Smart and Functional Materials in Technological Advancement of Solar Photovoltaic's

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ABSTRACT

Increased power production from solar energy is dependent on more research efforts aimed at developing and fine tuning new ways to make solar power increasingly competitive with traditional energy sources. Pure silicon is today the most important material in solar cell panels. The fabrication of solar photovoltaic with enhanced efficiency and affordable cost has been the great challenge to Technocrats and Scientists in sharing the future energy needs. The use of smart and functional materials can play an important role in this direction. The present paper analyze the recent advances in Photovoltaic technology in reference to material characterization, multi-junction solar cells and concentrating photovoltaic technology for maximum utilization of solar energy.

Keywords: Photovoltaic, solar energy, Functional materials, efficiency.

1. INTRODUCTION

Science and technology in the 21st century will rely heavily on the development of new materials that are expected to respond to the environmental changes and manifest their own functions according to the optimum conditions. The development of smart and functional materials will undoubtedly be an essential task in many fields of science and technology such as information science, microelectronics, computer science, medical treatment, life science, energy, transportation, safety engineering and military technologies. Materials development in the future, therefore, should be directed toward creation of hyper-functional materials which surpass even biological organ in some aspects. The current materials research is to develop various pathways that will lead the modern technology toward the smart and functional systems. Functional materials cover a wide range of organic and inorganic and oxide functional materials such as the ferroelectric $BaTiO_3$, the magnetic field sensor of La1-xCaxMnO_3, surface acoustic wave sensor of $LiNbO_3$, liquid petroleum gas sensor of Pd-doped SnO_2, semiconductor light detectors (CdS, CdTe), high temperature piezoelectric Ta_2O_5, the electric voltage induced reversible coloring of WO_3, and high temperature superconductors etc. In recent years, techniques for epitaxial crystal growth have made

it possible to grow oxides and metal thin films on silicon substrates, and this is the first step to integrate functional materials with the logic system. A key requirement in preparations of materials is to control the structural and compositional evolution for achieving superior properties.

With the continual increase in demand for global energy, scientists across the world are working to find a way to transition from fossil fuels to renewable energy sources that are more efficient and environmentally friendly. The sun delivers more energy to the Earth's surface in one hour than the entire world uses in one year, and realizing the full potential of solar power will require finding effective, inexpensive ways to utilize this vast energy source.

The development of the thin-film polycrystalline CdTe/CdS solar cell is driven by the possibility of producing photovoltaic modules more cheaply than ever before. As CdTe has a near optimal band gap (1.45 eV) for solar absorption, may be doped n- or p-type and has high optical absorption above the band gap, it was recognized early on as a good solar cell absorber layer[1]. However, homo-junction devices are impractical due to unacceptably high surface recombination loss. To avoid this the p-CdTe/n-CdS/TCO/glass super substrate configuration was developed [2]. The n-CdS forms one side of the electrical junction and acts as a window layer. Organic-lead halide perovskite solar cells have recently emerged as one of the most promising candidates for the next generation of solar cells, with record efficiencies increasing from just a few percent to more than 15 percent in just a few years. However, these solar cells have exclusively used organic hole conducting polymers, which are one of the components responsible for conducting electricity in the cells. These organic polymers are generally expensive because they are synthetically produced and must be pure for photovoltaic applications. Use of inorganic materials for perovskite solar cells, which provides a lower-cost alternative to the organic polymers, has recently identified [3]. A new technology called "screening-engineered field-effect photovoltaic's," or SFPV, has been developed which enables low-cost, high efficiency solar cells to be made from virtually any semiconductor material[4].

Theoretical Consideration

The total emitted spectral Electroluminescence (EL) photon flux is given by the reciprocity relation,

$$\phi_{\mathrm{EL}} = \mathrm{EQE}\cdot\phi_{\mathrm{BB}}\cdot\left[\exp\left(\frac{qV}{k_bT}\right) - 1\right] \qquad (1)$$

Where φ_{BB} is the black body photon flux, V is the internal voltage applied to the pn-junction, q is the electron charge, k_b is the Boltzmann constant, and T is the temperature of the cell. Thus, the

spectral EL is connected to the (External Quantum Efficiency) EQE via the voltages of the sub-cells.

