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Physics of the temperature coefficients of solar cells

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ABSTRACT

Physics ruling the temperature sensitivity of photovoltaic (PV) cells is discussed. Dependences with temperature of the fundamental losses for single junction solar cells are examined and fundamental temperature coefficients (TCs) are calculated. Impacts on TCs of the incident spectrum and of variations of the bandgap with temperature are highlighted. It is shown that the unusual behavior of the bandgaps of perovskite semiconductor compounds such as $CH_3NH_3PbI_{3-x}Cl_x$ and $CsSnI_3$ will ultimately, in the radiative limit, give PV cells made of these materials peculiar temperature sensitivities. The different losses limiting the efficiency of present commercial cells are depicted on a p–n junction diagram. This representation provides valuable information on the energy transfer mechanisms within PV cells. In particular, it is shown that an important fraction of the heat generation occurs at the junction. A review of the loss mechanisms driving the temperature coefficients of the different cell parameters (open circuit voltage V_{oc}, short circuit current density J_{sc}, fill factor *FF*) is proposed. The temperature sensitivity of open circuit voltage is connected to the balance between generation and recombination of carriers and its variation with temperature. A general expression that relates the temperature sensitivity of V_{oc} to the External Radiative Efficiency (ERE) of a solar cell is provided. Comparisons with experimental data are discussed. The impacts of bandgap temperature dependence and incident spectrum on the temperature sensitivity of short circuit current are demonstrated. Finally, it is argued that if the fill factor temperature sensitivity is ideally closely related to the open circuit voltage temperature sensitivity of the cell, it depends for some cells strongly on technological issues linked to carrier transport such as contact resistances.

1. Introduction

It has long been observed that temperature affects negatively the performances of photovoltaic (PV) devices [1,2]. This is an important issue for the PV industry because the efficiency of PV modules is lower under real operating conditions than under Standard Test Conditions (STC) and because it increases the difficulty in predicting PV energy production.

Several articles have investigated the theoretical temperature dependences of solar cell output parameters [1–9]. The analyses provided important information on the general trends of the temperature behavior of solar cells explaining for example the small temperature sensitivity of cells with large bandgaps. However, the use of one or several semi-empirical parameters to calculate the diode current restricted the generality of the conclusions and in some cases led to systematic errors in modeling as demonstrated elsewhere [10]. Identifying the different mechanisms driving the temperature sensitivity of solar cells, Green derived some general equations for temperature coefficients from internal device physics [10]. Siefer and Bett [11] made theoretical calculations illustrating that temperature coefficients are function of the dominant recombination processes. Recently, a group from NREL observed experimentally that metastable changes due to light exposure modify the temperature dependence of the fill factor of CIGS thin film cells [12]. Their analysis illustrates the depth of the correlation between device physics and temperature coefficients.

This paper investigates the physics that governs the temperature behavior of solar cells. First, building on the work of Hirst and Ekins-Daukes [13], the temperature dependences of the "fundamental" losses in photovoltaic conversion are discussed. Then, the analysis is extended to additional losses such as non-radiative recombinations in order to explain the physics behind the temperature coefficients of real devices. Finally, the different mechanisms driving the temperature sensitivity of open circuit voltage (V_{oc}), short circuit current (J_{sc}) and fill factor (*FF*) are discussed.

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2. Fundamental losses in photovoltaic conversion

2.1. Detailed balance principle and thermodynamics

Fundamentally, photovoltaic devices are energy converters that turn thermal energy from the sun into electrical energy. This means that a solar cell, like any heat engine, is ultimately limited by the Carnot efficiency [14,15]. However, even ideal PV devices differ from Carnot engines because the energy exchanged is radiative and because the energy emitted by the devices is considered a loss in PV conversion since the hot reservoir is the Sun. Moreover, typical PV cells absorb solar photons from a small solid angle while they emit in a much broader solid angle. Additionally, for typical single junction cells, there is an important loss due to the spectral mismatch between the incident radiation and the absorption in the cell that generates electrical carriers.

