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Growth and Characterization of Cadmium Telluride and Its Societal, Economic, and Environmental Impact

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Abstract

This paper examines the growth, characterization, and impact of Cadmium Telluride (CdTe) in solar technology applications. The research investigates CdTe's potential as a semiconductor material for solar cells, comparing it with conventional silicon-based cells and other competing technologies. The study analyzes various aspects including efficiency improvements, environmental safety considerations, material abundance, temperature response characteristics, and economic viability. The research also explores CdTe's applications beyond solar technology, particularly in medical imaging and radiation detection. The findings indicate that while CdTe faces challenges in terms of material abundance and manufacturing scale, its cost-effectiveness, improved efficiency, and versatile applications make it a promising material for future solar technology development.

Keywords: Cadmium Telluride (CdTe), Cadmium Zinc Telluride (CdZnTe), Cost effectiveness, Crystal growth, Environmental impact, Gallium Arsenide (GaAs), Indium Gallium Phosphide (InGaP), Manufacturing scalability, Medical applications, Open Circuit Voltage (VOC), Photovoltaics (PV), Radiation detection, Renewable energy, Semiconductors, Short Circuit Current Density (JSC), Solar cells, Solar efficiency, Temperature response, Thin-film solar cells

I. Introduction

A semiconductor is a material that partly conducts electricity. Its electrical conductivity is between that of a conductor and an insulator[1]. Semiconductors and their usage for obtaining energy since their development after the mid-20th century has made an impact in the field of non-conventional energy sources. Semiconductor applications range from solar energy conversion to computational systems to nuclear radiation detection[2]. Semiconductors have been used as solar cells since their first breakthrough with selenium in the late 19th century and silicon in the mid-20th century where it was used to power electrical equipment with an efficiency of 6%[3]. A device that converts sunlight into electricity is called a solar cell[4]. Solar energy is one of the cleanest and non-polluting forms of energy being used as it avoids the emission of greenhouse gases[5].

Recent advancements in technology and the way in which we grow and characterize these materials has enabled us to increase efficiency of these semiconductors[3]. Cadmium Telluride (CdTe) has led to better results in obtaining more energy cost effectively[6]. Apart from the economic advantages, there are some environmental aspects and drawbacks[7,8] which will be discussed further in this paper. Cadmium Zinc Telluride (CdZnTe or CZT) is also very advantageous in the field of nuclear radiation detection[9], which is one of the other subtopics for this paper. To completely understand the advantages and usability of CdTe as a solar material, it is essential to first look at the importance of using solar energy itself.

Why solar?

Solar cells and solar energy has an ongoing demand from this generation[10]. Companies like SolarCity are making huge factories that produce highly efficient solar panels in a very cost effective manner[11]. Since the commercialization of solar cells and their increased usage to obtain energy, the cost per panel has reduced from over a hundred dollars to about half a dollar. Simultaneously, the energy generated by solar panels and their efficiencies have risen in an exponential manner. This shows that the future of solar energy is promising and it is important to continue research to improve the efficiencies and reduce costs of semiconductor materials.

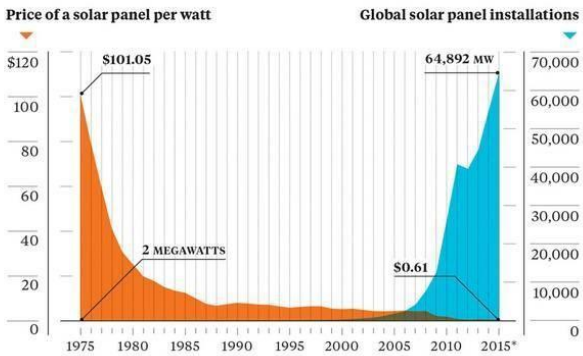

Fig. 1. Solar energy trends and projections[11]

A. Solar vs. non-renewable sources

Manufacturing processes for fossil fuels are ten times cheaper than manufacturing solar cells as they have been being used for a longer period commercially[12]. As compared to other non- renewable energy sources, it is not very straightforward to compare the solar energy costs because they differ in manufacturing processes. Although the amount of pollution caused by fossil fuels is harmful for the environment, it is cheaper to obtain and use fossil fuels as compared to manufacturing solar energy conversion devices. As solar technology has been researched extensively since the past century, it has gained a considerable economic initiative that has made its products cheaper. It is beneficial to use energy sources that are cheap as well as less damaging to the environment. For this, solar energy is a perfect fit.