This relationship enables us to extract the internal open-circuit voltage V_{OC}, which is generated across each sub-cell when operating under an injection carrier density equivalent to the photo-generated carrier density under illumination.

The high-energy luminescence is emitted from Boltzmann distributed carriers,

$$N \sim \exp\left(\frac{\Delta E}{k_b T}\right) \tag{2}$$

where N is the number of occupied states, and ΔE is the difference in carrier energy with respect to the Fermi energy of the semiconductor. Hence, both the exponentially rising and the falling edge of the luminescence can be identified in the reciprocity relation: the low-energy slope by the EQE and the high-energy slope by the black body photon flux.

It should be noted that the calculation of the voltage with Eq. (1) necessitates scaling by one remaining unknown constant in the reciprocity relation, which basically is the absolute photonic irradiance of the cell. Consequently, the sum of the derived sub-cell voltages features a constant offset with regard to the actual voltage. This offset δV, which remains constant under variation of current density, is determined from an automated comparison with a measured *I-V* curve of the sample under known illumination condition:

$$\delta V = \frac{1}{3}\left[\sum_{i=1}^{3} V_i^*\left(J_{\mathrm{EL},i} = J_{\mathrm{Photo},i}\right) - V_{\mathrm{OC,3J}}\right] \tag{3}$$

where is the calculated sub-cell voltage for a current density $J_{EL,}i$ equal to the current density $J_{Photo,}i$ generated under illumination.

Using above relations, it is possible to extract the spectral EL of monolithically stacked multi-junction solar cells, the *I–V* characteristics of all contributing sub-cells within this stack.

2. THIN-FILM POLYCRYSTALLINE CDTE/CDS SOLAR CELL

High optical absorption by a material is directly related to its conversion efficiency. CdTe with n or p type doping has high optical absorption above band gap and has been considered a suitable material for solar cell. A homojunction solar cell using CdTe are impractical since most absorption

of the solar spectrum occurs within 1-2 um of the CdTe surface and this makes the surface recombination loss unacceptably high. To avoid this the p-CdTe/n-CdS/TCO/glass "superstrate" configuration shown in Fig. 1 was developed [2]. The n-CdS (E_g =2.42 eV) forms one side of the electrical junction and acts as a window layer. Fig. 2 shows a calculated carrier generation profile in a CdTe/CdS structure resulting from illumination by the AM1.5 solar spectrum. Carriers generated in the CdTe are likely to be collected and contribute to the photocurrent, while those in the CdS are lost. Thin CdS, 50-100 nm, is therefore preferred to allow above-gap optical transmission. The CdTe need only be 1-2 um thick, but may be thicker to ensure homogeneity. Cells fabricated in this materials system are remarkably tolerant to the deposition methods used [5]. However, the majority of cells, and all those with notable conversion efficiencies, were subjected to a post-growth treatment of the CdTe.

Variations of the process are many but this so called ªactivationº or "type conversion" process usually involves annealing in the presence of $CdCl_2$. This results in an order of magnitude increase in the conversion efficiency and improvements in the open circuit voltage and short circuit current. The maximum efficiencies reported to date are 15.8% in 1993 and 16.0% in 1998[6]: advances have slowed in recent years. Study of cells fabricated with the $CdCl_2$ methods have revealed a wealth of detail. It is considered that the $CdCl_2$ treatment effects the conversion of the CdTe from n- to p-type , lowers series resistance and is accompanied by a change in current transport mechanism from tunneling/interface recombination to recombination in the depletion region[7]. Although the maximum efficiency of the cells has been estimated to be over 29% [8], the best reported to date fall some way short of that.

