PHYSICS AND CHEMISTRY
OF SOLID STATE
V. 22, No. 4 (2021) pp. 817-827

Section: Physics

DOI: 10.15330/pcss.22.4.817-827

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**ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 22, № 4 (2021) С. 817-827**

Фізико-математичні науки

PACS: 73.50.Pz

ISSN 1729-4428

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Solar cells based on CdTe thin films

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An analysis of the use of semiconductor solar cells based on thin-film cadmium telluride (CdTe) in power engineering is carried out. It is shown that the advantages of thin-film technology and CdTe itself as a direct-gap semiconductor open up the prospect of large-scale production of competitive CdTe solar modules. The physical and technical problems of increasing the efficiency of CdS/CdTe heterostructure solar cells, which are significantly inferior to the theoretically possible value in mass production, are discussed. The state of CdTe thin-film solar cells, which make CdTe a suitable material for ground-based photoelectric conversion of solar energy, the historical development of the CdTe compound, the application of CdTe thin films, the main methods and strategies of device production, device analysis and fundamental problems related to the future development of thin-film modules based on cadmium telluride.

Keywords: thin films, solar cells, CdTe, photovoltaic cells, modules.

Received 27 September 2021; Accepted 29 December 2021.

Content

Introduction

Fossil fuels such as coal, oil, natural gas, which until now have met the demand for energy around the world, are being used less and less due to the depletion of reserves. In addition, their extraction and consumption has an irreversible effect on environmental conditions, which leads to the threat of catastrophic climate change on Earth [1]. Every year, renewable energy sources receive more and more support at the level of states, which are trying to stimulate their development by various methods and, accordingly, strive to become more energy independent. The most promising in this direction is the development of solar energy, an inexhaustible source of thermal and photovoltaic energy.

The development of renewable energy and the transition to efficient alternative energy sources continues to develop rapidly and is an important priority for each state in order to prevent the emergence of an energy crisis. The most common photovoltaic modules, the main advantage of which is the use of an unlimited and environmentally friendly source of solar energy.

I. Advantages of CdTe for use in solar photovoltaic technology

Photovoltaic energy conversion plays an important role in promoting energy solutions [2]. There are three main generations of photovoltaic cells (PC): silicon, thin-film and organic solar cells (Fig. 1) [3]. Currently, the most commonly used solar cells (SC) are PC based on silicon technologies.

An alternative to these technologies is cadmium telluride (CdTe), which attracts special attention compared to other materials due to its optimal band gap of 1.5 eV at room temperature, high absorption coefficient (> 105/cm) in the visible region of the solar spectrum and high chemical stability. CdTe has a cubic zinc blende structure with a lattice period of 6.481 Å [4]. This width of the forbidden zone is optimally matched to the solar spectrum for energy conversion in photovoltaic systems [5]. In addition, CdTe is also characterized by a high optical absorption coefficient; with an active thickness of about 2 μm, more than 99% of the incident sunlight is absorbed. Therefore, high quality CdTe thin films are considered an ideal optical material and are widely used in various electronic and optoelectronic devices of a large area, such as solar cells, X-ray and γ-radiation detectors, photodetectors, LEDs, lasers, etc. [6,7]. Currently, interest in this material has been renewed in connection with the search for cheaper technologies for the productions of large solar cells. The theoretical value of the efficiency of SC based on CdTe is about 33%, and the practical efficiency is about 22% of thin-film photovoltaic materials [8].

Simple methods of manufacturing and forming a barrier structure that do not require complex and expensive equipment are an important advantage of CdTe-based solar cell technology [2,9,10].

II. Publications devoted to the study of the properties of CdTe

Even before 2010, thin-film elements based on CdTe had an efficiency factor (EF) that did not exceed 17%, and over the previous 7 years, the EF increased to 22.5% [8]. This is due to the fact that the leading manufacturers of solar panels are focused on reducing their cost. The cost of ~ 1 $/W at 16.7% in 2001 decreased to ~ 0.75 $/W at 22.1% in 2016 and in 2019 at First Solar Inc. was ~ 0.67 $/W with an efficiency of about 25%. A further decrease in prime cost and an increase in efficiency are predicted with the same cell structure [10].

The number of publications devoted to the study of the properties of CdTe and indexed in the international scientometric database Scopus is 23428 documents and is growing sharply in recent years. Ukraine is among the 10 countries where the properties of CdTe (2020) are most intensively studied (Fig. 2, Fig. 3) [11].

In Fig. 4 shows the 25-year development of improving the efficiency of cells and modules since the publication of the first version of the tables in 1993 [12]. Since January 1993, Progress in Photovoltaics has published 6 monthly lists with the highest proven efficiencies for a range of PV (photovoltaic) cell and module technologies. Such recommendations not only provide an authoritative overview of the state of the art, but also encourage researchers to seek new results. The most noticeable progress in recent years has been in the field of research on CdTe-based cells, along with CIGS (copper-indium-gallium diselenide) and mc-Si [12].