B. Solar vs. other renewable sources

Some other recently developed and competitive renewable energy sources are wind, hydro-electric (gravitational potential - dams), nuclear, and geothermal. Nuclear energy has safety risks that can be hazardous on a very large scale[13,14]. Wind energy has a narrow regional limit depending on areas which have good enough air flow and cost of transportation to high demand areas such as cities[15]. Geothermal energy has a similar limitation and is restricted to specific resource rich locations[16,17]. Solar energy surpasses these other sources as it has a wider regional limitation, has closer to none safety issues. However, alternative sources of energy are fundamentally different and each source of energy has its own advantages and disadvantages. A proactive outlook toward research enables the best fit of energy to use according to specific cases[18].

Power Plant Type	Cost $/kW-hr
Coal	$0.095-0.15
Natural Gas	$0.07-0.14
Nuclear	$0.095
Wind	$0.07-0.20
Solar PV	$0.125
Solar Thermal	$0.24
Geothermal	$0.05
Biomass	$0.10
Hydro	$0.08

Fig. 2. Comparison of different energy sources[19]

II. Why CdTe?

The development of CdTe solar cells was initially motivated by their potential space application in communication satellites. In 1963, the first thin film solar cell of the type n-CdTe/p-Cu2Te was demonstrated by a General Electric Research Laboratory[20]. CdTe is the second most common material used to generate electricity via solar cells contributing about 5% of the world market[21]. CdTe has a variety of other applications when used in radiation detection (CdZnTe). One of the main barriers that CdTe must cross to achieve a higher demand in the field of solar energy generation is overcome its rival technologies which are some of the more widely used and more efficient semiconductor materials like Silicon[22].

Silicon, in its crystalline form dominates the world market and represents about 90% of the total energy generated via solar cells[23]. A few advantages that CdTe has over the conventional silicon solar cells is that the process of manufacturing CdTe is simpler as well as cost effective as compared to Silicon[24]. Another very big advantage of CdTe is its versatility of wavelength absorption which allows the material to absorb electromagnetic radiation with shorter wavelengths than silicon cells[25]. CdTe, however, has certain disadvantages compared to Silicon, such as its efficiency, safety, the lack of abundance and manufacturing feasibility on a large scale[24]. If CdTe is to become a material with a larger footprint over the solar technology market, it must overcome these disadvantages through research and development.

A. Efficiency: research for VOC improvements

CdTe studies have shown to improve the short circuit current density (JSC)[26]. JSC is related to the short circuit current (ISC), which is defined as the current passing through the solar cell when the applied voltage across it is zero. This depends upon several factors like the area of the cell, the wavelength of incident light (sunlight), number of photons as well as the material being used itself[27]. To remove the factor of area and make this a more common term for similar materials, the term short circuit current density (JSC) is used instead of the current itself (ISC). The JSC for a circuit depends upon generation rate of the given material as well as the electron diffusion rate and proton diffusion rate[28].

The recent research on CdTe has led to an increased efficiency of the open circuit current density which has reached values of silicon crystalline samples[29]. Researchers have started to work on other aspects of this material like open circuit voltage (VOC). VOC - the maximum voltage obtained in a circuit when the current through the circuit is zero, depends on the saturation current of the solar cell and the light-generated current[30]. Often, the voltage corresponds to the forward bias of a solar cell which shows very little current passage of current until the injection barrier is reached[31]. VOC can be limited by interface and grain boundary defects[26]. Research in crystal growth and post processing these crystal samples will lead to incrementing the solar cell efficiencies.

