ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 13, № 2 (2012) С. 478-481

PHYSICS AND CHEMISTRY OF SOLID STATE
V. 13, № 2 (2012) P. 478-481

PACS:71.55.GS, 72.80.EY, 73.20.HB, 73.40.GK, 73.40.LQ

ISSN 1729-4428

V.V. Brus[1], M.I. Ilashchuk[2], Z.D. Kovalyuk[1], P.D. Maryanchuk[2], K.S. Ulyanytsky[2], B.M. Gritsyuk[2]

A Solar Cell Based on a Heterojunction n-TiO_2/p-CdTe

[1]Frantsevich Institute for Problems of Materials Science NAS of Ukraine, Chernivtsi Branch, Iryna Vilde str. 5, 58001, Chernivtsi, Ukraine, e-mail: victorbrus@mail.ru
[2]Yuriy Fedkovych Chernivtsi National University, 2 Kotsybynsky str., 58012, Chernivtsi, Ukraine, e-mail: p.maryanchuk@chnu.edu.ua

Photosensitive n-TiO_2/p-CdTe heterojunctions were fabricated by DC reactive magnetron deposition of TiO_2 thin films with n-type conductivity onto freshly cleaved p-CdTe single crystal substrates (110). Methods of formation of ohmic contacts to n-TiO_2 and p-CdTe were proposed and their ohmic properties were tested.

The solar cell possesses the following photoelectrical parameters under 100 mW/cm^2 illumination: the open-circuit voltage V_{oc} = 0.69 V, the short-circuit current I_{sc} = 6 mA/cm^2 and fill factor FF = 0.42.

Kay words: solar cell, thin film, TiO_2, CdTe.

Стаття поступила до редакції 16.08.2011; прийнята до друку 15.03.2012.

Introduction

Many different prospective materials and structures for application in highly efficient solar cells have been under intensive search and investigation for the lust decades. The application of heterojunctions in photoelectric convertors enhances their functional capabilities and operational characteristics comparing with photoelectrical devices based on homojunctions [1, 2].

Solar cells based on heterojuctions, generally consist of a wide-band semiconductor “window” and a solar radiation “absorber”. It is worth noting that TiO_2 and CdTe, due to their electrical, optical and operational properties, are well suited to be the “window” and “absrober” materials, respectively [3 - 7]. The feasibility of TiO_2/CdTe heterojuctions for photoelectrical conversion is shown in a number of works [8, 9], where the ETA-solar cells based on TiO_2/CdTe heterojuctions were investigated.

One of the main obstacles in production of the solar cells based on p-CdTe is the problem of back contacts, because there are no metals that form an ohmic contact to CdTe with p-type conductivity. The conventional back contacts to p-CdTe, Cu/Au and Au, were found to create a reverse potential barrier (< 0.3 eV) according to a main separating potential barrier [10, 11].

This paper reports the results of an investigation into the electrical and photoelectrical properties of a solar cell based on a n-TiO_2/p-CdTe heterojunction fabricated by means of deposition of a TiO_2 thin film onto a freshly cleaved p-CdTe single crystal substrate.

The relatively simple methods of ohmic contacts formation were proposed as well as their electric properties were studied.

I. Experimental methods

1.1. The n-TiO_2/p-CdTe heterojuction fabrication

The CdTe single crystals with p-type conductivity were grown by Bridgman method at low cadmium vapor pressure (P_{Cd} = 0.02 bar). The values of specific electrical conductance and majority carriers concentration at 295 K for these crystals were measured to be $\sigma = 8.9\cdot10^{-2}$ Ohm$^{-1}\cdot$cm^{-1} and $p = 7.2\cdot10^{15}$ cm^{-3}, respectively.

The TiO_2 thin film was deposited onto the freshly cleaved p-CdTe single crystal substrate (110) with typical dimensions 5×4×1 mm in an universal coating system Laybold – Heraeus L560 by DC reactive magnetron sputtering of a titanium target in atmosphere of argon and oxygen mixture.