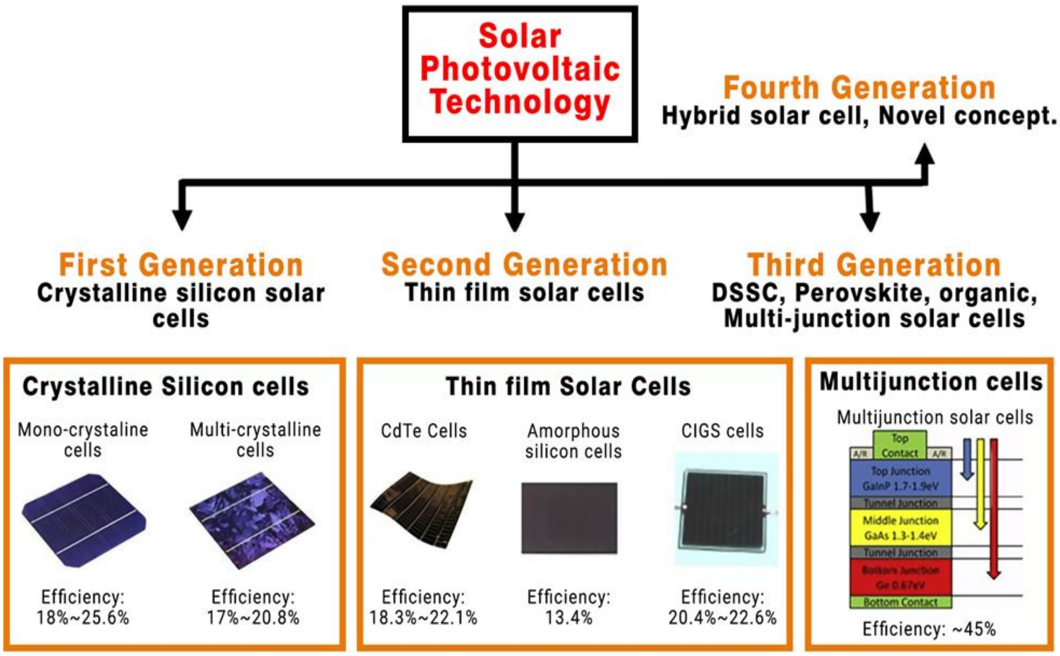
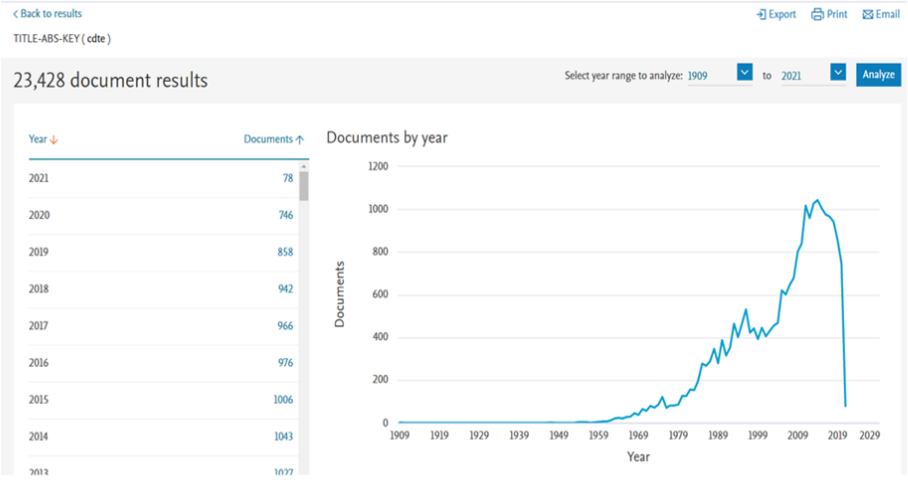


Fig. 1. Classification of solar photovoltaic technologies with a range of achieved efficiency [3].



TITLE-ABS-KEY (cdte)

23,428 document results

Select year range to analyze: 1909 to 2021

Year ↓	Documents ↑
2021	78
2020	746
2019	858
2018	942
2017	966
2016	976
2015	1006
2014	1043
2013	1027

Fig. 2. The number of publications over the years on the key tag "CdTe", published in journals indexed in the international scientometric base Scopus [11].

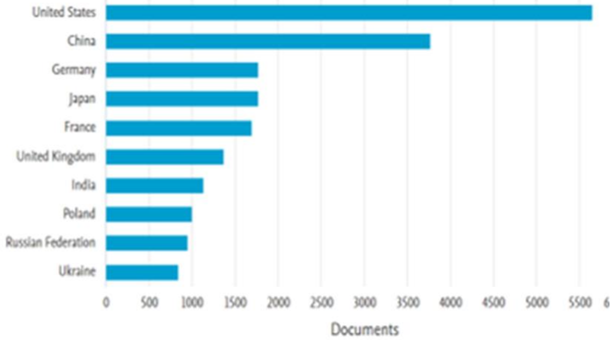


Fig. 3. List of countries in which the characteristics of CdTe are studied most intensively. The sample was made on the basis of the analytical capabilities of the Scopus database, taking into account the countries authors of publications devoted to the study of CdTe [11].

The values of the quantum efficiency and current-voltage characteristics (CVC) of such cells are shown in Fig. 5. According to fig. 5 (a), the highest efficiency of a large area CdTe module (2.4 m2, manufactured by First Solar) is 19.0% [13].

The highest temperature and radiation stability of CdTe, in comparison with Si and GaAs [14], makes it possible to use SC based on cadmium telluride at elevated temperatures and a significant flux of ionizing radiation. A possible alternative to CdTe with a similar band gap is gallium arsenide and its solid solutions; however, it is much more difficult to obtain them due to the small amount of Ga element in nature [14].

In view of the analyzed works, it can be stated that in recent years, studies devoted to the transition from the use of bulk photovoltaic materials (mono and polycrystalline) to thin-film ones have become increasingly important. Studies of the technology of thin-film materials based on CdTe are topical, namely, the development of cheap and reliable technologies, as well as studies devoted to the study of the optical and photoelectric properties of multilayer thin-film structures based on CdTe for opto- and photoelectronics [7,15].

