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The analysis of current flow mechanism in CdS/CdTe heterojunction

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Abstract

An analysis of current–voltage dependencies of CdS/CdTe heterojunction in the 78–370 K temperature range has been carried out. According to this analysis the current flow mechanism is determined by the tunneling processes through dislocations, which penetrate the heterojunction space charge region. The concentration of dislocations has been estimated as $2 \cdot 10^5$ cm^{-2}. The number of steps necessary for tunneling varies: $2.5 \cdot 10^2$–$1.7 \cdot 10^3$. The characteristic energy has a weak temperature dependence (−0.2 meV/K) and its value vary 120–200 meV. The increase of the annealing duration results in the decrease of the characteristic energy.

The multistep tunneling processes through local centres, determined by impurity centres, interface states and defects in the space charge region, predominate at reverse biases. The number of tunneling steps is 1–$4 \cdot 10^2$. The concentration of local centres (traps) in the heterojunction have been estimated as $2.37 \cdot 10^5$–$1.63 \cdot 10^6$ cm^{-3}.

The thermal annealing in the presence of $CdCl_2$ up to 60 min does not modify the current flow mechanism in CdS/CdTe heterojunctions.
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Keywords: CdS/CdTe; Heterojunction; Current flow mechanism

1. Introduction

For a photovoltaic energy conversion the maximum efficiency can be reached if a binary semiconductor with the band gap close to 1.5 eV is chosen [1]. The theoretical maximum efficiency for solar cells with a thin film CdTe absorber is 26.6% [1]. Recently, one of the most perspective heterojunction used for photovoltaic solar energy conversion is CdS/CdTe. The maximum efficiency for CdS/CdTe-based solar cells is 16.5% [2].

High photovoltaic parameters can be achieved if CdS/CdTe heterojunctions are annealed in the presence of $CdCl_2$ for 10–40 min at temperatures close to 400 °C [3]. As a result of deposition and annealing procedures, a layer consisting CdS_xTe_{1-x} solid solutions is formed at the interface of CdS/CdTe heterojunction. This fact as has been proven by different methods [4–7] such as photoluminescence, cathodoluminescence, modulation spectroscopy and other. This layer is believed to be the one influencing the electrical, photovoltaic and optical properties of the heterojunction.

The current flow mechanism in CdS/CdTe heterojunction is a complex one. Recently, several models, which explain more or less the experimental current–voltage dependencies, exist. CdS and CdTe lattice mismatch $\frac{\Delta a}{a}$ is >10% is causing the appearance of growth defects at the CdS/CdTe interface with a concentration of $\sim 10^{14}$ cm^{-3}. The interface states related to the growth defects influenced the characterstics of the heterojunctions.

The authors [8] are considering a model consisting of an anizotypic heterojunction with a high concentration of the interface states. The Schottky-like states are present on the both sides of the heterojunction. For a high concentration of the interface states with a high capture cross-section for both types of charge carriers, the current flow will be determined by the recombination through the interface states. If the captured cross-section has a low value, the redistribution of the potential between the two semiconductors plays an important role.

One of the most often used mechanism for explaining the current–voltage characteristics [9,10] is the classic Shockley-Noyce-Sah model, considering the generation recombination mechanism in the space charge region. Unfortunately there are no current–voltage and saturation current vs temperature dependencies presented. It is known that the $\ln I \sim T^{-1}$ (I — the current) only for a narrow temperature interval (temperatures higher than

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300 K) and the diode quality factor has values as 2.5 up to 4. So, the classic current flow theory cannot be applied always.

One of the models, satisfactorily explaining the experimental J-U plots and accepted by several authors [11–13], is the one considering the tunneling in the space charge region. This model can be used for to explain both current–voltage dependencies at forward and reverse biases.

This paper is presenting the analysis of the temperature current–voltage dependencies with the consideration of tunneling of the charge carried through the space charge region of the heterojunction.

