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PHYSICS OF SEMICONDUCTOR DEVICES

Effect of a Rear Contact on the Electrical Properties of the CdS/CdTe-Based Thin-Film Solar Cells

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Abstract—The comparative study of dark current–voltage and capacitance–voltage characteristics of the CdS/CdTe/Cu/Au and CdS/CdTe/ITO thin-film solar cells is carried out. The physical properties of the p^+-CdTe/n^+-ITO rear contact are experimentally determined for the first time.

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1. INTRODUCTION

Cadmium telluride with *p*-type conductivity is the best material for the fabrication of base layers of highly efficient thin-film solar cells for ground-based application [1]. The *p*-CdTe band gap of 1.45 eV is in the best-adapted way to the conversion of the solar radiation in ground-based conditions. Therefore, solar cells with a CdTe base layer have the highest theoretical efficiency of 29% among the unijunction photoelectrical converters [1]. The highest experimental efficiency of 16.5% was reported for solar cells based on the CdS/CdTe heterostructures [1]. A crucial physical problem in the development of CdS/CdTe-based solar cells consists in the fabrication of the rear electrical contacts to the base layers. To form nonrectifying contact to *p*-CdTe, metal with a work function higher than 5.7 eV is required. Since such metal is nonexistent, the Schottky barrier is used as the rear contact. To reduce the contact resistance, the electrical conductivity of the CdTe surface was increased using chemical etching and impurity thermal diffusion from the buffer layer. Thus modified p^+-CdTe surface is coated with metals or degenerate p^+-semiconductors thereby forming potential barriers no higher than 0.5 eV. Conventionally, the following thin-film contacts are used: Cu/Au [2], Cu/Mo [3], Cu/graphite [4], and ZnTe:Cu/Au [5]. The main problem in the use of such layers in the design of the CdS/CdTe-based solar cell is that the impurity diffusion from the contact into the regions of the *p*–*n* junction during operation leads to the degradation of output characteristics [6].

Recently, the films of degenerate n^+-type semiconductor ITO (indium–tin oxide) were approved as the rear electrodes to the base p^+-CdTe layers [7]. The use of highly stable ITO layers provides a radical decrease in the degradation rate of the output characteristics of the CdS/CdTe-based solar cells. However, the efficiency of the obtained CdS/CdTe/ITO solar cells is still no higher than 8% [7]. To further increase the efficiency of the CdS/CdTe/ITO solar cells, it is urgent to study the effect of the rear contact p^+-CdTe/n^+-ITO on the charge transport in the device structure. For this purpose, we carried out comparative studies of the dark current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) characteristics for the CdS/CdTe/ITO-based solar cells and CdS/CdTe-based solar cells with the conventional Cu/Au rear electrode.

2. EXPERIMENTAL

The CdS and CdTe thin films were deposited on glass substrates with the SnO_x:F layer by the technology described previously [7]. Prior to the formation of rear electrodes, the surface of the CdTe base layer was etched in a bromine–methanol solution. Then the ITO layers were deposited on the etched surface by nonreactive high-frequency magnetron sputtering at 250°C. To form the rear electrode of the CdS/CdTe/Cu/Au solar cell, the Cu films 11 nm thick and Au films 50 nm thick were sequentially deposited on the surface of the etched base layer. Then the solar cells were annealed in the air at 250°C for 25 min.

The *I*–*V* characteristics were measured using an automated 4145A Semiconductor Analyzer (Hewlett Packard). To measure the *I*–*V* characteristics of solar cells at various temperatures, the sample was placed in a constant-temperature box. The temperature was measured accurately to ±1°C using a Peltier cell (PRG H100 control unit, Peltron GmbH). To exclude the effect of water vapor condensation, on the solar cell surface, on the results of measurements, a constant nitrogen flow was passed through the box.

The *C*–*V* characteristics were measured using a high-frequency HP4275A Hewlett Packard LCR-meter; during measurements, a constant voltage in the range from