B. Efficiency: comparison with other solar technologies

The major competitors for CdTe include Silicon (mono-crystalline and polycrystalline) and other cells that have higher efficiencies like Gallium Arsenide (GaAs). As seen in the table below, as of 2015, only Silicon, CdTe, Indium Phosphide (InP) and Gallium Arsenide (GaAs) are the materials with efficiencies above 20%. Some cells like Indium Gallium Phosphide (InGaP) have efficiencies above 35% which shows that competitive nature of newly discovered materials.

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification[a]	Efficiency (%)	Area[b] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre[c] (date)	Description
Silicon							
Si (crystalline)	25.6 ± 0.5	143.7 (da)	0.740	41.8[d]	82.7	AIST (2/14)	Panasonic HIT, rear junction [25]
Si (multicrystalline)	**20.8 ± 0.6**	**243.9 (ap)**	**0.6626**	**39.03**	**80.3**	**FhG-ISE (11/14)[e]**	**Trina Solar [4]**
Si (thin transfer submodule)	**21.2 ± 0.4**	**239.7 (ap)**	**0.687[f]**	**38.50[e,f]**	**80.3**	**NREL (4/14)**	**Solexel (35 µm thick) [5,26]**
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[f]	29.7[f]	72.1	FhG-ISE (8/07)[g]	CSG Solar (<2 µm on glass; 20 cells) [27]
III–V cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[h]	86.5	NREL (5/12)	Alta Devices [28]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[g]	RTI, Ge substrate [29]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[g]	Spire, epitaxial [30]
Thin film chalcogenide							
CIGS (cell)	20.5 ± 0.6	0.9882 (ap)	0.752	35.3[d]	77.2	NREL (3/14)	Solibro, on glass [31]
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[f]	35.29[f,i]	75.6	FhG-ISE (9/13)	Solibro, 4 serial cells [32]
CdTe (cell)	**21.0 ± 0.4**	**1.0623 (ap)**	**0.8759**	**30.25[e]**	**79.4**	**Newport (8/14)**	**First Solar, on glass [33]**
Amorphous/microcrystalline Si							
Si (amorphous)	**10.2 ± 0.3[k]**	**1.001 (da)**	**0.896**	**16.36[e]**	**69.8**	**AIST (7/14)**	**AIST [6]**
Si (microcrystalline)	**11.4 ± 0.3[l]**	**1.046 (da)**	**0.535**	**29.07[e]**	**73.1**	**AIST (7/14)**	**AIST [7]**
Dye sensitised							
Dye	11.9 ± 0.4[m]	1.005 (da)	0.744	22.47[n]	71.2	AIST (9/12)	Sharp [34]
Dye (minimodule)	**10.0 ± 0.4[m]**	**24.19 (da)**	**0.718**	**20.46[e]**	**67.7**	**AIST (6/14)**	**Fujikura/Tokyo U. Science [9,10]**
Dye (submodule)	8.8 ± 0.3[m]	398.8 (da)	0.697[f]	18.42[f]	68.7	AIST (9/12)	Sharp, 26 serial cells [35]
Organic							
Organic thin-film	**11.0 ± 0.3[o]**	**0.993 (da)**	**0.793**	**19.40[e]**	**71.4**	**AIST (9/14)**	**Toshiba [11]**
Organic (minimodule)	**9.5 ± 0.3[o]**	**25.05 (da)**	**0.789[f]**	**17.01[e,f]**	**70.9**	**AIST (8/14)**	**Toshiba (4 series cells) [11]**
Multijunction devices							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[j]	86.7	AIST (2/13)	Sharp [36]
a-Si/nc-Si/nc-Si (thin-film)	13.4 ± 0.4[p]	1.006 (ap)	1.963	9.52[n]	71.9	NREL (7/12)	LG Electronics [37]
a-Si/nc-Si (thin-film cell)	**12.7 ± 0.4%[k]**	**1.000(da)**	**1.342**	**13.45[e]**	**70.2**	**AIST (10/14)**	**AIST [8]**

