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Spectral sensitivity of hot carrier solar cells

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ABSTRACT

In this paper we present detailed balance simulations which determine the material parameters required to produce hot carrier solar cell (HCSC) annual energy yields comparable with that of multi-junction (MJ) systems. We demonstrate that HCSCs are less spectrally sensitive than equivalent MJ devices providing significant motivation for pursuing their development. Spectral variation in a given location over the course of the day and throughout the year means that the HCSC provides more consistent power production. The HCSC can also be developed for a standard reference spectrum and still perform optimally in a variety of locations with different atmospheric conditions, unlike the location sensitive performance of MJ devices. We show that an ideal hot carrier solar cell with bandgap 0.69 eV under 2000× concentration would require a thermalization coefficient $<0.1\ W\,K^{-1}\,cm^{-2}$ to produce more power over the course of the year than an InGaP/GaAs/Ge triple junction device located at Solar Village in Saudi Arabia. The lowest experimentally demonstrated thermalization coefficient is $9.5\ W\,K^{-1}\,cm^{-2}$ indicating that further materials development is required to achieve this target.

1. Introduction

A hot carrier solar cell (HCSC) is a device in which the dissipation of heat energy from the photo-excited carrier population to the surrounding lattice is restricted, allowing for substantial efficiency enhancement over traditional single junction devices. In an ideal single junction device 55% of incident solar radiation is lost due to the mismatch between the broad solar spectrum and the step-like semiconductor absorption profile [1]. The HCSC targets these intrinsic losses allowing for substantial solar energy conversion efficiency enhancement [2–6]. These devices require a low bandgap (E_g) absorber in which carrier–phonon interaction is sufficiently restricted such that the steady-state carrier population remains hot relative to the lattice [7–9]. Hot carriers are then extracted from the absorber via mono-energetic contacts [10–12]. The spectral selectivity of the contacts forces carrier cooling to occur isoentropically and chemical potential is thus created with efficiency which approaches that of a Carnot engine.

Restricted carrier–phonon interaction can be characterized by a low material thermalization coefficient (Q) [13]. Creating materials which exhibit this key characteristic is one of the main challenges associated with HCSC development. In recent years some progress has been made towards this objective, with $Q = 9.5\ W\,K^{-1}\,cm^{-2}$ demonstrated for single InGaAs quantum well samples [14].

Multi-junction solar cells target the same intrinsic losses as HCSCs by selectively absorbing regions of the spectrum in materials with comparable bandgaps. Multi-junction solar cells currently dominate the field of high efficiency photovoltaics research and consequently this technology is much more developed than other high efficiency alternatives, with research device peak efficiencies well in excess of 40% reported [15]. It is well established in the literature that the standard test conditions AM1.5D [16] used to rate devices cannot be used to determine annual energy yields under realistic operating conditions because multi-junction devices are particularly sensitive to spectral variation [17–21]. The solar spectrum changes with variation in aerosol optical depth and precipitable water in the atmosphere [22–24]. These features are highly location dependent as well as varying seasonally and diurnally.

In this paper we use a detailed balance, energy and particle conservation model to evaluate the Q and E_g requirements of a HCSC absorber in order to produce efficiencies and energy yields which are comparable with multi-junction devices. We calculate a range of different spectra using the SMARTS atmospheric model [25–27], to identify trends in optimal material parameters as a function of air mass and solar concentration. The SMARTS model has also been used to calculate spectra for hourly intervals over the course of a year for three different locations on Earth: Solar Village Saudi Arabia; Boulder, CO, USA and La Parguera, Puerto Rico.

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Multi-junction energy yields for these locations have previously been considered [28–30]. Using these spectra it is found that the HCSC is less spectrally sensitive than devices with three or two junctions and also traditional (thermal equilibrium) single junction devices.

Spectral sensitivity is a key consideration when estimating the cost effectiveness of a particular installation. A device which is less spectrally sensitive thus benefits from a greater annual energy yield relative to the device peak efficiency. The power output in these devices is also less variable. In addition, reduced spectral sensitivity allows devices which are optimized for one location to perform efficiently in other global locations with different spectral conditions without the need for time consuming and expensive device development and optimization for every proposed installation. Another consideration for prospective PV investors is the reliability of estimated power outputs, given the uncertainty of future atmospheric conditions. Devices which are less spectrally sensitive are better able to meet energy yield targets when actual spectral irradiance deviates from predictions.

2. Modeling approach

2.1. HCSC simulations

The HCSC solar cell structure is illustrated in Fig. 1a. Incident photons generate a photo-excited carrier population in the absorber region of the device. Limited carrier–phonon interaction occurs in the absorber region and the carrier population thermalizes to a temperature (T_{eh}) greater than that of the surrounding lattice (T_L) but less than the solar temperature (T_S), entropically generating some chemical potential (μ_{eh}). The degree of carrier cooling is determined by the thermalization coefficient of the absorber material. Carriers are extracted from the hot carrier population via energy selective contacts (ESCs), separated by energy ε_{eh}. Here the carriers form a thermal equilibrium ($T_{eh} = T_L$) with chemical potential μ. The restricted range of energy states in the ESC forces this cooling to occur isoentropically, without dissipating heat to the surrounding lattice.

