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HELIOTECHNICAL MATERIALS SCIENCE

Approximate Effectiveness Evaluation of Si Solar Cell Tandem with Photothermopile

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Abstract—The idea that it is feasible to develop commercial solar cells tandem with a photothermopile based on a narrow-gap semiconductor is proposed. The operation and efficiency of a Si solar cell in tandem with a photothermopile based on a semiconductor with a band gap of ~0.3 eV is discussed. It is shown that, at an operating temperature of 60–75°C, the tandem efficiency can be increased by more than 50% as compared with the Si solar cell efficiency.

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INTRODUCTION

The marginal efficiency of solar cells (SCs) is restricted by the power loss of the incident solar radiation as a result of thermalization of high-energy photoelectrons generated by photons with energies greater than that of the band gap (E_g) of the semiconductor; the lack of absorption of photons with energies less than E_g; and the fact that the product of open-circuit voltage (V_{oc}) and the elementary charge, qV_{oc}, is significantly less than E_g of the SC semiconductor. In case of Si of solar cells, these losses were, respectively, 33, 23, and 15%. In numerous publications—in particular [1–3]—calculations have been made of the impurity photovoltaic (IPV) effect that occurs due to absorption of photons with energies less than E_g under doping of the semiconductor with deep impurities. However, to date, the IPV effect has not been detected. This apparently is due to the fact that, in the best case, the impurity concentration can be two orders of magnitude smaller than the concentration of atoms of the main semiconductor material, as well as due to the impossibility of achieving the condition necessary for implementation of the IPV effect consisting in the fact that the impurity level has to be half-occupied by electrons. The effectiveness of the commercial Si solar cells is in the range of 15–20%. This means that about 80% of the solar-radiation power is converted to heat, raising the temperature and reducing the efficiency of solar cells. In [4, 5], the idea was raised of photothermopiles (PTPs) and an attempt to justify the possibility of developing PTPs with high efficiency. Despite this, it is of interest to develop a tandem of widely produced Si, $CuInSe_2$, and CdTe solar cells with PTPs based on semiconductors with $E_g = 0.30–0.35$ eV. The selection of Si SCs for the tandem was determined by the fact that more than 80% of commercial solar cells are manufactured on the basis of Si.

STRUCTURE AND OPERATION OF A TANDEM

The main additional technical challenges of manufacturing the Si SC tandem with PTP consists in depositing a transparent metal layer on a back surface of the Si *n*–*p* structure, which was noted in [6], and obtaining on it PTP out of the narrow-gap semiconductor. Apparently, it is not necessary to apply a composite transparent metal layer between the *n*–*p* structures of the tandem, as it was suggested in [6], and it may be sufficient just to create an ohmic contact between the *n*–*p* junctions of the tandem in the form of a metal grid (Fig. 1, *5*), similar to the ohmic contact on the front surface of Si SCs.

Let us discuss the action of the tandem, the structure of which is shown in Fig. 1. To conserve the heat energy that arose in solar Si and a PTP as a result of thermalization of photoelectrons, it is necessary to apply a transparent plate on the front surface of the tandem (Fig. 1, *6*) and thermal insulation on the back surface (Fig. 1, *7*).

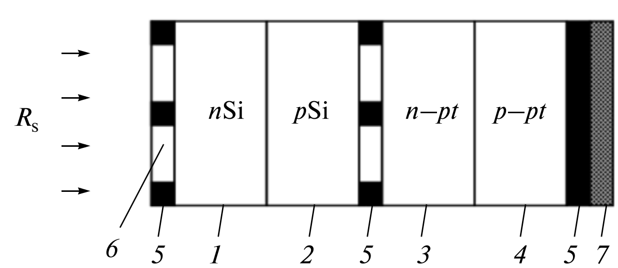

Fig. 1. Tandem scheme: (*1*) *n*Si, (2) *p*Si—*n*–*p* structure of Si solar cell, (*3*) *n*–*pt*, (*4*) *p*–*pt*—*n*–*p* structure of photothermopile, (*5*) ohmic contacts, (*6*) transparent plate, (*7*) thermally insulating layer; R_s, solar radiation.

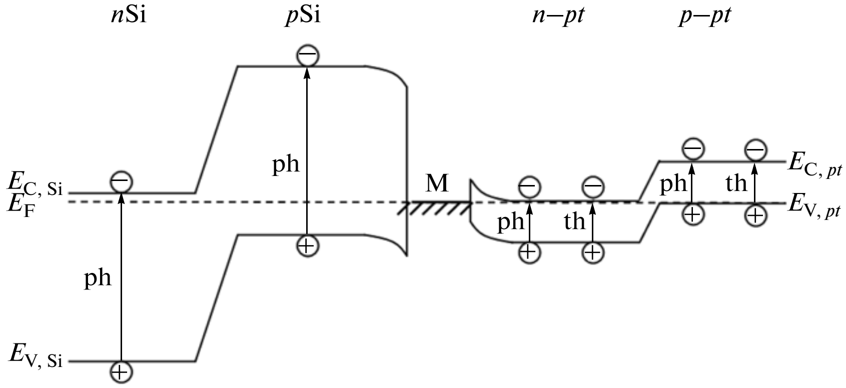

Fig. 2. Band energy diagram of a tandem consisting of a Si solar cell and photothermopile, *n*Si–*p*Si–metal–(*n–pt*)–(*p–pt*). *n–pt*, *p–pt–n*, and *p* are layers of the photothermopile, respectively; ph is photogeneration; th is thermogeneration of electron–hole pairs; and M is the metal contact.