The titanium target, a cylinder 100 mm in diameter and 5 mm thick, was mounted, on the magnetron table under water cooling, 7 cm from the substrates.

The CdTe substrate was mounted over the magnetron on a rotating substrate holder for providing uniform thickness of the film. Before the deposition process started, the vacuum chamber was pumped down to a residual pressure of $5\cdot10^{-5}$ mbar.

The mixing of pure argon and oxygen gasses in the desirable ratio was carried out from two separate sources.

A short-term sputter-cleaning of the target and substrate by Ar ions was applied to eliminate the surface contaminants.

During the deposition process, the partial pressures of argon and oxygen were equal to $7 \cdot 10^{-3}$ and $2 \cdot 10^{-4}$ mbar, respectively. The magnetron power was 350 W. The substrate temperature was 300 ºC. The deposition process lasted for 20 minutes.

The TiO_2 thin film was also simultaneously deposited onto glass ceramic substrates for determining of electrical parameters of the thin film. The obtained TiO_2 thin film possessed n-type of conductivity. The measured values of specific electrical conductance and majority carriers concentration at 295 K for the TiO_2 thin film were $\sigma = 7.1$ $Ohm^{-1} \cdot cm^{-1}$ and $n = 4.8 \cdot 10^{18}$ cm^{-3}, respectively.

1.2 The ohmic contacts fabrication

The frontal electric contact to the solar cell (TiO_2 thin film) was fabricated by thermal evaporation of indium at the substrate temperature of 100 ºC.

Before the back electrical contact was made, the back surface of the solar cell (p - CdTe) was exposed by a monopulse of a powerful ruby laser with the wavelength $\lambda = 0.694$ μm and pulse duration $\tau = 1.2$ ms in order to create a p^+-layer due to additionally generated cadmium vacancies on the back surface. The Au and Cu layers were successively deposited onto the laser-treated back surface by means of reduction from aqueous solutions of gold chloride and copper vitriol, respectively.

In order to study the electric properties of the contacts, a symmetrical structure Cu-Au/p^+/p-CdTe/p^+/Au-Cu and a TiO_2 thin film with three concentric indium contacts were fabricated. The method of impedance spectroscopy [12] and the three probe method [2] were applied.

The electrophysical parameters of the components of the solar cell were measured by means of the conventional two probe method in the direct current mode.

The current-voltage (*I-V*) characteristics of the solar cell and frequency dependence of the impedance $Z(\nu)$ of the symmetrical structure Cu-Au/p^+/p-CdTe/p^+/Au-Cu were measured by a SOLARTRON SI 1286, SI 1255 complex. The *I-V* characteristic of the thermal evaporated indium contact to the TiO_2 thin film (In/TiO_2 contact) was measured by employing the three probe method [2].

The spectral quantum efficiency $QE(\lambda)$ of the solar cell was measured by a conventional spectrophotometer within the range of wavelength from 350 to 900 nm.

II. Results and their discussion

The straight and symmetrical *I-V* characteristic of the In/TiO_2 contact as well as its relatively small specific resistance ($\rho = 4.5 \cdot 10^{-2}$ $Ohm \cdot cm^2$) provide evidence that the thermally evaporated indium contact to the TiO_2 thin film is a highly quality ohmic contact (fig. 1).

The frequency dependence of the *I-V* phase shifting $\theta(\nu)$ and that of the absolute value of impedance $|Z(\nu)|$ of the symmetrical structure Cu-Au/p^+/p-CdTe/p^+/Au-Cu

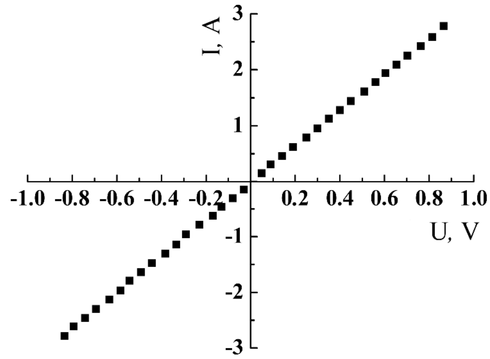

Fig. 1. The *I-V* characteristic of the In/TiO_2 contact.