III. Historical development of the CdTe compound

CdTe was first chemically synthesized by the French chemist Margotte in 1879 [16], but emerged as a viable electronic material in 1947, when Freerichs synthesized CdTe crystals by reacting Cd and Te vapors in a hydrogen atmosphere and measured the crystal photoconductivity [17]. The fundamental principles for understanding the electronic nature of CdTe arose from studies of single crystals obtained using zone cleaning. In 1954, Jenny and Booby [18] first reported that p-type and n-type conductivity can be obtained in CdTe by doping with foreign impurities. Shortly thereafter, Krueger and de Nobel [19] showed that the type of conductivity can also be controlled by changing the stoichiometry of Cd–Te. Excess Cd gives n-type, and excess Te gives p-type conductivity, similar to PbS, PbSe, and PbTe. In 1959, de Nobel [20] proposed a p–T–x diagram of the Cd–Te system and its relationship with the internal and external conductivity through the inclusion of a foreign atom. This diagram suggested the existence of two electronic levels associated with Cd vacancies and one with Cd insertion to take into account the measured changes in conductivity at different temperatures and partial pressures of Cd. In addition, the electronic levels associated with In as an n-type dopant and Au as a p-type dopant were evaluated [20].

Loferski first proposed using CdTe for photovoltaic conversion of solar energy in 1956 [21]. Although methods for controlling the n and p-type conductivity in CdTe crystals were established before 1960, limited research has focused on the development of p/n–homojunctions. In 1959, Rappoport demonstrated single-crystal homojunction CdTe cells with a conversion efficiency of ~ 2%, fabricated by In diffusion into p-type CdTe crystals [22]. In 1979, a group of scientists in France achieved > 7% conversion efficiency for a device made by vapor deposition from p-type arsenic-doped CdTe films into n-type crystals [23]. They later reported cells with > 10.5% efficiency [23].

In contrast to the development of the p/n–homojunction, SC with CdTe heterojunctions have been

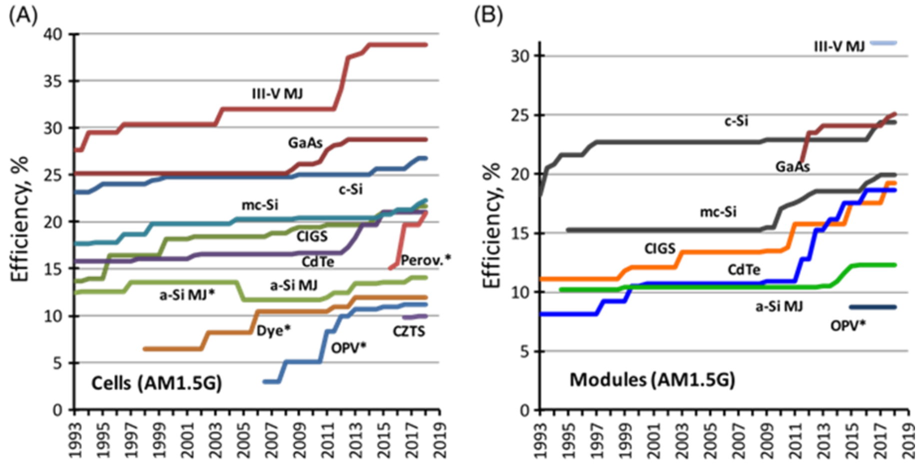


Fig. 4. Twenty-five years of progress: A - highest proven efficiency for cells ≥1 cm^2, manufactured using modern technologies; B - the highest confirmed results for modules ≥800 cm^2 [12].

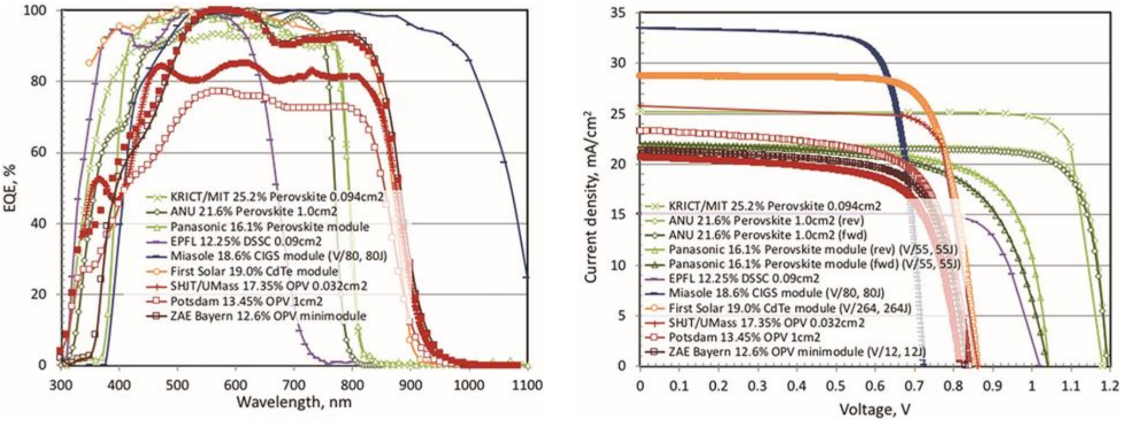


Fig. 5. External quantum efficiency (EQE) (a) of a thin-film cell or module and their CVC characteristics (b) [13].

widely studied since 1960, passing along two paths, in accordance with the type of conductivity of CdTe. For n-type CdTe single crystals and polycrystalline films, the p-type Cu2Te heterojunction was studied [24]. By the early 1970s, the best CdTe/Cu2Te thin-film layers achieved a conversion efficiency of > 7% [25]. Interestingly, these cells used an n-type CdS layer 5 μm thick, which was placed below to improve the adhesion and electrical contact of a 20 μm thick CdTe film on molybdenum substrates. Difficulties in controlling the Cu2Te formation process, poor device stability in CdTe/Cu2Te cells, and the absence of a transparent p-type conductor ultimately shifted the emphasis on studies of heterojunction structures using p-type CdTe. In other works with n-type CdTe, Schottky barrier devices were used, formed by heating Pt or Au lattices in contact with n-type CdTe single crystals or electrodeposited with thin CdTe films, with an efficiency approaching 9% [25].