The tandem action is explained by the band diagrams of consecutively connected Si SCs and PTPs (Fig. 2). The photons with energy greater than that of the band gap of silicon ($E_{g, Si}$) generate electron–hole (e–h) pairs in *n*Si-, *p*Si-layers of the structure of the photodetector, and with energy smaller than $E_{g, Si}$—in the *n*-and *p*-layers of the PTP structure, which we denote by *n–pt* and *p–pt*, respectively. With the power of solar radiation ~0.1 W/cm^2 (the Sun only), the tandem can be heated to 60–75°C, since ~50% of solar radiation is converted into heat in Si SCs and ~15% in PTPs. For PTPs, the semiconductor material should be selected so that at a temperature of 60–75°C, the concentration of its intrinsic carriers was greater than 1×10^{15} cm^{-3} and exceeded by more than 4 times the concentration of e–h pairs equal to ~3×10^{15} cm^{-3}, photogenerated in Si SCs. It is desirable that the PTP material was direct-gap and the thickness of its *n–p* structure was not more than 10 μm. It is obvious that the tandem temperature will be uneven, because the front layer of Si SCs is ~10 μm thick and PTPs have the maximum temperature since a thermalization of photoelectrons occurs in them. Therefore, there is heat removal in the front and rear areas of the tandem, and the e–h pairs thermogenerated in a PTP are separated by its *n–p* junction, as are those photogenerated in Si SCs, and create the appropriate voltage, the sum of which forms an open circuit voltage of the tandem. The concentration of the photogenerated carriers in the tandem components does not depend on temperature, and the thermogenerated e–h pairs in PTP can significantly increase the short circuit current of PTP ($I_{sc, pt}$).

APPROXIMATE EFFECTIVENESS EVALUATION OF THE TANDEM

To assess the tandem efficiency, as the source data we will consider a tandem consisting of Si SCs with efficiency of 15% and with open circuit voltage $V_{oc, Si}$ = 0.6 V, short-circuit current $I_{sc, Si}$ = 30 mA/cm^2, fill factor FF = 80% [7], and PTP based on a semiconductor with $E_g \approx 0.30$ eV. Let us note that the concentrations of e–h pairs photogenerated in Si SCs and PTP are similar [8]. Therefore, short-circuit currents caused by photogeneration of e–h pairs in Si SCs and PTP are roughly equal—$I_{sc, Si} \approx I_{sc, pt}$. Let at the operating temperature of 70°C the excess in $I_{sc\,pt}$, due to thermogeneration of the e–h pairs, be five times more than that in $I_{sc, Si}$. To evaluate the effectiveness of the tandem, we will use the resistance of the tandem elements. It can be assumed that the resistance of Si SCs, $R_{Si} = V_{oc, Si}/I_{sc, Si}$. The resistance of PTP, $R_{pt} = V_{oc, pt}/(6I_{sc, Si})$. The resistance of the tandem consists of consecutively connected resistors Si SCs and PTPs; thus, the short-circuit current of the tandem ($I_{sc, tan}$) will be defined as $I_{sc, tan} = I_{sc, Si}(1 + V_{oc, pt}/V_{oc, Si})$. Choosing a doping level of the *n* and *p* layers of PTP, $V_{oc, pt} \approx 0.2$ V can be achieved. Thus, the efficiency of the tandem is proportional to the product $(V_{oc, Si} + V_{oc, pt})I_{sc, Si}(1 + V_{oc, pt}/V_{oc, Si})$. At room temperature, when there is no thermocurrent in a PTP, the tandem efficiency increases up to ~30% due to $V_{oc, pt}$ = 0.2 V. At an operating temperature, the efficiency of Si SCs will decrease from 15 to 12%, as a result of reduction in $V_{oc, Si}$ from 0.6 to 0.5 V. Therefore, the tandem efficiency is determined by multiplying $V_{oc, tan}I_{sc, tan}FF_{tan}$ = (0.5 V + 0.2 V) × 1.4 × 30 mA/cm^2 × 0.8 = 23.5 with tandem fill factor FF_{tan} = 0.8 twice as much as the efficiency of Si SCs, which is 12%.

In the case of separate use, the power of Si SCs and PTP consists of the sum of their efficiencies, namely, the efficiency of Si SCs, which is 12%, and the efficiency of PTP, which is 0.2B × $6I_{sc, Si}FF$; consequently, the tandem efficiency reaches 39%.

Let us also determine the efficiency of the tandem consisting of Si SCs with an efficiency of 20% and PTP.

Thus, one can hope that development and large-scale production of tandem solar cells using Si SCs and PTP can reduce the cost of generated electricity. The above-discussed approach can be used to develop $CuInSe_2$ with PTP and CdTe SCs with PTP tandems.

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