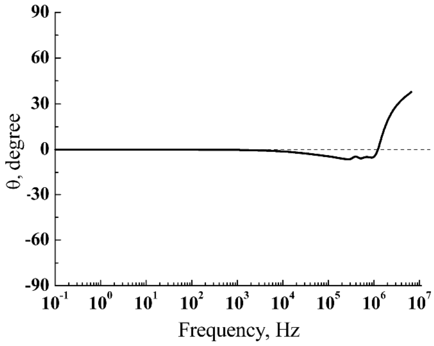

Fig. 2. The frequency dependence of the *I-V* phase shifting $\theta(\nu)$.

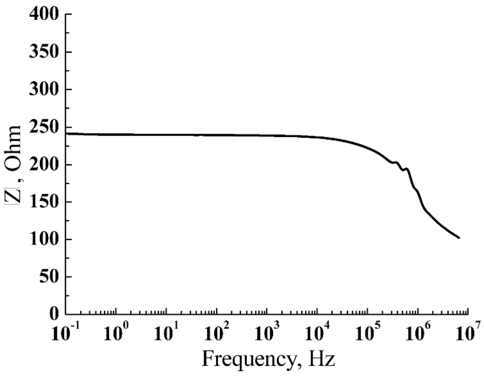

Fig. 3. The frequency dependence of the absolute value of impedance $|Z(\nu)|$ of the Cu-Au/p^+/p-CdTe/p^+/Au-Cu structure.

with type dimensions 5×4×1 mm are shown on fig. 2 and fig. 3, respectively. Within the range of low frequencies ($\nu < 10^4$ Hz) the absolute value of impedance ($|Z(\nu)|$) and the *I-V* phase shifting ($\theta(\nu)$) become frequency independent, $|Z| = 240$ Ohm and $\theta = 0$, respectively. In this case one can neglect with the reactive component of the impedance and consider its absolute value equal to the serial resistance of the symmetric structure. Since the p^+-layer with enhanced concentration of the majority carriers is created on the back surface one may assume that the depletion region at the interface Cu-Au/p^+-CdTe is tunnel-thin and provides good electric properties of this contact.

Fig. 4 shows dark and light *I-V* curves of the solar

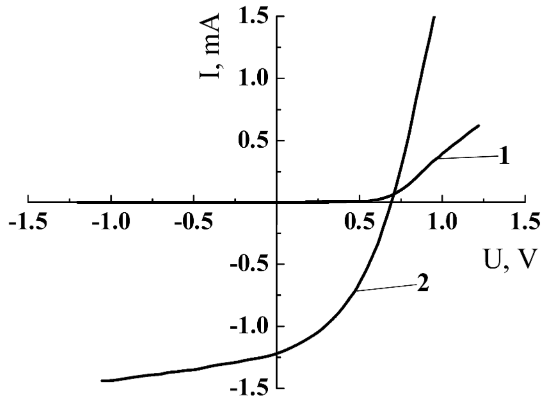

Fig. 4. The dark and light *I-V* curves of the solar cell.

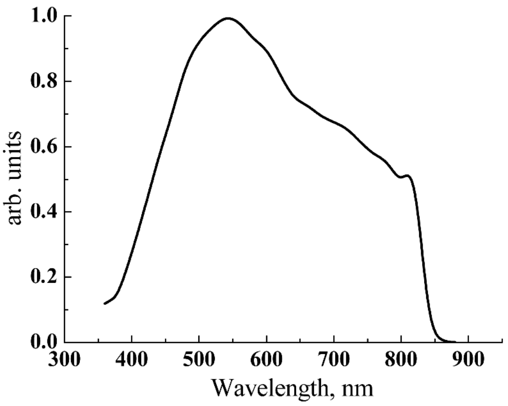

Fig. 5. The spectral quantum efficiency of the solar cell.