Fig. 3. Comparison of solar cell efficiencies[29]

C. Safety: environmental effects/hazards

Cadmium is a byproduct of the zinc ores found and is mostly found along in small quantities with mining of such other metallic ores as opposed to finding cadmium as one of the primary element. As cadmium is a risk to human health, it is important to handle it wisely. Excess cadmium is usually disposed of using procedures that cause minimal damage to the environment. This ensures that no unnecessary cadmium is causing environmental hazards. Short term effects of exposure to pure cadmium include lung illnesses like pulmonary irritation whereas long term and prolonged exposure to cadmium and only specific compounds that contain it have been seen to have detrimental effects on the kidneys as well which might lead to diseases in the peripheral organs[7].

Noted that these effects are commonly seen in animals and there has been no evidence to support such a conclusion for human bodies. Some studies on animals have reported though, the long-term effects of inhalation of cadmium causing some lung problems. It has been stated that "EPA has classified cadmium as a Group B1 which is a probable human carcinogen"[7]. CdTe thin films utilize the cadmium very effectively limiting the hazardous waste generation. CdTe PV modules use less cadmium than conventional Ni-Cad batteries[33]. A kilowatt of CdTe PV module has less cadmium than 10 Ni- Cad batteries. It can be concluded that using cadmium in CdTe PV is a better alternative to its counterpart uses. In a lab test for monitoring cadmium concentrations at a lab (ETRL 242) in WSU, it was found out that during the most crucial processes for manufacturing solar cells, that is, after cadmium telluride is obtained and handled for further processing, the volume of the 1040-liter lab contained less than 2 micrograms per meter cube, which was below what the device could measure[34]. CdTe is seen to be a safer compound than cadmium in its elemental form and does not pose an immediate risk to human health.

D. Abundance: Cadmium & Tellurium

Silicon is the second most abundant element in the earth's crust at 27.7% by weight[35]. This is one of the primary reasons it is used for mass production of solar cells[36]. The same however cannot be said for cadmium and tellurium. Cadmium is primarily found in zinc by-products that are mined and are in abundance. This is somewhat of an advantage for CdTe as it increases its chances of mass reproducibility[25]. Tellurium, however, is a rare metal which is a probable cause for the hindrance of CdTe production. Some sources do state that there is an unexplored abundance of Tellurium in sea beds. Manganese nodules have been said to contain an abundance of tellurium especially on the ocean floors in a research conducted in 1964. The Pacific Ocean floors were shown to have almost 125 ppm of tellurium in these nodules[37]. Although these sources state a probability, they are far too outdated to be considered for tellurium abundance today.

E. Advantages: Temperature response

Temperature plays an important role in solar cell power production rate. The power generated by a solar cell is inversely proportional to temperature, which means that most solar cells do not operate as efficiently at higher temperatures as they would do at lower temperatures[38].

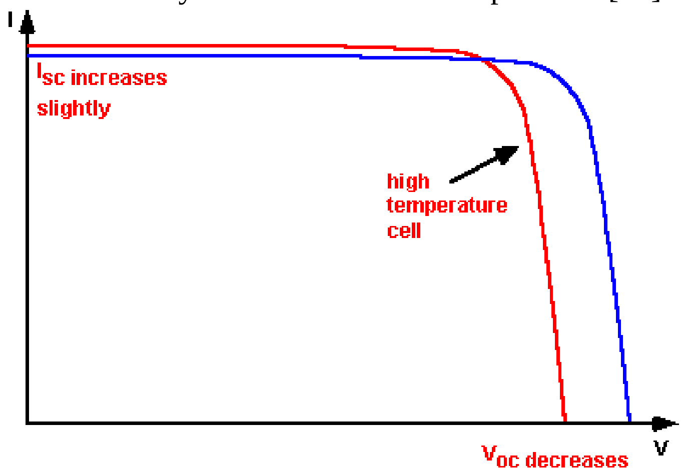

Fig. 4. Temperature response of solar cells[39]