Hirst and Ekins-Daukes derived from the detailed balance principle [16] an approximate relation between a PV cell bandgap (E_g) and its voltage at maximum power point (V_{MPP}) [13]:

$$qV_{MPP} \approx E_g\left(1-\frac{T_c}{T_s}\right)-kT_c\ \ln\left(\frac{\Omega_{emit}}{\Omega_{abs}}\right) \tag{1}$$

q, k, T_c and T_s, Ω_{abs} and Ω_{emit} are respectively the electron charge, Boltzmann's constant, the cell and sun temperatures, the absorption and emission solid angles. Interestingly, this equation displays classical thermodynamic terms. The first term on the right hand side contains the Carnot efficiency which expresses the necessity of evacuating the incoming entropy. The second term on the right hand side is the voltage loss related to the entropy generated due to the solid angle mismatch between absorption and emission.

The current density at maximum power point J_{MPP} is given by

$$J_{MPP} = q(n_{abs} - n_{emit}(V_{MPP})) \tag{2}$$

where n_{abs} and n_{emit} are the photon absorption and emission rates given by the generalized Planck's equation [17]:

$$n_{abs}(E_g, T_s, \Omega_{abs}) = \frac{2\,\Omega_{abs}}{c^2\,h^3}\int_{E_g}^{\infty}\frac{E^2}{e^{\frac{E}{kT_s}}-1}\,dE \tag{3}$$

$$n_{emit}(E_g, V, T_c, \Omega_{emit}) = \frac{2\,\Omega_{emit}}{c^2\,h^3}\int_{E_g}^{\infty}\frac{E^2}{e^{\frac{E-qV}{kT_c}}-1}\,dE \tag{4}$$

where c and h are the speed of light in vacuum and Planck's constant, respectively. Perfect charge transport is assumed so the free enthalpy of the photogenerated electron–hole pairs – namely the chemical potential μ of the electron–hole system [18] – is equal to qV where V is the voltage across the cell terminals.

Table 1 shows the analytical expressions, similar to that in Ref. [13], of the energy losses related to the effects mentioned previously. These loss mechanisms are depicted in Fig. 1 which shows how the energy of the incident photons is converted within an ideal p–n junction solar cell. The first two losses are related to the spectral mismatch between the broadband incident radiation and the spectrally limited cell absorption: (1) some photons have more energy than E_g and this "extra" energy is quickly lost by the excited electrons to the lattice atoms in a process called thermalization and (2) some photons have less energy than E_g and are not able to excite any electron ("below E_g" loss). The last three losses impact the balance between absorption and emission rates; we will call them in the following "balance losses". The emission term limits the cell current and corresponds to the energy of the emitted photons at MPP. The Carnot and angle mismatch terms represent the energy lost because of the voltage drop at the junction necessary to efficiently collect the excited charges (illustrated in Fig. 1). Physically, all the charges that go through the junction are accelerated by the electric field and gain some kinetic energy at the expense of a fraction of their potential energy. Then, they quickly relax to the potential energy of the conduction band of the other side through collisions with the lattice atoms. This heat generation process can be identified as Peltier heating [19]. This phenomenon, rarely reported in the PV literature, means that a large part of the heat generation in PV cells is located at the junction. In most PV cells, the p–n junction is located near the front of the cell. High energy photons which contribute to most of the heat generation by thermalization also happen to be absorbed near the front of the cell.

Fig. 1 illustrates that some losses limit the voltage of the cell while others limit its current. This is why angle mismatch, Carnot and emission losses are distinguished even though they stem from the same physical mechanism: radiative recombination. In fact, any recombination process has this dual impact: (1) a current loss because some excited charges don't make it to the external circuit

Table 1
Fundamental losses in a single junction solar cell.

Spectral mismatch	Thermalization	$\frac{2\,\Omega_{abs}}{c^2\,h^3}\int_{Eg}^{\infty}\frac{E^2}{e^{\frac{E}{kTs}}-1}(E-E_g)dE$	(5)
	Below E_g	$\frac{2\,\Omega_{abs}}{c^2\,h^3}\int_{0}^{Eg}\frac{E^2}{e^{\frac{E}{kTs}}-1}\,E\,dE$	(6)
Absorption–emission balance	Emission	$E_g\frac{2\,\Omega_{emit}}{c^2\,h^3}\int_{Eg}^{\infty}\frac{E^2}{e^{\frac{E-qV\,MPP}{kTc}}-1}dE$	(7)
	Angle mismatch	$kT_c\ \ln\left(\frac{\Omega_{emit}}{\Omega_{abs}}\right)J_{MPP}$	(8)
	Carnot	$E_g\left(\frac{T_c}{T_s}\right)J_{MPP}$	(9)