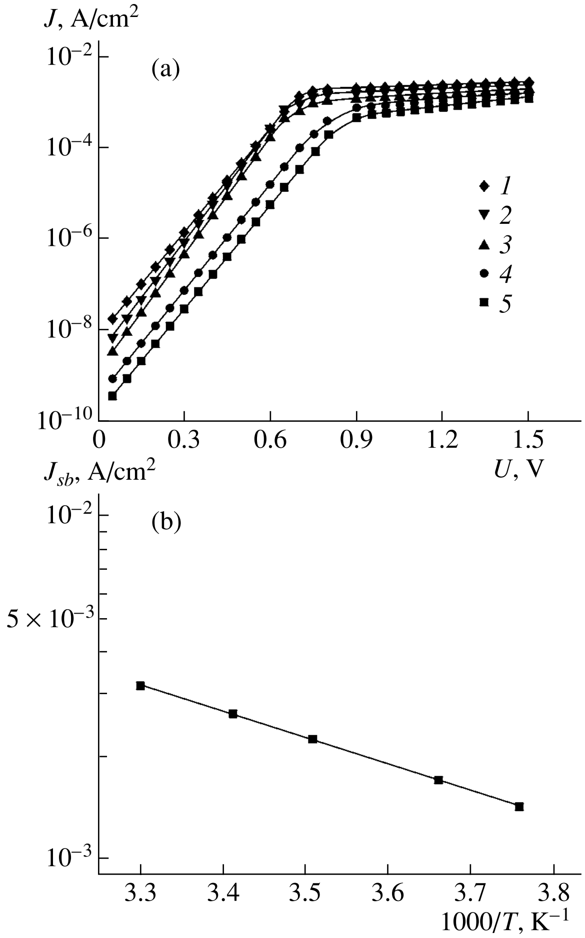

Fig. 1. (a) Current–voltage characteristics of the CdS/CdTe/Cu/Au solar cells under the forward bias at T = (*1*) 30, (*2*) 20, (*3*) 12, (*4*) 0, and (*5*) –7°C. (b) Temperature dependence of the saturation current J_{sb}.

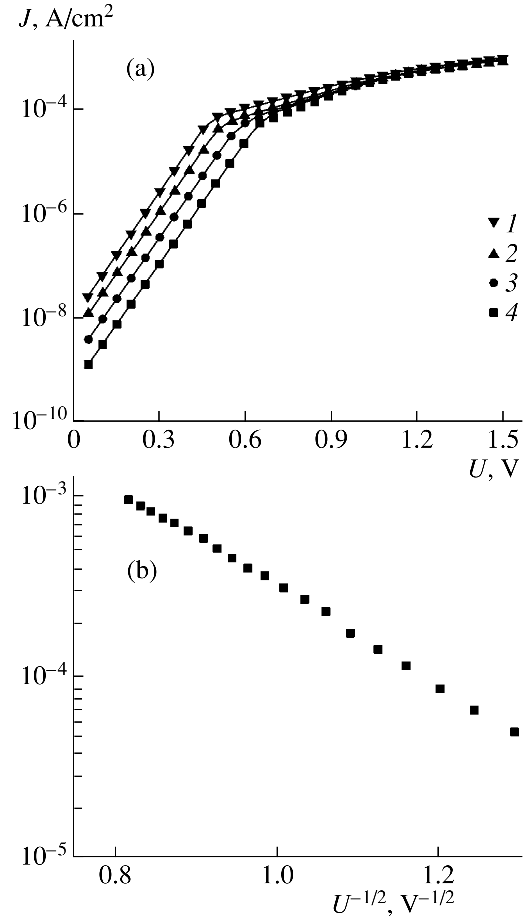

Fig. 2. (a) Current–voltage characteristics of the CdS/CdTe/ITO solar cells under the forward bias at T = (*1*) 20, (*2*) 12, (*3*) 0, and (*4*) –10°C. (b) Current J versus $U^{-1/2}$ under the forward bias $U > 1$ V.

–2 V to + 2 V and a sinusoidal signal with the frequency 100 kHz and amplitude 10 mV were fed simultaneously to the sample. According to the published data [6], the shape of the *C–V* characteristics of the CdTe-based thin-film solar cells at this frequency is mainly determined by the variations in the sizes of the space charge regions.

3. RESULTS AND DISCUSSION

3.1. I–V Characteristics of the CdS/CdTe/Cu/Au and CdS/CdTe/ITO Solar Cells

The typical dark forward *I–V* characteristics of the studied CdS/CdTe/Cu/Au and CdS/CdTe/ITO solar cells are shown in Figs. 1a and 2a, respectively. The analysis of the *I–V* characteristics and temperature dependences of the density of the diode saturation current J_s indicate that a thermally activated recombination mechanism of the charge transport is in effect under the forward bias voltages as high as 0.6–0.8 V for the CdS/CdTe/Cu/Au device structures and 0.5–0.7 V for the CdS/CdTe/ITO device structures. For this mechanism, the *I–V* characteristics of the studied solar cells can be represented by the relation [8, 9]

$$J = J_s[\exp(eU/AkT) - 1]. \quad (1)$$

Here, J_s is the density of the diode saturation current, U is the bias voltage, e is the elementary charge, A is the ideality factor, k is the Boltzmann constant, and T is temperature;

$$J_s = J_{s0}\exp(-E_a/kT), \quad (2)$$

where E_a is the activation energy of the saturation current. It was shown that this energy is related to the potential-barrier height E_b, specifically, $E_a = E_b/A$ [10].