First Solar's CdTe thin film model has been proved to lose less efficiency in higher temperatures, providing higher usability in desert, arid and hotter temperature regions[40]. Silicon solar cells are best when operated at 25°C whereas CdTe thin film solar cells can be operated at temperatures as high as 50°C to 60°C[41].

F. Advantages: Spectroscopy

CdTe and CdZnTe are wide band gap semiconductors, which is one of the primary reasons they have attracted the interest from x-ray equipment companies and gamma ray detection facilities. Due to the larger band gap the noise generated in CdTe modules is lower than conventional semiconductors providing very clear and high quality images. Conventional high performance spectrometers like silicon and germanium are also used in industry, but are not as efficient as CdTe and CdZnTe detectors[42]. Italy - a leading country in this field, is working on the scientific development of such materials so that they can be largely used in the fields ranging from astrophysics to medical applications[9]. This shows that the scope for CdTe encompasses multiple scientific applications in today's industry apart from its solar technology applications.

Advantages: Medical applications

Sensors made from CdTe are widely used today in fields such as nuclear radiation and medicine. Early on these sensory models were used only upon animals such as tests pertaining dental pathology in dogs, however they have progressed to surgeries with cardiovascular prosthetics and orthopedics. Some medical imaging is done with the help of CdTe gamma sensors[41]. This depicts the breadth of potential for CdTe and its variety of applications in the medical field. X-Ray detectors made using CdTe are used widely today. Elden Imaging mentions the advantages of CdTe such as it requires significantly low radiation to operate[43]. CdTe has a large scope in medical sector and has a bright future with such technologies[41]. The usage of CdTe in medical applications seems to be increasing for the better.

G. Advantages: Economics and future opportunities

CdTe, especially thin film solar cells are a low cost- high yield replacement for mono-crystalline silicon[44]. As stated earlier, CdTe is now on par in terms of output current and open circuit voltage with polycrystalline silicon. About 15 years ago, CdTe solar cells efficiencies were below 15% in terms of energy conversion. As of now, these efficiencies have reached more than 20%[44]. Today's solar power generators contribute and create more than 13GW of power. This is 13 times of what was predicted for the year 2020. A little over 2 million Americans work in solar technology sectors - more than twice of those in 2010. This number is said to exceed 3 million by the end of this decade[44]. As the solar industry grows, CdTe applications in the industry will naturally grow as well. CdTe has transcended its expectations compared to its counterpart materials like silicon. CdTe solar cells costs as low as 50 cents per watt of electricity it provides which is significant as compared to the efficiency and costs of other materials[40,45,46].

Conclusion

Solar energy has been researched extensively since the 19th century. However, breakthroughs that this field has made have not yet surpassed some other conventional sources in terms of economics and energy efficiencies. CdTe is one of the branches of solar technology that has a potential to get past these current standards which makes it essential to keep analyzing it. Cadmium and tellurium are not the most abundant elements on this planet, which hinders the CdTe reproducibility on a larger scale. It has been theorized that the cadmium in CdTe is far less harmful and has diminishing damages to the environment. This makes it arguably smarter to use cadmium for solar photovoltaics (PV) and other purposes to keep it from the environmental damages rather than its disposal alternatives. Recent research in improving CdTe has brought it to par with polycrystalline silicon[26]. If such advancements continue with constant research, CdTe can be said to have a potential in becoming a market leading solar cell material. It is up to the future research that might help this material get to a higher standing in the world of semiconductors, especially in solar photovoltaics.

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