Analysis of efficiency of solar energy conversion by tandem Cd$_x$Zn$_{1-x}$Te/Si solar cell

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Abstract. In this work efficiency of solar energy conversion by solar cell based on tandem structure CdZnTe/Si is analyzed. It is shown that CdTe-CdZnTe-ZnTe material system is promising for creation of high-performance cascade solar cells.

Search of material systems effective for creation of high-performance monolithic multi-junction solar cells (SCs) is an urgent task of today’s research. Such material systems must allow designers to intentionally select the band gap energy and prepare on silicon substrate specified semiconductor structures of required quality. The systems of A2B6 semiconductor solid solutions, in particular CdTe-CdZnTe-ZnTe material system, as well as A3B5 compounds are very promising materials for creation of high-performance solar cells [1]. For example, CdTe has a band gap of 1.5 eV that is optimum for creation of solar cells with high efficiency. This material system allows designers to change material’s band gap from 1.5 to 2.28 eV. Besides that, there are some advantages of using such structures on Si substrates for creation of high-performance solar cells.

Only high-performance tandem solar cells parameters may successfully compete with those of cascade solar cells based on A3B5 materials. For creation of such high efficiency solar cells CdTe-CdZnTe-ZnTe heteroepitaxial structures of high quality are necessary. The method of molecular beam epitaxy (MBE) allows researchers to obtain heterostructures of such quality.

The aim of this work is to perform analysis of limiting efficiency of tandem solar cells based on Ga$_x$In$_{1-x}$P/Ge and Cd$_x$Zn$_{1-x}$Te/Si for AM0 solar spectrum and to carry out numerical modelling of such solar cells operating characteristics for AM0 and AM1.5 solar spectra. For achieving of optimum efficiency it is necessary to choose band gap energy of semiconductor solid solution (Cd$_x$Zn$_{1-x}$Te) from the condition that photocurrents in the maximum power points of the first and the second (Si, Ge) junctions are equal. Molar percentage $x$, that determines materials band gap energy, was being varied during calculations. Standard expressions obtained in [2] were used.

Maximum efficiency of the solar cell is determined as

$$\eta(E_s) = \frac{V_m(E_s)J_m(E_s)}{P_0},$$

where $V_m$, $J_m$ are the operating voltage and current in the maximum power point, $P_0$ is the incident power of solar radiation. Maximum power point $(V_m, J_m)$ is found from current-voltage characteristic.

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of solar cell by the condition \( d(JV)/dV = 0 \). Maximum power point is determined from the solution of the system of equations for band gap energy \( E_g \) of photoabsorption area material:

\[
e V_m(E_g) = e V_{oc}(E_g) - kT \ln \left( 1 - \frac{e V_m(E_g)}{kT} \right),
\]

\[
J_m(E_g) = \frac{e n_{ph}(E_g)}{1 + kT/e V_m(E_g)},
\]

\[
e V_{oc}(E_g) = E_g - kT \ln \left( \frac{A(E_g)}{e n_{ph}(E_g)} \right),
\]

\[
n_{ph}(E_g) = \int_{E_g}^{\infty} \frac{dn_{ph}}{d\hbar\omega} d\hbar\omega,
\]

where \( V_{oc} \) is the open circuit voltage, \( n_{ph} \) is the number of photons absorbed in solar cell, and \( dn_{ph}/d\hbar\omega \) is the spectral density of number of photons absorbed in solar cell. Constant \( A \) depends on bad gap energy and is defined as \( A = 5639 E_g^2 \text{ A/cm}^2 \).

Results of calculations have shown that for tandem solar cell containing two CdZnTe/Si \( p-n \) junctions optimum value of molar percentage \( x \) for Cd\(_x\)Zn\(_{1-x}\)Te is equal to 0.68. At this \( x \) value band gap energy is \( E_g(CdZnTe) = 1.75 \text{ eV} \), and limiting efficiency of solar energy conversion is \( \eta_{lim} = 38.9 \% \). The operating voltage for these conditions is 2.03 V and operating current is 25 mA/cm\(^2\).

Comparison of calculated solar cell characteristics with characteristics of tandem GaInP/Ge-based solar cell was conducted. For estimation of GaInP/Ge solar cell characteristics similar procedure was used. Calculations have shown that for GaInP/Ge solar cell \( \eta_{lim} \) is 2.4 \% less and is equal to 36.5 \% for GaInP band gap energy is \( E_g(GaInP) = 1.41 \text{ eV} \). Operating voltage and current are equal to 1.3 V and 36 mA/cm\(^2\), respectively. Additionally, limiting efficiency of solar energy conversion for CdZnTe/Si tandem solar cell is 5 \% higher than for GaNPAs/Si photoconverter [3].