The solar energy conversion efficiency of the hot carrier solar cell was calculated using an energy and particle conservation model (Eqs. (1) and (2)). This model was first developed by Ross and Nozik [2] for an ideal non-thermalizing ($Q=0$) hot carrier absorber and later adapted by Le Bris et al. to include the effects of a non-ideal absorber with some thermalization ($Q > 0$) [13].

$$J = J_{abs} - J_{emit} = e \cdot \int_{E_g}^{\infty} \dot{n}_{spectra}\, dE - e \cdot \int_{E_g}^{\infty} \dot{n}(E, T_{eh}, \mu_{eh})\, dE \quad (1)$$

$$P = P_{abs} - P_{emit} - P_{th} = \int_{E_g}^{\infty} E \cdot \dot{n}_{spectra}\, dE - \int_{E_g}^{\infty} E \cdot \dot{n}(E, T_{eh}, \mu_{eh})\, dE - P_{th} \quad (2)$$

The rate of carrier extraction through the contacts J is the difference between the rate of photon absorption (J_{abs}) and emission (J_{emit}). The rate of energy extraction P is given by the rate of absorbed power P_{abs} less the rate of emitted and thermalized power, P_{emit} and P_{th} respectively. Particle and energy absorption rates are calculated by integrating the rate of incident photons with energy above the bandgap of the material per unit area per energy interval for a given spectra ($\dot{n}_{spectra}$). Particle and energy emission from the solar cell is calculated by integrating the generalized Planck equation (Eq. (3)), which describes the rate of photon emission per unit area per energy interval ($\dot{n}(E, T_{eh}, \mu_{eh})$) as a function of carrier temperature T_{eh} and carrier chemical potential μ_{eh}. The speed of light, Planck's constant and Boltzmann's constant are denoted by characters c, h and k respectively

$$\dot{n}(E, T_{eh}, \mu_{eh}) = \frac{2\pi}{c^2 h^3} \frac{E^2}{\exp\left(\frac{E - \mu_{eh}}{kT_{eh}}\right) - 1} \quad (3)$$

Heat dissipation from the carrier population occurs via phonon interaction, the rate of which is given by Eq. (4). The phonon energy E_{vib} is lost with every scattering event. In this study we have assumed that $E_{vib} = 36$ meV, corresponding to the GaAs longitudinal optical phonon energy

$$P_{th} = Q \cdot \Delta T \exp\left(-\frac{E_{vib}}{kT_{eh}}\right) \quad (4)$$

The chemical potential of the carrier distribution in the ESCs (μ_{eh}) and the corresponding voltage drop across the device are give by Eq. (5), derived from the Helmholtz free energy equation [3]. The HCSC efficiency (η) is the product of J and V as a fraction of total incident power (Eq. (6)). The energy separation between ESCs is denoted by ε_{eh}. In the limit $Q \to 0$ the optimal value of ε_{eh} is equal to the average energy of the incident spectrum

$$\frac{V}{e} = \mu = \mu_{eh}\left(\frac{T_L}{T_{eh}}\right) + \varepsilon_{eh}\left(1 - \frac{T_L}{T_{eh}}\right) \quad (5)$$

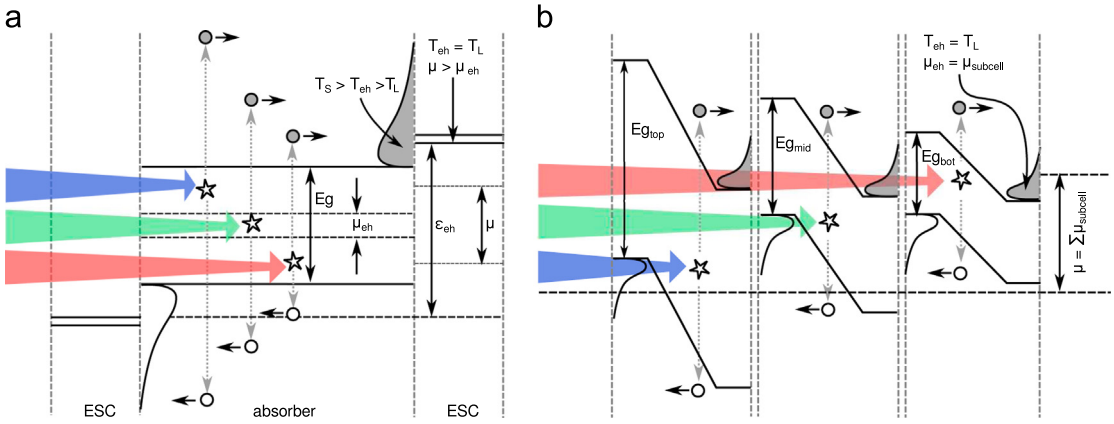

Fig. 1. (a) Band diagram of a HCSC. Photons with energy $> Eg$ are generated in a single absorbing layer. Photo-excited carriers form a hot population ($T_{eh} > T_L$) with chemical potential μ_{eh}. Carriers are extracted through ESCs separated by energy ε_{eh}. Chemical potential μ is isoentropically generated in the contact as the carriers thermally equilibrate with the lattice. (b) Band diagram of a MJ solar cell. High energy photons are absorbed in the large bandgap top layer and lower energy photons are absorbed in the subsequent, smaller bandgap layers. Carriers photo-excited in each sub-cell generate chemical potential $\mu_{subcell}$ as they thermal equilibrate with the lattice. Sub-cells are connected in series via tunnel junctions and the chemical potential across the device is equal to the sum of $\mu_{subcell}$ generated in each layer.