

Letter

Impact of the Thomson 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 temperature gradient that is significant in concentrating photovoltaic (CPV) cells subject to high incident radiation flux. The Thomson effect interaction between this temperature gradient and the electrical current in the cell can either increase or decrease the electrical power output of the cell. Here we show that the Thomson effect has a non-negligible impact on the conversion efficiency of Ge-based CPV cells, which is comparable to the impact of typical series resistance, and therefore this effect should be considered in cell modeling. The effect may also have a significant impact on the performance 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]. While the effect of the resulting increase in cell temperature on the conversion efficiency has been well established [2], the effect of the temperature gradient created by removal of the generated heat by thermal conduction has so far been ignored in cell modeling. This temperature gradient can be significant in concentrating photovoltaic (CPV) cells, typically exposed to illumination fluxes 500–2000 times higher than natural sunlight [3]. The simultaneous presence of a temperature gradient and an electrical current produces the Thomson effect, a thermoelectric phenomenon whereby heat is converted to electrical energy, or vice versa, depending on the relative direction of the heat flux and the electrical current [4]. The Thomson effect can therefore either increase or decrease the cell's conversion efficiency. This effect and its impact on cell conversion efficiency are currently not included in photovoltaic cell models. The existing gap between theoretical model predictions of CPV cell efficiency and experimental results reveals that the current models of CPV cells are inadequate [1]. Here we investigate whether the missing Thomson effect can be partially responsible for this gap.

CPV technology employs optics to concentrate sunlight from a large collection area onto a small cell area. One advantage is a reduction in the amount of expensive semiconductor cell material

per unit power of collected sunlight. Another advantage is an increase in cell conversion efficiency, since both cell current and voltage increase with concentration [3]. The cell current increases approximately linearly with the concentration ratio and so do the heat flux and therefore the temperature gradient. The magnitude of the Thomson effect increases then by the square of the concentration ratio compared to conventional cells, and the significance of this effect should then be more pronounced at high concentration. In this work we estimate the magnitude and significance of the Thomson effect in III–V Triple-junction (TJ) cells subject to concentrated sunlight and evaluate whether this effect should be added to models of cell performance.

2. Analysis

The thermal power per unit volume generated within the cell due to the Thomson effect is [5,6]

$$-T \frac{dS}{dT} \nabla T_j \quad (1)$$

where T is the temperature, j is the projection of the electric current density vector onto the direction of the temperature gradient, and S is the Seebeck coefficient of thermoelectric power. The corresponding thermal power per unit volume due to Joule heating is ρj^2 where the electrical resistivity is ρ . While the Joule heating is always positive, the Thomson heating may assume either sign: a positive value ($-T(dS/dT)\nabla T_j > 0$) indicates dissipation of electrical energy into heat, whereas a negative value indicates conversion of heat into electrical power. In a typical n-over-p cell $\nabla T_j < 0$ and the sign of the Thomson term is

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Nomenclature

C	Flux concentration ratio [–]
A	Area [m ²]
F	Direct normal solar flux [W m ⁻²]
j	Current density [A m ⁻²]
L	Cell thickness [m]
k	Thermal conductivity [W m ⁻¹ K ⁻¹]
l	Fractional loss [–]
R	Electrical resistance [Ω]

S	Seebeck coefficient [V K ⁻¹]
T	Temperature [K]
V	Voltage [V]

Greek

η	Efficiency [–]
ρ	Electrical resistivity [Ω m]

determined by dS/dT , which is a property of the cell material. In conventional cells without concentration both ∇T and j are small, but both are large in CPV cells and therefore the magnitude of the Thomson term can be significantly higher. The conversion of electrical energy to thermal energy by the Thomson heating may be represented as an effective electrical resistivity in the cell, in analogy to the Joule heating but noting that this effective resistivity may be negative

$$\rho_T = -T \frac{dS}{dT} \nabla T / j \quad (2)$$

We represent the cell by a simple equivalent electrical circuit model (Fig. 1a) with negligible leakage current (large shunt resistance), where the Thomson effect is modeled as an additional series resistance R_T . The relation of the cell's measured efficiency