The calculations showed that the activation energy is 0.75 eV for the CdS/CdTe/Cu/Au structures and 0.68 eV for the CdS/CdTe/ITO structures. Taking into account that the factor of room-temperature is ideally 1.9 and 2.1 for the studied CdS/CdTe/Cu/Au and CdS/CdTe/ITO solar cells, respectively, we obtain practically identical potential-barrier height E_b =

1.43 eV for both types of the solar cells. It was previously found that the theoretical potential-barrier height for the *p*-CdS/*n*-CdTe heterojunction is 1.02 eV [11]. Therefore, making allowance for the fact that the band gap for the CdTe films equals 1.45 eV, we can affirm that the charge carriers in the solar cells under study are separated by the *p–n* junction that forms in the base CdTe layer. Indeed, the region of the built-in electric field is shifted into the depth of the base layer during the high-temperature preparation of the CdS/CdTe-based solar cells [12]. This circumstance has a beneficial effect on the efficiency of photoelectric processes due to a reduction in the negative influence of the surface recombination on the separation of nonequilibrium charge carriers generated by optical radiation.

Under high forward biases ($U > 1$ V), the shape of the studied *I–V* characteristics is affected by the rear contact. The rear contact with the base CdTe layer is the Schottky barrier. Therefore, when describing the specific features of charge transport in the CdS/CdTe/Cu/Au solar cells under forward bias voltages lower than 1 V, it was suggested [13] to consider the rear contact as for the series diode, which is biased reversely to the main *p–n* junction.

The studies show that a plateau is observed in the *I–V* characteristics of the studied CdS/CdTe/Cu/Au solar cells under the forward bias $U > 1$ V. The current density, which corresponds to the plateau, increases as the temperature increases (Fig. 1b). Consequently, the density of the current flowing across the solar cell starts to be limited by the density of the saturation current of the rear contact J_{sb}. The exponential dependence of $J_{sb}(T)$ on $1/T$ indicates that the thermal emission mechanism of the charge transport exists in the device structure in the mentioned voltage range:

$$J_{sb} = J_{sb0}\exp(-E_{ab}/kT). \quad (3)$$

Here, E_{ab} is the activation energy of the saturation current of the rear contact. This quantity is related to the potential-barrier height E_{bb} of the rear contact by the relation $E_{ab} = E_{bb}/A$. For the samples under study, $E_{ab} =$ 0.16 eV and $A = 1.9$. Consequently, $E_{bb} = 0.30$ eV. The obtained value of the potential-barrier height virtually coincides with the value $E_{bb} = (0.31–0.33)$ eV, which was obtained for such solar cells using a similar method [10].

In the *I–V* characteristics of the CdS/CdTe/ITO structures, no temperature dependence of the saturation current is observed under the forward bias $U > 1$ V. For such bias-voltage values, the current J depends exponentially on $U^{-1/2}$ (Fig. 2b). Sharma and Purohit [14] believe that this fact is indicative of the existence of the tunnel–recombination mechanism of the charge transport in the device structure, for which the expression for current density is written as