For SC with single-crystal p-type CdTe, heterojunctions using stable oxides such as In2O3:Sn (ITO), ZnO, SnO2 and CdO have been studied more extensively. In these devices, the shortwave spectral response is mainly influenced by the transmission of the heteropartner and low resistance contact, which are collectively referred to as the window layer. SC based on p-type CdTe single crystals with electron-beam-evaporated indium tin oxide (ITO) window layers with an efficiency of = 10.5% were developed by the Stanford group in 1977 [26]. In 1987, cells obtained by reactive deposition of indium oxide In2O3 on p-type CdTe single crystals gave an overall efficiency of = 13.4% [27].

Cells obtained by evaporation of n-type CdS films onto single-crystal p-type CdTe were first obtained by Muller et al. in the mid-1960s [28], the conversion efficiency was less than 5%. In 1977, Mitchell et al. reported a conversion efficiency of 7.9% [29]. The highest efficiency for a cell made from thin-film CdS on a p-type CdTe single crystal was reported by Yamaguchi et al. in 1977, where CdS 0.5 μm thick was used in their cell, obtained by chemical vapor deposition on the facet (111) of a single crystal of CdTe doped with phosphorus, with an efficiency of 11.7% [30].

Thin-film SC with CdTe/CdS heterojunctions on polycrystalline substrates were first demonstrated in 1969 by Adirovich et al. with evaporated CdTe on a CdS/SnO2/glass substrate, yield > 2% [31]. And in 1972, Bonnet and Rabenhorst, at the 9th European Conference of Photovoltaic Technologies, described a 5-6% effective design of a CdS/CdTe/Mo substrate made of chemically deposited CdTe vapors and CdS films with vacuum evaporation [32].

The development of processes for making thin film SC CdTe/CdS during the 1980s and 1990s, almost always in ultra-high speed configuration, was achieved through improvements in device design, post-deposition processing, and low resistance contact formation rather than refinements in specific deposition methods. This is primarily due to the relatively high chemical stability of CdTe in comparison with the previous elements and compounds used to obtain it. Thus, numerous film making techniques have been used to deposit CdTe for medium to high efficiency solar cells. The photoelectric characteristic of SC CdTe/CdS with conversion efficiency from ~ 10 to ~ 16% was largely independent of the CdTe deposition method [33].

Despite the unpretentiousness of the deposition method, two mysterious aspects of the processing of high-performance thin-film SC CdTe/CdS remain, namely, the use of a supersonic device configuration with CdTe deposition on CdS and the need for a processing step (s) exposing CdTe and CdS films to Cl and O. In the 1980s, significant productivity gains were achieved by empirically optimizing substrate fabrication processes for processing variables such as CdTe deposition temperature, post-deposition heat treatment, growth or processing environment, and CdTe contact formation. For example, Matsushita Battery Industrial Company reported that it is very important for stencil/baked CdTe cells to control the concentrations of CdCl2, O and Cu in the structure by adjusting the suspensions and temperature-time sequences of the sintering step [34]. The monosolar electrodeposition process was optimized to a 10% efficiency level by adding Cl to a CdTe plating bath and using a post-formation "type conversion" deposition treatment to electrically activate the cell [35]. The Kodak Group achieved an efficiency level of 10% thanks to a CdTe mixture that sublimates, optimizing the deposition temperature of CdTe and the oxygen content of the deposition medium [33].

A turning point in the efficiency of CdTe thin-film cells with an additional advantage for technological stability was the application of air-thermal treatment after the deposition of CdTe/CdS structures coated with CdCl2 by groups at Ametek and at the Institute for Energy Conversion [36]. The combination of "CdCl2 treatment" with advances in low resistance contact formation resulted in a group at the University of South Florida achieving in 1993 > 15% efficient cell with CdTe sublimated in a confined space. Improvements in window layer processing and the use of CdCl2 steam treatment have led to further improvements [37]. As of 2001, the record efficiency was 16.5% [38]. Current-voltage characteristics and quantum efficiency of this cell are shown in Fig. 6.

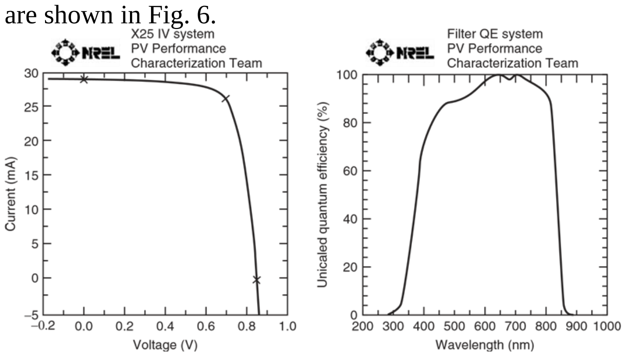


Fig. 6. Current-voltage and relative quantum curves efficiency for a thin-film solar cell CdTe/CdS with an efficiency of 16.4% [38].

Since 2000, the development of ultra-high-speed polycrystalline CdTe/CdS solar cells has become a very successful source of photovoltaic energy. Commercial CdTe modules accounted for about half of all photovoltaic product manufactured in the USA in 2008 [33].