cell. The serial resistance value R_s = 820 Ohm was evaluated from the slope of the linear segment of the straight branch of the dark *I-V* curve. The determined value of the serial resistance far exceeds the resistance of the base region of the solar cell (p-CdTe substrate) as measured by the impedance spectroscopy method (240 Ohm). This indicates that a transition layer with high resistance is formed at the n-TiO_2/p-CdTe interface. This can be explained by the p-CdTe substrate diffusion of Ti atoms during the TiO_2 thin film deposition.

It is known that the elements with the unfilled 3d-shell, including Ti, dissolve in the Cd sublattice and create deep energy levels in CdTe [13 - 16]. According to the work [16] injection of Ti atoms into the CdTe lattice results in obtaining of high-resistance material, with electric conductance induced by ionization of the deep energy level E_c-(0.73 ± 0.03) eV, which can not be attributed to isolated Ti ions. Thereby the cadmium vacancies passivation by Ti atoms as well as the generated deep energy levels can result in appearance of the above-mentioned high-resistance layer at the TiO_2/CdTe interface.

The light *I-V* curve of the solar cell shows that it produces the open-circuit voltage V_{oc} = 0.69 V and the short-circuit current I_{sc} = 6 mA/cm^2 under illumination of 100 mW/cm^2. It should be noted that the obtained value of the fill factor *FF* = 0.42 is twice as large as that of the ETA solar cells based on the TiO_2/CdTe heterojunction declared in [8, 9]. This can be caused by lesser surface-state density at the dense TiO_2 thin film/cleaved CdTe single crystal substrate interface comparing with that at the structured TiO_2 film/electrodeposited CdTe thin film interface.

The spectral quantum efficiency *QE(λ)* of the solar cell investigated in this paper was measured as the ratio of the short-circuit current to the number of the incident photons and is shown in fig. 5. An interesting feature of this spectral quantum efficiency is a good matching with the solar radiation spectrum under AM1.5 [17].

Conclusions

The solar cell based on the anisotype heterojunction n-TiO_2/p-CdTe was fabricated by deposition of the TiO_2 thin films onto the freshly cleaved p-CdTe single crystal substrate using the DC reactive magnetron sputtering technique.

Methods for the formation of the front and back contacts were proposed, the contacts were fabricated and their electrical properties were investigated.

The solar cell possesses open-circuit voltage V_{oc} = 0.69 V, short-circuit current 6 mA/cm^2 and fill factor *FF* = 0.42 under 100 mW/cm^2 illumination.

Reasons for the relatively large value of the serial resistance were discussed.

The good match between the spectral quantum efficiency of the solar cell and the solar radiation spectrum under AM1.5 was noticed.

[1] T. Soga. *Nanostructured Materials for Solar Energy Convertion*. Elsevier, Amsterdam (2006).

[2] A.L. Fahrenbruch, R.H. Bube. *Fundamentals of solar cells. Photovoltaic solar energy conversion*. Academic Press, New York, (1983).

[3] U. Diebold. The surface science of titanium dioxide // *Surface Science Reports*, **43**, pp. 53-229 (2003).

[4] Barrera, J. Pla, C. Bocchi, A. Migliori. Antireflecting-passivating dielectric films on crystalline silicon solar cells for space applications // *Solar Energy Materials & Solar Cells*, **92,** pp.1115-1122 (2008).

[5] B.S. Richards. *Novel uses of titanium dioxide for silicon solar cells*, PhD Thesis, Sydney (2002).

[6] L.A. Kosyachenko. Problems of photoelectric conversion in thin-film CdS/CdTe devices // *Fiz. Tekh. Poluprov.*, **40**, pp. 730-746 (2006).

[7] R.S. Singh, V.K. Rangari, S. Sanagapalli, V. Jayaraman, S. Mahendra, V.P. Singh. Nano-structured CdTe, CdS and TiO_2 for thin film solar cell applications // *Solar Energy Materials & Solar Cells*, **82**, pp. 315-330 (2004).

