are currently not included in common photovoltaic cell models. Here we investigate whether the missing Peltier effect can have a significant and measurable impact on the cell’s performance.

In previous work [5] we considered the impact of the Thomson effect, a thermoelectric phenomenon that generates a distributed heat source or sink throughout the CPV cell. In this work we estimate the magnitude of the Peltier effect, a distinct manifestation of thermoelectric energy transport that is expressed at interfaces between dissimilar materials. The significance of this effect is evaluated for Ge based III–V triple-junction (TJ) cells subject to concentrated sunlight, based on published data of cell properties and performance.

2. Analysis

2.1. Heat transport effects

The total heat flux in the bulk of a heat conductor is the sum of two terms, a thermal diffusion or conduction (Fourier) flux contribution $q_F = -k\nabla T$ and a thermoelectric (Peltier) heat flux contribution $q_P = jT\alpha$ [4]

$$q = q_P + q_F = jT\alpha - k\nabla T \quad (1)$$

At a junction between two dissimilar materials 1 and 2, the electrical current j and the temperature T are continuous, but the Seebeck coefficient α may differ for the two materials. Energy conservation then implies a step change in the diffusion heat flux

$$q_{F,1} - q_{F,2} = q_{P,2} - q_{P,1} = jT(\alpha_2 - \alpha_1) \quad (2)$$

When considering only the heat transport by diffusion, this discontinuity appears as a heat source localized at the interface between the two materials, and can assume either sign indicating apparent absorption or generation of heat. In the literature the

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Nomenclature		Subscripts	
C	Flux concentration ratio [–]	c	Cell base
e	Elementary charge, $e = 1.602 \times 10^{-19}$ C	e	Cell back electrode
F	Direct normal solar flux [W m^{-2}]	el	Electric
j	Current density [A m^{-2}]	F	Fourier
k	Thermal conductivity [$\text{W m}^{-1} \text{K}^{-1}$]	M	Maximum power point
k_B	Boltzmann's constant, $k_B = 1.381 \times 10^{-23}$ JK ⁻¹	P	Peltier
q	Heat flux [W m^{-2}]	th	Thermal
r	Ratio of heat fluxes [–]		
T	Temperature [K]		
V	Voltage [V]		
Greek			
η	Cell efficiency [–]		
α	Seebeck coefficient [V K^{-1}]		

Peltier effect is sometimes presented in an isothermal context, with $\nabla T = 0$ on both sides of the junction [4]. In this case, the apparent heat source is assumed to be linked to an external entity that provides or removes the needed amount of heat without creating a local temperature gradient. In the context of a photovoltaic cell, however, heat is removed by thermal conduction through the cell toward the back surface, and a temperature gradient exists throughout the cell. The relevant junctions, where a Peltier apparent heat source may appear, include the internal interfaces between the active layers at the top of the cell, and the interfaces between the semiconductor and the metal at the bottom and top electrodes.

The top electrode area is usually very small, to minimize shading of the incident light, and therefore its thermal resistance is high. Heat removal by natural convection from the exposed top cell surface is also small relative to the high incident flux. Therefore, the top surface is approximated as an adiabatic (thermally isolated) surface. The internal interfaces between adjacent layers in the cell are thermally isolated from the surroundings. Due to the very small cell thickness compared with its width, heat transfer from the cell side surfaces is negligible [6], and the problem can be treated as one-dimensional. Heat removal from the cell occurs then mostly at the bottom electrode, which is

attached to a heat sink with a passive or active mechanism for heat transport to the environment. Heat generated anywhere in the cell, and heat generated by the Peltier apparent heat sources, can therefore be removed only through diffusion heat transfer across the cell via a temperature gradient.

Absorption of sunlight, and recombination and thermalization of charge carriers, occur mostly within the relatively thin active layer at the top of the cell [7,8], and the related heat must be transferred by conduction to the bottom of the cell. Joule heating occurs throughout the cell, but the dominant contribution to the series resistance is in the thin emitter layers [9], and therefore most of this heat generation also occurs at the top of the cell. The Thomson effect heat is distributed across the cell base, but it is significantly smaller than the other sources [5]. Therefore, for the purpose of estimating the size of the Peltier effect heat transfer compared with the Fourier conduction heat transfer, we assume non-isothermal conditions where the heat is generated only at the top active layer of the cell, and removed only at the bottom electrode of the cell.

The Seebeck coefficient for the metal electrode is: $\alpha_e \cong 0$ [10], and heat passing into the electrode is then by thermal conduction only. The energy balance at the interface between the cell base and the bottom electrode is then

$$q_{F,e} = (jT\alpha - k\nabla T)_c \tag{3}$$

Since heat is removed from the entire cell only via the bottom electrode, the total heat flux conducted through the bottom electrode to the heat sink is equal to the incident solar flux, less the part that is converted into electrical energy

$$q_{F,e} = FC - q_{el} = FC(1 - \eta) \tag{4}$$

We substitute Eq. (4) into Eq. (3) and solve for ∇T_c

$$\nabla T_c = (jT\alpha_c - FC(1 - \eta)) / k_c \tag{5}$$

Using measured data for the incident flux, current and cell efficiency at maximum power point, it is possible to compare the magnitude of the temperature gradient at the cell base, with and without the thermoelectric contribution (first term in Eq. (5)).

The information available on Seebeck coefficient in semiconductors is still incomplete [11] and to the best of our knowledge no experimental $\alpha(T)$ values are available for the p-type Ge of the cell base at the usual temperature range of cell operation. The temperature dependence of α has been measured in the

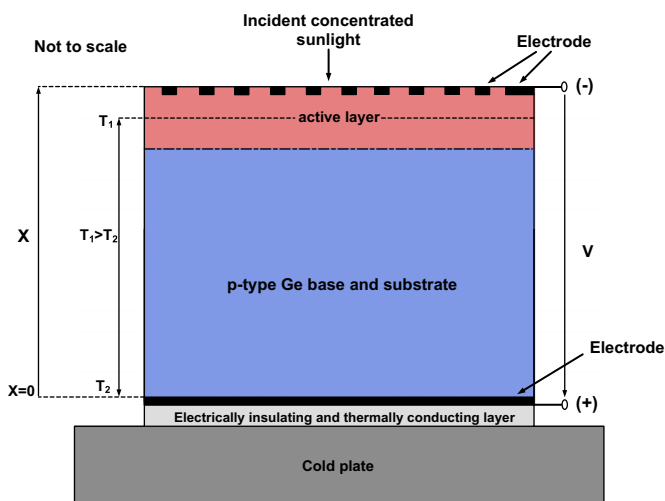


Fig. 1. Structure of a typical TJ CPV cell: a thin active layer containing the depletion regions of the three junctions; a thick Ge base and substrate; an electrically insulating and thermally conducting mounting layer; and a cold plate.

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