To date, the value of the efficiency of a photovoltaic cell based on it is already 22.1% [34, 35]. Taking into account the peculiarities of thin-film technologies with respect to the commensurability of the lattice constant, mechanical and thermal characteristics of individual films (layers), the n-CdS/p-CdTe heterostructure is also popular [36].

IV. Applied application of CdTe thin films

Calculations of the dependence of the conversion efficiency of an ideal solar cell on the energy width of the forbidden zone show that the spectrum of CdTe perfectly coincides with our Sun, a G2 star with an effective blackbody photosphere surface temperature of 5700 K and a total luminosity of 3.9×1033 erg/s. CdTe is a group II-VI semiconductor compound with a direct optical bandgap, which almost optimally corresponds to the solar spectrum for the conversion of photovoltaic energy [33].

The thickness of the CdTe layer of only a few microns is sufficient for almost complete absorption of photons with energies hν>Eg. Therefore, thin films of cadmium telluride are the predominant layers in solar cells and modules for photoelectric energy conversion [39].

CdTe solar cells grown on ultrathin glass substrates are lightweight and flexible. These characteristics allow you to create devices that do not require high power density, unique form factors and have low manufacturing costs. Ultra-thin glasses can reduce manufacturing costs and increase productivity through lower heat capacity, which can shorten heating and cooling times during processing. This glass can be used to produce solar cells with CdTe in a roll-to-roll process. Flexible CdTe solar panels can be installed as structural-integrated photovoltaic cells or in other configurations not suitable for rigid flat panels. Lightweight and flexible solar panels have significant advantages over traditional technologies for power density applications such as consumer electronics, transportation, military appliances, etc. [33].

The direct band gap and high absorption coefficient of CdTe, which is more than 5×105 /cm, for photons with E>Eg means that one can expect a high quantum yield from the ultraviolet spectral region to the CdTe band gap wavelength, λ≈825 nm. The high absorption coefficient of CdTe for photons with E>Eg leads to 99% absorption of photons with energies above the forbidden zone at a depth of 2 μm from the CdTe surface. The theoretical efficiency of SC, depending on the forbidden zone and the optical absorption coefficient, for CdTe and other selected photovoltaic materials are compared in Fig. 7 [40].

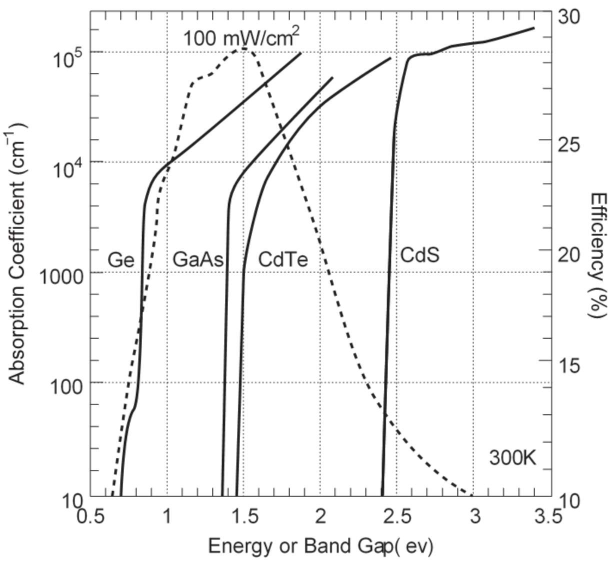


Fig. 7. The theoretical efficiency of the solar cell (dotted line) for spectral radiation AM1.5 depending on the band gap and the absorption coefficient.

Also, CdTe demonstrates stable and highly efficient luminescence in the visible range (500~730 nm) [41]. In addition, its high absorption coefficient in the visible region (105 cm-1) and the fact that its optoelectronic properties are practically independent of synthesis methods make CdTe a potential material for use both in bio-identifiers and in light-emitting devices and photocells [42].

Subsequent successes in increasing the efficiency of solar modules based on CdTe are restrained by the lack of fundamental knowledge about the predominant form and charge state of intrinsic point defects (IPD) in thin films of cadmium telluride, although the defect state in crystals has been investigated in sufficient detail [15,40].

V. Modules based on CdTe

At the beginning of the XXI century. it was possible to reach a compromise acceptable for production between the two main criteria for a solar module - sufficient efficiency of photoelectric conversion and low cost of production [10,43]. This became possible due to the development of a number of relatively simple and properly controlled methods of deposition of thin layers of CdTe and CdS of a large area, which are easy to implement in large-scale production: sublimation in a closed volume, chemical vapor deposition, chemical and electrolytic deposition. The difficulty caused by the discrepancy between the crystal lattice parameters of CdTe and CdS (~5%) is largely overcome by simple temperature treatment of the already fabricated CdTe/CdS structure. It is believed that, in this case, the mutual substitution of S and Te atoms occurs, and a CdTe1−xSx transition layer with a reduced density of states is formed at the CdTe – CdS interface, which can negatively affect the SC efficiency [1, 9].

A PV module based on CdTe usually consists of sequentially deposited layers of semiconductor materials and contacts on a substrate, which simultaneously acts as a mechanical base. The electrical characteristics of the module depend on the properties of an individual cell, their connection scheme, as well as on possible losses due to non-generating zones and resistive losses on contacts. Achieving a highly efficient cell depends on many factors, including various treatments with certain substances, for example, CdCl2, as well as minimizing resistive losses, optical losses due to the use of inexpensive glass and locally defective areas. In fact, the end manufacturer's goal is to obtain large-area CdTe/CdS diodes connected in series with spatially homogeneous physical and electrical properties [37,43].

