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Modeling of hot carrier solar cell with semi-infinite energy filtering

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ABSTRACT

Electrical parameters of a symmetrical hot carrier solar cell double heterostructure with metallic absorber layer and high-pass energy filters are calculated within thermionic emission theory. An efficiency limit of 73% is predicted for infinite characteristic cooling time and full solar concentration. Carrier cooling is treated within linear thermal conductivity model. Heat loss through carrier cooling in the absorber layer depends not only on the characteristic cooling time, but also on the specific volumetric heat capacity of the carrier gas and on the thickness of the absorber layer. Optimal absorption of light together with small thermal loss to the lattice require high carrier mobility in the absorber layer.

1. Introduction

There are several approaches to increase the efficiency of solar cells: the most successful so far is multijunction solar cell. Unfortunately, multijunction solar cells require infinite number of layers made of infinite number of different semiconductors, in order to reach their efficiency limit. Another concept, hot carrier solar cell, should be able to reach about the same efficiency limit with only three layers: absorber and two energy selective contacts (Würfel, 1997). The sun radiation heats the electrons and holes (e-gas) in the absorber layer, which are called hot carriers. Only a small fraction of the carriers having high kinetic energy is filtered out towards the cell terminals. Traditional implementation of a hot carrier solar cell, as proposed by Würfel (1997), requires infinitely fine energy filtering contacts. An alternative concept suggests energy barriers as energy selective contacts. Energy barriers are high pass energy filters, instead of narrowband filters (semi-infinite filtering (Konovalov et al., 2015, Le Bris and Guillemoles, 2010). This high pass filter is not only simpler to implement, the carriers are also extracted faster so that their cooldown time in the absorber shortened. This approach results in a hot carrier solar cell being structurally a double heterostructure, where the middle layer acts as absorber. There are several practical questions to be answered with respect to this new concept: (1) What is the price in terms of limiting efficiency for utilizing simple high-pass energy filters instead of more complex infinitely narrow bandpass filters; does such a hot carrier solar cell offer any benefit in efficiency, as compared to a single gap structure with the gap as high as the sum of the barrier heights; (2) How can the optimal barrier height for energy filtering be calculated; (3) What are the requirements for the characteristic e-gas cooling time in the absorber; (4) Are there any possibilities to make a successful hot carrier solar cell with a conventional for bulk materials cooling time of 10 ps; (5) What would be the electrical characteristics of a good hot carrier solar cell. In this paper, we extend thermionic emission theory so that it can answer these questions and present a study for a specific model case of a hot carrier solar cell. As we show in the following, the hot carrier double heterostructure solar cell has about twice as large limiting efficiency with respect to the single gap limit (Shockley-Queisser limit).

2. Structure of the model solar cell

In order to limit the number of free parameters, we limit consideration here to a symmetrical with respect to electrons and holes structure utilizing a thin metallic film as absorber. The band diagram of the model device is shown in Fig. 1. Thin metallic films were indeed utilized in hot carrier solar cells in the past (Dimmock et al., 2015). Consideration of a narrow gap semiconductor instead of the metal for the absorber layer is possible, but brings additional free parameters and complications. Infinitely fast inelastic electron-electron and electron-hole scattering, impact ionization and Auger recombination are assumed throughout the paper, so that the electron energy distribution corresponds to equilibrium. As it is shown later, this assumption is consistent with parameters derived from the model. Furthermore, free electron approximation is used, being adequate in many specific cases of semiconductors with quasi-parabolic bands and of some metals close to the Fermi energy (see discussion after Eq. (6) in (Leenheer et al., 2014)).

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