Conducted calculations of limiting efficiency of solar energy conversion \( \eta_{lim} \) have shown that CdZnTe/Si structures a very promising for creation of tandem solar cells. The same result was obtained in the work [1] where comparison of limiting efficiencies of solar energy conversion \( \eta_{lim} \) for CdZnTe/Si and GaInP/InGaAs/Ge structures for solar spectrum AM1.5 was carried out. The calculations of the mentioned authors have shown that limiting efficiency of CdZnTe/Si solar cell is 2.1 \% higher.

Numerical modelling of CdZnTe/Si tandem solar cell operating characteristics was conducted with the assumption that bottom junction was created on the standard 300 \( \mu \)m thick silicon plate. The aim of numerical modelling was to determine optimum band gap of photoabsorption area of top CdZnTe cell. Numerical modelling was conducted for AM0 and AM1.5 solar spectra with the help of SCAPS program complex [4]. The structure of the solar cell under consideration is shown in the figure 1. The top junction of the tandem solar cell consists of dopped heterostructure CdZnTe/n-ZnTe. In this structure ZnTe plays a role of optical window [5]. The thickness of photoabsorption area of CdZnTe equals to 4 \( \mu \)m. The thickness of ZnTe layer is 0.025 \( \mu \)m. Due to complexity of numerical estimation of electrical current through the tunnel junction p'-CdZnTe/n'-Si calculations were conducted separately for the top and the bottom junctions of CdZnTe/Si tandem solar cell. During calculations of the bottom Si \( p-n \) junction parameters it was considered that photons with energy \( E > E^*_{CdZnTe} \), where \( E^*_{CdZnTe} \) is the band gap of photoabsorption area material in the top CdZnTe/ZnTe junction, are absorbed in the top junction completely.
The structure of tandem ZnTe/CdZnTe/Si solar cell.

The results of calculations of maximum power point operating current dependence on the band gap $E_g$ of the photoabsorption CdZnTe layer in the top $p$-$n$ junction for AM0 and AM1.5 solar spectra are shown in the figure 2. For AM0 solar spectrum the photocurrent value for the top junction decreases from 32 to 12 mA/cm$^2$ with the band gap of photoabsorption area increasing from 1.5 to 2.28 eV. Meanwhile, at the same conditions value of photocurrent in the bottom Si solar cell increases from 9 to 27 mA/cm$^2$. Intersection of these two curves gives us optimum value of the CdZnTe band gap.

For the AM0 solar spectrum optimum value of the CdZnTe band gap is equal to 1.88 eV and photocurrent at this conditions is equal to 21 mA/cm$^2$. This band gap corresponds to the molar percentage $x = 0.51$ in the Cd$_{x}$Zn$_{1-x}$Te.

The dependence of operating voltage in the top and the bottom $p$-$n$ junctions on the band gap is shown in figure 3.

It may be seen that for the band gap of 1.88 eV operating voltage is equal to 1.1 V for the top Cd$_{0.51}$Zn$_{0.49}$Te junction and 0.48 V for the bottom Si junction. Maximum output power of tandem solar cell equals to 33.1 mW/cm$^2$ and corresponds to the efficiency of 25.4 % for solar energy conversion. The obtained value is 13.5 % less than limiting efficiency.

For the AM1.5 solar spectrum optimum value of the CdZnTe band gap is equal to 1.85 eV and photocurrent at these conditions is equal to 17.5 mA/cm$^2$. This band gap corresponds to the molar percentage $x = 0.55$ in the Cd$_{x}$Zn$_{1-x}$Te. Operating voltage for the band gap of 1.85 eV is equal to 1.08 V for the top Cd$_{0.55}$Zn$_{0.45}$Te junction and 0.49 V for the bottom Si junction. In this case maximum output power of tandem solar cell equals to 27.4 mW/cm$^2$ and corresponds to the efficiency of 27.4 % for solar energy conversion.
Thus, the calculations for tandem solar cells based on A4B4 and A2B6 compounds have shown that limiting efficiency of solar energy conversion for the CdZnTe/Si solar cell is 2% higher than for GaInP/Ge. It makes CdTe-CdZnTe-ZnTe material system promising for the creation of high performance cascade solar cells.

Conducted numerical modelling of operating characteristics of CdZnTe/Si tandem solar cell created on the 300 μm thick silicon substrate have shown that maximum efficiency of solar energy conversion by this tandem solar cell is equal to 25.4% and 27.4% for AM0 and AM1.5 solar spectra, respectively. Given conversion efficiencies correspond to the optimum band gap of the photoabsorption area in the top solar cell. These band gaps are 1.88 eV for AM0 solar spectrum and 1.85 eV for AM1.5 solar spectrum. Corresponding photoabsorption materials of the top junction are Cd$_{0.51}$Zn$_{0.49}$Te and Cd$_{0.55}$Zn$_{0.45}$Te, respectively.

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