VI. Industrial systems using cadmium telluride modules

Unlike cells built on chains of crystal cells, thin film SCs CdTe can be bonded in monolithic aggregates, which have proven to be reliable and produce modules that are less sensitive to partial dimming. In monolithic joining, cells on a single substrate or on a large area are isolated and interconnected by carefully marking the deposited layers at different stages of production. Scribing can be achieved mechanically or, as a rule, by laser scribing, in which the stopping point is determined by comparing the absorbing properties of different layers with the corresponding wavelength and power density [44]. A monolithically interconnected module is shown in Fig. 8. Three types of scribing are commonly used: the first separates the front TCO contact (transparent conductive oxide) to identify neighboring cells, the second, through CdS and CdTe, provides an electrical path from the TCO to the back contact of the neighboring cell, and the third insulates the return contact between the cells. Together, these types of scribing introduce a dead zone on the module, which should be as small as possible. The photocurrent generated by each cell flows from one end of the module to the other.

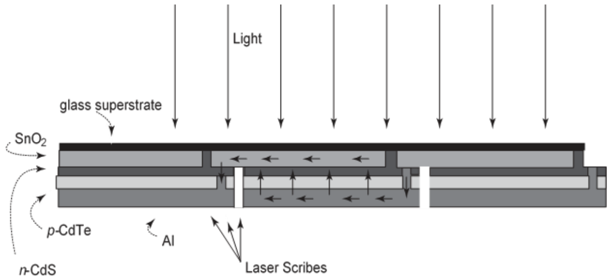


Fig. 8. Diagram of a series-connected built-in CdTe module with three laser scribes.

The module voltage is simply the sum of the voltages from the individual cells connected in series. This monolithic structure and its three laser scribers are very similar to the large number of amorphous silicon and CIGS photovoltaic modules deposited on glass. Significant design analysis of module geometry and side sheet resistances to minimize resistance loss and dead zone was performed for amorphous silicon photoelectric modules and applied to CdTe photoelectric modules [45].

The structure shown in Fig. 8 uses a sheet of glass as a reference on top. The choice of glass is based on cost per watt, optical loss and heat resistance of the glass. For example, the light-generated current in CdTe cells deposited on borosilicate glass is about 2 mA/cm2 higher than that on soda-lime glass, due to the higher optical absorption in soda-lime glass at wavelengths above 600 nm. However, highly transparent glasses such as borosilicate glass or as fused silica require more thorough cleaning and are generally significantly more expensive than soda lime glass commonly used for cells. An additional problem with cheap soda lime glass is that it has a lower softening point, which limits its compatibility with high temperature processing [45]. A compromise is to reduce the iron content in soda-lime glasses to improve their transparency at wavelengths over 600 nm and increase their melting point, but at a lower cost than borosilicate or other highly purified glasses [33, 43].

The commercialization of CdTe photovoltaic modules depends on a constant supply of readily available raw materials, especially cadmium and tellurium. The material requirements for a plant with a production capacity of 1GW/year 100% Cd and Te for the production of an absorbent layer with a thickness of 2 μm is approximately 40 metric tons of cadmium and 60 metric tons of tellurium. Both elements are obtained as by-products in the smelting of ores: cadmium is obtained as a result of refining zinc, copper and lead, while tellurium is mainly obtained as a product of electrolytic refining of copper and degreasing from lead production [46]. Tellurium is a rarer and more expensive component, however, the estimated presence of tellurium is about 1600 metric tons per year [47]. Currently, the cost of 95% of pure cadmium and tellurium are ~$US 12/lb ($US 24000/ton) and ~$US 20/lb ($US 40000/ton), respectively. Thus, the total annual cost of cadmium and tellurium for a 1 GW power plant is ~$US 2.6M, which is less than $US 0.03 per watt. This is significantly less than the price of superstrate glass/TCO air defense per 100km2 required for a 1 GW capacity, which is currently about $US 5.00/m2 [48], or about $US 0.50 per watt.

Current generation CdTe photovoltaic modules typically have an area of 0.72 m2 and an efficiency in excess of 10% with a peak power of about 75 W. Large-scale commercial CdTe modules were manufactured by First Solar, LLC, in Toledo, Ohio, Germany and Malaysia (see Fig. 9), with an annual production of over 300 MW [49]. Three other CdTe module manufacturers have produced CdTe modules on a smaller scale: Matsushita Battery Company in Japan; BP Solar in Fairfield, California; and Antec Solar GmbH, in Germany. Three other companies, Abound Solar (formerly AVA), Calixo/Q-cells and PrimeStar Solar, are actively expanding their capacity and expect their manufacturing capacity to compete with First Solar. Several companies are developing alternatives to the supersonic module or are engaged in "lift-off" and "transfer" technologies. Solexant Inc., in San Jose, California, is developing «Roll-to-Roll» technology [49].

The first solar module used the deposition of CdTe vapor on movable substrates to achieve a high growth rate while maintaining a high substrate temperature. The production line is reported to have a productivity of 2.9 m2 per minute [50]. First Solar's success confirms the concept of high performance, large footprint, reliable manufacturing of the cheapest modules currently on the market. A photograph showing a First Solar module and an array of modules is shown in Fig. 9.

Fig. 9. CdTe module and an array of modules made by First Solar.