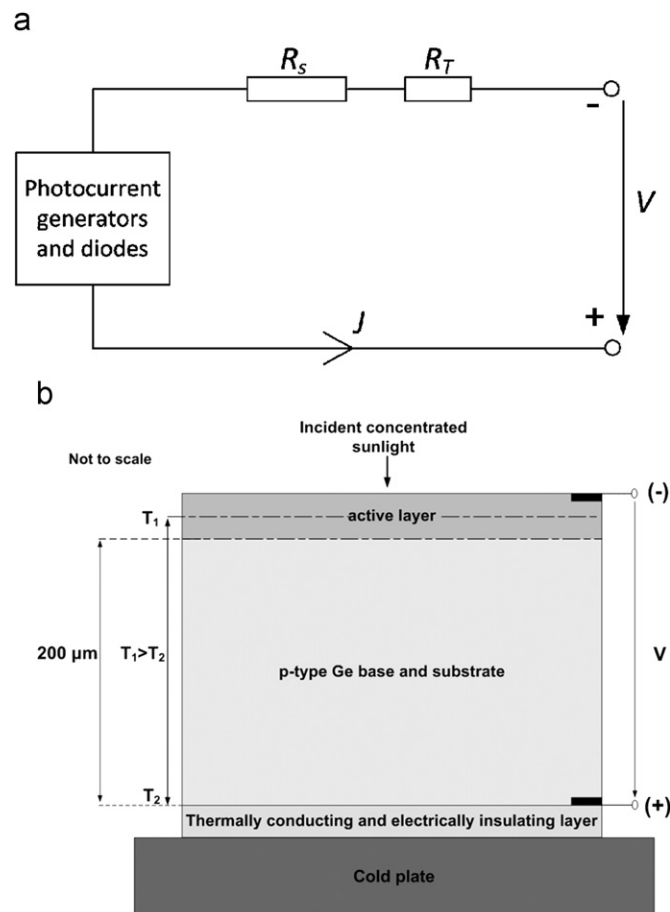


Fig. 1. Cell representation. (a) Equivalent electrical circuit and (b) typical structure of a TJ CPV cell comprising: a thin active layer containing the depletion regions of the three junctions; a thick Ge base and substrate; an electrically insulating and thermally conducting mounting layer; and a cold plate.

η_M to the ideal photogeneration efficiency η_P (photogenerated power divided by incident power), and the fractions of the incident power lost due to series resistance l_S and to the Thomson effect l_T is

$$\eta_M = \eta_P - l_S - l_T \quad (3)$$

Efficiencies, currents, and voltages all refer to operation at the cell's Maximum Power Point. Given direct normal solar flux F and flux concentration ratio C , the photogenerated power per unit area is $FC\eta_P$, and the measured power per unit area is $FC\eta_M$. Current density across the cell substrate is $j = FC\eta_M/V_M$, where V_M is the measured voltage. The fractional loss due to series resistance is then

$$l_S = \frac{R_S A j^2}{FC} = R_S A F C \left(\frac{\eta_M}{V_M} \right)^2 \quad (4)$$

where R_S is the cell's series resistance and A is its area. $R_S A$ is a size-independent quantity that depends on the emitter properties and on the front grid layout. The $R_S A$ value was set to $9.3 \times 10^{-7} \Omega \text{ m}^2$, based on measured data [7] and consistent with other CPV cells [8].

In a typical TJ cell the depletion regions of the three junctions lie in a relatively thin active layer above a significantly thicker p-type Ge base and substrate (Fig. 1b). Most photon absorption and carrier thermalization occur within the active layer [9,10]; Joule heating also occurs mostly in the thin emitter layers which provide the dominant contribution to the series resistance [11]; and the Thomson effect heat source (or sink) distributed across the cell base is significantly smaller than the other sources. Therefore for the purpose of estimating the temperature gradient we assume that heat is generated only at the top active layer and then transferred by conduction through the base. Due to the very small cell thickness compared to its width, heat transfer from the cell side surfaces is negligible [12]. The temperature gradient across the cell base is then

$$\nabla T = \frac{1}{k} F C (1 - \eta_M) \quad (5)$$

where k is the thermal conductivity. The fractional loss or contribution due to the Thomson effect is then

$$l_T = \frac{-T \frac{dS}{dT} \nabla T j L}{FC} = -\frac{F C L T}{k} \frac{dS}{dT} \frac{(1 - \eta_M) \eta_M}{V_M} \quad (6)$$

where L is the thickness of the cell base and substrate. Substituting Eqs. (4) and (6) into (3) we find the ideal efficiency η_P and estimate the cell efficiency η that would have been measured if the Thomson effect were absent

$$\eta = \eta_P - l_S \quad (7)$$

The information available on thermoelectric power in semiconductors is still incomplete [13] and to the best of our knowledge no experimental $S(T)$ values are available for the p-type Ge at the usual temperature range of cell operation. The temperature dependence of S has been measured in the range

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