2. Experimental

Thin film CdS/CdTe heterojunctions were fabricated by successive deposition of CdS and CdTe by CSS (closed spaced sublimation) technique, onto SnO_2 covered glass plates (2×2 cm^2), with a transparency of ~80% in the visible spectral region and the resistivity ~10^{-3} Ω cm. The CdTe:Sb single crystals have been used as a source material for CdTe thin films deposition and vacuum annealed CdS powder has been used as CdS layers deposition. Our studies show, that the optimum temperatures for substrate and source are: 445 °C and 640 °C for CdS layers and 445 °C and 550 °C CdTe thin films respectively. The thickness of CdS and CdTe thin films was 0.3–1.6 μm and 2.3–6.6 μm respectively. As-deposited samples have low photovoltaic parameters: I_{sc}=0.17 mA (0.25 cm^2) and U_{oc}=0.45 V. For, to increase the cell's efficiency a chloride annealing step followed the deposition procedure. The investigations of the influence of annealing in the presence of $CdCl_2$ (at 390–420 °C for 15–60 min) influence on current flow mechanism in CdS/CdTe heterojunction, has been studied. The cleaning of the sample has been performed with a 350 ml 85% H_3PO_4+140 ml H_2O+4.4 ml 70% HNO_3 solution or with a Br-methanol etchant. Magnetron-deposited Ni has been used as back contact to CdTe. After CdS/CdTe heterojunction annealing the open circuit voltage is U_{oc}=0.70 V and the short circuit-current is I_{sc}=21.6 mA/cm^2, and the fill factor ff=0.43 at the illumination of 100 mW/cm^2 were recorded.

3. Results and discussions

3.1. Current flow mechanism at forward bias

For, to establish the current flow mechanism, the current–voltage (I–U) dependencies of CdS/CdTe heterojunctions have been studied in the 78–370 K temperature intervals. Their I–U plot has a diode behavior for the entire temperature interval analyzed. The built-in voltage (U_D) vs temperature dependence is determined by the band gap and Fermi level variation. This dependence is a linear one with a tangent of $-1.7\cdot 10^{-3}$ V/K. The $I(U)$ plot, is minorily influenced by the heterojunction annealing duration variations from 15 to 60 min. So, all the analysis presented further is done for a 60 min annealed samples, as an example. The $I(U)$ plot for different temperatures is presented in Fig. 1. There can be distinguished up to two linear regions, depending on the applied bias, pointing at an exponential current vs voltage dependence. In the first approximation the I–U plot can be described by:

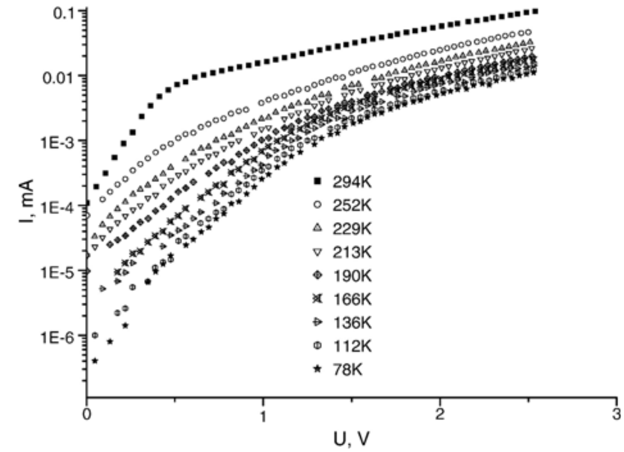

Fig. 1. The current-voltage dependencies for the samples annealed in $CdCl_2$ for 60 min ($S_{junction}$=0.25 cm^2).

$$I = I_s \exp(AU). \tag{1}$$

The values for A and satuation current I_s, for a given voltage interval ($0<U<0.45$ V) vary: at 78 K A=13.60 V^{-1}, I_s=4.86 · 10^{-11} and at 369 K A=6.67 V^{-1}, I_s=4.79 · 10^{-6} A ($S_{junction}$=0.25 cm^2).

The direct current vs temperature for different forward biases is given in Fig. 2. The presented data can be approximated with straight lines the slopes being equal to 0.034 K^{-1}, for 0.1–0.3 V biases. As it comes from the analysis of the experimental data for different biases and temperatures, the dependence on the direct current on applied voltage and on temperature can be described by the equation:

$$I_{direct} = I_0 \exp(BT)\exp(AU) \tag{2}$$

where I_0, A and B — are constants, which do not depend on temperature. The same equation [12,14,15] is characteristic for a current flow mechanism, which considers tunneling through the interface states from CdS/CdTe heterojunctions determined by the lattice mismatch. For a direct, band to band tunneling, a charge carrier concentration of 10^{18}–10^{19} cm^{-3} [15] is needed, but the concentration of charge carriers in CdTe has a quite low value ~10^{16} cm^{-3}. As it comes from the data presented above, the nature of the interface states and their high concentration still remain inexplicable. For, to proceed with the analysis of the experimental results, we have applied another model, presented in [16] with a further development in [17]. This model considers the tunneling process (nonhomogeneous tunneling) through the dislocation lines, which penetrate the space charge region. The I–U dependence can be described analytically by the following expression [17]:

$$I = I_s\left(\exp\left\{\frac{eU}{\varepsilon}\right\}-1\right) \tag{3}$$

where ε — is the characteristic energy.

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