Challenges faced by manufacturers of thin film CE CdTe include transferring small area efficiency to module scale, controlling CdTe uniformity during growth, reproducibility, and product life expectancy certification. An example of a key tradeoff is CdS film thickness; thick CdS films improve processing capabilities, but reduce the current generated by the light. With ultra-thin CdS films used to achieve state-of-the-art performance in small-area cells, spatial changes in the microstructure of the CdTe film can affect the diffusion of CdS in CdTe and the resulting compound structure, highlighting the importance of the area-controlled film morphology and the CdCl2 treatment process. To increase the current density in CdTe modules, buffer layers are included in the window layer of the structure, post-application procedures are improved, and built-in diagnostic probing tools are developed [37].

VII. Safe recycling of used modules

Concerns about the toxicity of cadmium and the release of significant amounts of cadmium into the environment are essentially unfounded. It has been shown that the total emission of cadmium in the life cycle, normalized to GW h of generated electrical energy, is much less than in coal production and much less than at nuclear generation or photovoltaic panels based on silicon [51]. The management of cadmium in the workplace consists of combining and adhering to appropriate engineering and chemical hygiene practices [9].

The CdTe compound is chemically stable, biologically inert and does not pose a threat to the environment and human health both in the conditions of production and operation of solar modules [51]. Release of Cd into the atmosphere is possible as soon as the temperature exceeds ∼1050°C, for example, in a fire. However, in a solar module, CdTe is sealed between two glass plates. With this design, the glass will melt at a temperature well below ∼1050°C, CdTe will be in the molten mass, which will prevent the release of Cd and Te into the atmosphere [51].

The installed modules are well protected, which serves both to protect cells from environmental influences and to protect semiconductor materials from mechanical damage. By recycling the modules at the end of their life in the same way as metal products, almost all of the cadmium in a module can be recycled at a cost of about 5 cents/W [51]. Alternatively, the installation of the module under a lease agreement or the use of modular systems as an industrial one can provide complete control over the established distribution of cadmium.

Since the amount of cadmium used in CdTe thin film modules is small enough, the CdTe thin film technology is a minor environmental problem. A CdTe module with an area of 1 m 2, producing a power of about 100 W using a CdTe layer less than 2 μm thick, contains less than 10 g of cadmium, or about the same as a single nickel-cadmium flashlight battery [33].

VIII. The future of solar cells based on cadmium telluride

The CdTe thin film industry is currently well established, but its future depends on the further introduction of creative ideas into the study of material properties of CdTe devices, the characteristics of laboratory-scale devices, and the improvement of photovoltaic modules. However, achieving these goals requires a deeper understanding of the relationship between processing conditions and critical material properties required to ensure high efficiency and long-term reliability [15].

Although the fundamental nature of polycrystalline CdTe is not fully understood, there are reliable ways to create high-performance single-junction thin-film elements that demonstrate the practical value of the empirical approach. In addition, some CdTe film deposition methods give similar device performance due to an appropriate combination of post-deposition processing and back-contact formation [33]. Achieving the 20% efficiency target and transforming it into high module performance depends on identifying and overcoming open circuit voltage limiting mechanisms and, to a lesser extent, duty cycle in current generation cells. The current density in the best thin-film CdTe cells has already reached 90% of its theoretical maximum for AM1.5 illumination and is mainly limited by the well-understood optical loss in the glass/TCO/CdS structure [37, 51].

Despite advances in the development of commercial modules, VOC (open circuit voltage) 850 mV and FF (fill factor) 75% have not changed for several years and do not meet expectations based on the size of the band gap. An increase in the CdTe cell voltage to 200 mV would bring it very close to what is achieved by similar GaAs with a band gap and would increase the efficiency up to 20% [14]. There are two possibilities to increase the voltage by this value [51]. One of them consists in a simultaneous increase in the density of CdTe carriers by three orders of magnitude and their lifetime by a factor of ten. This strategy, however, requires a significant improvement in the quality of the materials, and attempts to increase these parameters have so far been unsuccessful. A second and possibly more realistic possibility is to create a completely depleted n-i-p – structure with a carrier density and lifetime comparable to those achieved at present, but add a backward electron reflector layer between the absorber and the back contact. There should be a sufficiently wide exclusion zone of an appropriate alloy such as Cd1−xZnxTe or Cd1−xMgxTe. The caveat is that its deposition should proceed continuously with a CdTe absorber and not cause significant interfacial states [52].

The second area that is available for future studies of CdTe cells is the possibility of creating much thinner absorbent layers. Advantages in terms of material use and deposition time would be obvious, but the most efficient use of an electronic back-reflector is also possible. Work at the University of Toledo made it possible to achieve 10% efficiency for a CdTe absorber 0.5 μm thick [53]. In part, this success was a result of adjusting the CdTe treatment length to be proportional to the thickness of the CdTe layer.

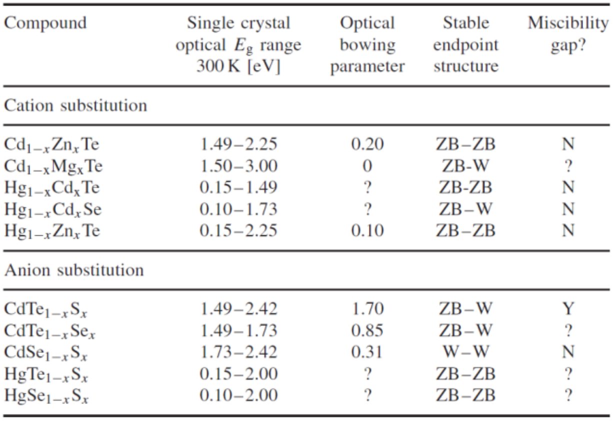
In addition to being a good candidate for use in single-junction photovoltaic devices, CdTe can be fused with other II-VI compounds to alter its bandgap and enable the fabrication of multi-junction thin-film elements [54]. Multi-junction cell structures using CdTe-based broadband cells in monolithic structures must take into account the cell design, processing temperature, and chemical stability. Materials based on alloys between CdTe and other compounds of group II-VI, in principle, will allow the design of a wide range of optoelectronic properties in devices. These semiconductor compounds provide the basis for the development of materials obtained by doping various compounds in pseudo-binary configurations. For photovoltaic heterojunction devices, semiconductors using Cd, Zn, Hg cations and S, Se, Te anions exhibit a wide band gap, which makes it possible to assess their potential for use in optimized device designs by adapting material properties (Table 1). The typically high optical absorption coefficients, ~105 cm, and direct optical band gaps of many II-VI semiconductors make them suitable for use in thin-film photovoltaic devices. For the development of two-junction structures, the upper cells with a band gap of about 1.7 eV and the lower cells of about 1.1 eV are preferable [55]. Another possibility is to reduce the thickness of the CdTe to achieve current matching.