[8] K. Ernst, R. Engelhardt, K. Ellmer, C. Kelch, H.-J. Muffler, M.-Ch. Lux-Steiner, R. Konenkamp. Contacts to a solar cell with extremely thin CdTe absorber // *Thin Solid Films*, **387**, pp. 26-28 (2001).

[9] K. Ernst, A. Belaidi, R. Konenkamp. Solar cell with extremely thin absorber on highly structured substrate // *Semicond. Sci. Technol.*, **18**, pp. 475-479 (2003).
[10] J.P. Ponpon. A review of ohmic and rectifying contacts on cadmium telluride // *Solid State Electronics*, **28**, pp. 689-706 (1985).
[11] A.V. Meriuts, G.S. Khrypunov, T.N. Shelest, N.V. Deyneko. Peculiarities of light current-voltage characteristics of bifacial solar cells on the thin CdTe base layer // *Fiz. Tekh. Poluprov.*, **44**, pp. 829-832 (2010).
[12] E. Barsoukov, J.R. Macdonald. *Impedance Spectroscopy Theory, Experiment and Application, second ed.*, John Wiley & Sons, Inc., New Jersey (2005).
[13] K.A. Kikoin, I.G. Kurik, S.V. Melnichuk. Chemical tendencies for deep 3d-levels in semiconductor compounds A^2B^6 // *Fiz. Tekh. Poluprov.*, **24**, pp. 587-589 (1990).
[14] D.M. Hofmann, W. Stadler, P. Christmann, B.K. Meyer. Defects in CdTe and $Cd_{1-x}Zn_xTe$ // *Nuclear Instruments and Methods in Physics Research A*, **380**, pp. 117-120 (1996).
[15] E. Rzepka, Y. Marfaing, M. Cuniot, R. Triboulet. Deep centres for optical processing in CdTe // *Material Science and Engineering*, **B16**, pp. 262-267 (1993).
[16] P.I. Babiy, B.B. Slyn'ko, Yu.P. Gnatenko, M.I. Ilashchuk, O.A. Parfenyuk. Isoelectronic substitutional impurities Sc and Ti in CdTe // *Fiz. Tek. Poluprov.*, **24**, pp. 1444-1448 (1990).
[17] Standart tables for reference solar spectral irradiance for air mass 1.5, ISO 9845-1:1992. International organization for standardization, www.iso.ch.

В.В. Брус[1], М.І. Ілащук[2], З.Д. Ковалюк[1], П.Д. Мар'янчук[2],
К.С. Ульяницький[2], Б.М. Грицюк[2]

Сонячний елемент на основі гетеропереходу n-TiO_2/p-CdTe

[1]Інститут проблем матеріалознавства НАН України, Чернівецьке відділення, вул. І. Вільде, 5, Чернівці, Україна 58001, e-mail: victorbrus@mail.ru
[2]Чернівецький національний університет ім. Ю. Федьковича, вул. Коцюбинсоко 2, Чернівці, Україна 58012, e-mail: p.maryanchuk@chnu.edu.ua

Виготовлені фоточутливі гетеропереходи n-TiO_2/p-CdTe шляхом нанесення методом реактивного магнетронного розпилення при постійній напрузі тонких плівок TiO_2 n-типу провідності на свіжо сколоті монокристалічні підкладки p-CdTe (110). Запропоновано методи формування омічних контактів до n - TiO_2 та p - CdTe, а також досліджено їхні електричні властивості.

Сонячний елемент при освітленні 100 мВт/см^2 володіє наступними фотоелектричними параметрами: напруга холостого ходу V_{oc} = 0,69 В, струм короткого замикання I_{sc} = 6 мА/см^2 і коефіцієнтом заповнення FF = 0,42.

Ключові слова: сонячний елемент, тонка плівка, TiO_2, CdTe.