$$J \propto \exp[-B(U_{bb} - U)^{-1/2}]. \quad (4)$$

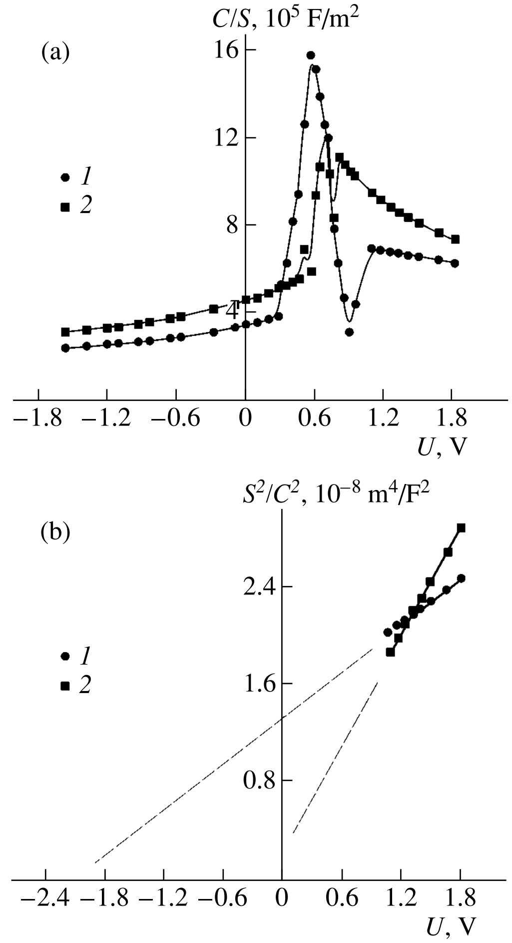

Fig. 3. (a) Capacitance–voltage characteristics of the (*1*) CdS/CdTe/ITO and (*2*) CdS/CdTe/Cu/Au solar cells. (b) Dependences $S^2/C^2 = f(U)$ at $U > 0.7$ V.

Here, B is a parameter determined by the physical characteristics of the *n*-type material and U_{bb} is the contact potential difference ($E_{bb} = eU_{bb}$).

3.2. Capacitance–Voltage Characteristics of the CdS/CdTe/Cu/Au and CdS/CdTe/ITO Solar Cells

The typical experimental voltage dependences of the specific capacitance C/S, where S is the solar cell cross-sectional area, for the studied CdS/CdTe/Cu/Au and CdS/CdTe/ITO solar cells are shown in Fig. 3a. The voltage–capacitance (*C–V*) characteristics for both types of solar cells include several typical portions. The first portion corresponds to the reverse bias and a low forward bias ($U \lesssim 0.2–0.3$ V). In this portion, the *C–V* characteristics are linearized in the coordinates $S^2/C^2 = f(U)$. Niemegeers and Burgelman [13] believe that, for this portion, the current density across the CdS/CdTe/Cu/Au solar cell is much lower that the saturation current density of the rear contact J_{sb}. Therefore, the voltage applied drops completely across the *p–n* junction. Consequently, the total capacitance of the solar cell for this portion corresponds to the capacitance of the *p–n* junction. This capacitance is described by the relation, which is characteristic of the semiconductor structures with an abrupt *p–n* junction or the Schottky barrier [15]:

$$\frac{C}{S} = \frac{\varepsilon\varepsilon_0 eN}{[2(V_b - U)]^{1/2}}. \quad (5)$$

Here, S is the area of the depletion layer, ε is the relative permittivity, ε_0 is the permittivity of free space, V_b is the contact potential difference ($E_b = eV_b$), and N is the concentration of the charge carriers.

The potential-barrier height of the *p–n* junction was determined from the intersection of the extrapolated linear part of the dependence $S^2/C^2 = f(U)$ with the abscissa. This height was almost identical for the CdS/CdTe/Cu/Au and CdS/CdTe/ITO solar cells and equaled eV_b = 1.41 and 1.44 eV, respectively. The obtained value of the potential-barrier height almost coincides with the values of E_b determined by processing the *I–V* characteristics. The impurity concentration N in the base layers of the solar cells was determined from the slope of the linear portion of the dependence $S^2/C^2 = f(U)$ according to the relation (5). For the CdS/CdTe/Cu/Au structures, $N = 3 \times 10^{20}$ m^{-3}, and for the CdS/CdTe/ITO structures, $N = 2 \times 10^{20}$ m^{-3}. It is our opinion that the higher value of N for the CdS/CdTe/Cu/Au structures is caused by the Cu diffusion from the rear contact to the region of the *p–n* junction [16].