Thin film photovoltaic cells based on CdTe are also suitable for devices designed to convert energy outside the earth's atmosphere, including energy production in space, infrared detectors and γ-ray detectors. Using the current-voltage characteristics of modern devices, it is possible to determine the operation of AM0 at 60◦C by correcting the temperature dependence of the bandgap and differences in the lighting spectrum. State-of-the-art cells with 16.5% AM1.5 efficiency at 25◦C translate to 13.9% AM0 efficiency at 60◦C, and typical cells having 12% AM1.5 efficiency at 25◦C translate to 10% AM0 efficiency at 60◦C. For cells on 0.05-mm-thick polyimide substrate at AM0 conditions, the 12% CdTe cells should yield a power-to-weight ratio of 1500W/kg [55]. CdTe research and development for space applications, in which AM0 power-to-weight ratio greater than 1000W/kg is desired, has followed three approaches: 1) 6–7% AM1.5 deposition in the substrate configuration on lightweight flexible substrates [56]; 2) 11% AM1.5 efficiency for transfer of completed superstrate cells from rigid superstrates to lightweight flexible substrates [57];

3) 11% efficiency for direct superstrate deposition onto 100 µm thick glass foils [58]. Encouraging results of CdTe/CdS cell stability were obtained under 1 MeV electron bombardment at fluences of 10^{14}–10^{16}/cm^2 [59].

Table 1.

Properties of pseudobinary II – VI alloys suitable for absorber layers.



Compound	Single crystal optical E_g range 300 K [eV]	Optical bowing parameter	Stable endpoint structure	Miscibility gap?
Cation substitution				
$Cd_{1-x}Zn_xTe$	1.49–2.25	0.20	ZB–ZB	N
$Cd_{1-x}Mg_xTe$	1.50–3.00	0	ZB-W	?
$Hg_{1-x}Cd_xTe$	0.15–1.49	?	ZB-ZB	N
$Hg_{1-x}Cd_xSe$	0.10–1.73	?	ZB–W	N
$Hg_{1-x}Zn_xTe$	0.15–2.25	0.10	ZB–ZB	N
Anion substitution				
$CdTe_{1-x}S_x$	1.49–2.42	1.70	ZB–W	Y
$CdTe_{1-x}Se_x$	1.49–1.73	0.85	ZB–W	?
$CdSe_{1-x}S_x$	1.73–2.42	0.31	W–W	N
$HgTe_{1-x}S_x$	0.15–2.00	?	ZB–ZB	?
$HgSe_{1-x}S_x$	0.10–2.00	?	ZB–ZB	?

Conclusions

Thin film cadmium telluride (CdTe) solar cells are the backbone of a rapidly evolving technology with a large commercial impact on solar power generation. As the leading technology for the supply of thin film modules, CdTe thin film modules have demonstrated long-term stability, competitiveness, and continue to attract capital expenditures on a production scale.

Cells (modules) level research has evolved into a large and astonishingly fast growing CdTe industry over the past three decades. It is reasonable to expect that rapid growth will continue and production costs will be further reduced. However, as with all photovoltaic technologies, the ultimate success of the CdTe industry will depend on further improvements in thin films, device structures, and large-scale manufacturing processes.

The main advantages of thin-film photovoltaic converters based on CdTe in comparison with silicon crystalline photovoltaic converters are: their significantly lower specific cost; significantly lower material consumption; using fewer technological operations; the ability to manufacture devices for large areas; the ability to receive weak and diffused sunlight.

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Solar cells based on CdTe thin films

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Сонячні елементи на основі тонких плівок CdTe

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Проведено аналіз застосування в енергетиці напівпровідникових сонячних елементів на основі тонкоплівкового телуриду кадмію (CdTe). Показано, що переваги тонкоплівкової технології й самого CdTe, як прямозонного напівпровідника, відкривають перспективу широкомасштабного виробництва конкурентоспроможних CdTe сонячних модулів. Обговорено фізико-технічні проблеми збільшення коефіцієнта корисної дії гетероструктурних сонячних елементів CdS/CdTe, який при масовому виробництві значно поступається теоретично можливому значенню. Розглядається стан тонкоплівкових сонячних елементів на основі CdTe, які роблять CdTe відповідним матеріалом для наземного фотоелектричного перетворення сонячної енергії, історичний розвиток сполуки CdTe, прикладне застосування тонких плівок CdTe, основні методи та стратегії виготовлення приладів, аналіз роботи приладів, а також фундаментальні технічні проблеми, пов'язані з майбутнім розвитком тонкоплівкових модулів на основі кадмій телуриду.

Ключові слова: тонкі плівки, сонячні елементи, CdTe, фотоелектричні елементи, модулі.