It was experimentally found that the second characteristic portion in the dependences $C/S = f(U)$ for the studied device structures exists under the positive bias $U > 1$ V for the CdS/CdTe/Cu/Au structures and $U >$ 0.8 V for the CdS/CdTe/ITO structures. In this range of the voltages applied, the *C–V* characteristics for both types of solar cells are also linearized if represented as $S^2/C^2 = f(U)$ (see Fig. 3b). It was shown that, in this portion, the voltage applied drops mainly across the rear rectifying contact, which is reverse-biased in this case, and the total capacitance of the solar cell is determined by the contact capacitance [13]. Under such forward biases, the sizes of the depletion region of the *p–n* junction and, correspondingly, the resistance of the depletion region decrease. The height of the potential barrier, which emerges during formation of the rear contact to the base CdTe layer, and the carrier concentration near the rear contact (N_b) were determined from the linear portion of the dependence $S^2/C^2 = f(U)$, similarly to study [16]. For the CdS/CdTe/Cu/Au structures, E_{bb} = 0.25 eV, which corresponds to the value of this parameter found by us from the analysis of the dark *I–V* characteristic. For the CdS/CdTe/ITO structures, E_{bb} = 2.20 eV. In this case, $N_b = 9.5 \times 10^{20}$ m^{-3} for the CdS/CdTe/Cu/Au structures, and $N_b = 2.2 \times 10^{21}$ m^{-3} for the CdS/CdTe/ITO structures. A high carrier concentration near the back contact and a high potential barrier of the rear contact gave rise to the tunnel–recombination mechanism of the charge transport in the CdS/CdTe/ITO solar cells under the forward-bias voltage above 0.8 V, which follows from the analysis of the dark *I–V* characteristics.

4. CONCLUSIONS

It is shown that the front potential barrier of the CdS/CdTe/Cu/Au and CdS/CdTe/ITO solar cells is the *p–n* junction formed in the base layer. Under the reverse biases and forward biases up to 0.8 eV for the CdS/CdTe/Cu/Au structures and up to 0.7 eV for the CdS/CdTe/ITO structures, the existence of this *p–n* junction gives rise to the thermally activated recombination mechanism of the charge transport in the studied device structures.

It is found that the height of the rear potential barrier CdTe–Cu/Au is 0.25–0.30 eV. The existence of this barrier leads to the thermal-emission mechanism of the charge transport in the CdS/CdTe/Cu/Au structures under the applied forward bias above 1 V.

For the first time, the height of the rear potential barrier of the CdS/CdTe/ITO solar cell is experimentally found to be 2.2 eV. The carrier concentration in the base CdTe layer near the back contact is as high as 2.2×10^{21} m^{-3}. These two circumstances give rise to the tunnel–recombination mechanism of the charge transport in the CdS/CdTe/ITO solar cell, if the forward bias applied is higher than 0.8 eV.

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REFERENCES

1. K. Durose, P. R. Edwards, and D. P. Halliday, J. Cryst. Growth **197**, 733 (1999).
2. J. Sarlund, M. Ritala, M. Leskela, and R. Zilliacus, Sol. Energy Mater. Sol. Cells **44**, 177 (1996).
3. N. Romeo, A. Bosio, and V. Canevari, Int. J. Sol. Energy **12**, 183 (1999).
4. N. Suyama, T. Arita, Y. Nishiyama, *et al.*, in *Conference Record of the 26th IEEE Photovoltaic Specialist Conference* (Anaheim, USA, 1997), p. 419.
5. J. Tang, D. Mao, T. R. Ohno, *et al.*, in *Conference Record of the 26th IEEE Photovoltaic Specialist Conference* (Anaheim, USA, 1997), p. 439.
6. D. L. Batzner, R. Wendt, A. Romeo, *et al.*, Thin Solid Films **361–362**, 463 (2000).
7. A. N. Tiwari, G. Khrypunov, F. Kurtzesau, *et al.*, Prog. Photovoltaics: Res. Appl. **12**, 33 (2004).

8. K. W. Mitchell, A. L. Fahrenbruch, and R. H. Bube, J. Appl. Phys. **48**, 4365 (1977).
9. T. L. Chu, S. S. Chu, and S. T. Ang, J. Appl. Phys. **64**, 1233 (1988).
10. M. Wimbor, A. Romeo, and M. Igalson, Optoelectron. Rev. **8**, 375 (2000).
11. R. Bube, *Properties of Semiconductors Materials. Photovoltaic Materials* (Imperial College Press, USA, 1999), Vol. 1, p. 281.
12. D. Bonnet and P. Meyers, J. Mater. Res. **13**, 2740 (1999).
13. A. Niemegeers and M. Burgelman, J. Appl. Phys. **81**, 2881 (1997).
14. B. L. Sharma and R. L. Purohit, *Semiconductor Heterojunctions* (Pergamon, Oxford, 1974; Radio i Svyaz', Moscow, 1979).
15. V. V. Batavin, Yu. A. Kontsevoĭ, and Yu. V. Fedorovich, *Measurement of Parameters of Semiconductor Materials and Structures* (Radio i Svyaz', Moscow, 1985) [in Russian].
16. D. L. Batzner, A. Romeo, H. Zogg, *et al.*, Thin Solid Films **381**, 151 (2001).

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