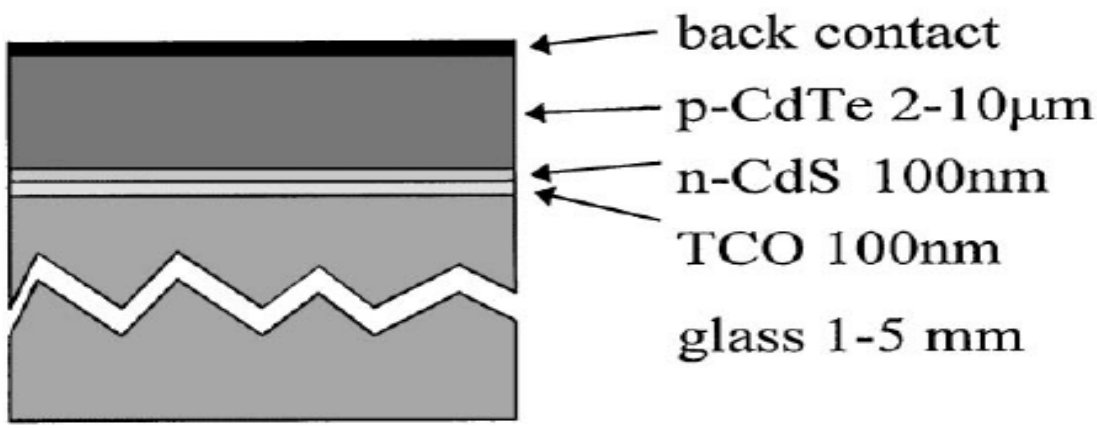

Fig. 1 The superstrate configuration used for CdTe/CdS heterojunction solar cells.

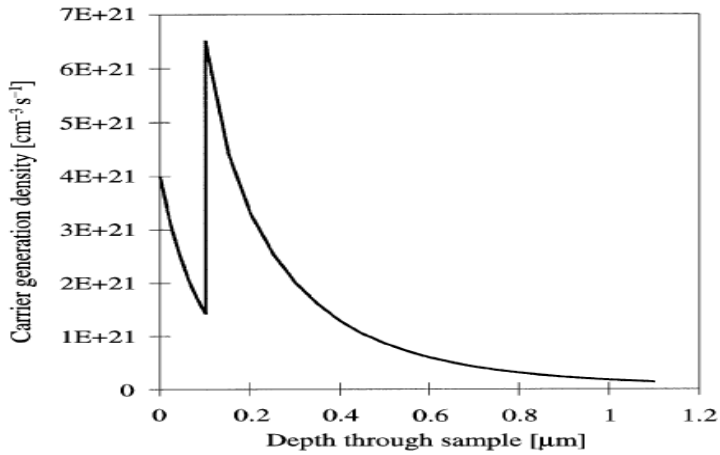

Fig. 2 Stimulated profile of carriers generated in a CdTe/CdS heterostructure by AM 1.5 Sunlight.

The function of the transparent conducting oxide (TCO) coated glass substrate is to provide a highly transparent and conductive contact to the CdS window layer. Both SnO_2 and In_2O_3-SnO_2 (ITO) have been used successfully, but the latter is sometimes avoided to rule out diffusion of In.

The n-CdS window layer is an essential component of the cell as it is highly conductive (n=10^{16} cm^{-3}), thin to allow high transmission (50-100 nm) and uniform to avoid short circuit effects. Techniques used to deposit it include physical vapor deposition (PVD) and close space sublimation [9]. The current-voltage characteristics of CdTe cell with different Schottky barrier heights is given in table 2.

Table 2: Current- voltage characteristics of a CdTe cell with different Schottky Barrier heights.

Barrier height(eV)	V_{oc} (eV)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
0.1	916	28.36	75.91	19.72
0.2	916	28.35	75.76	19.67
0.4	830	28.23	69.80	16.36

3. DESIGN PRINCIPLE OF MULTI-JUNCTION SOLAR CELL

The InGaAs/GaAsP quantum wells in general use are composed of InGaAs well layers, GaAsP barrier layers, with GaAs interlayer between them. Here, the GaAs interlayer are optional, and the band for a single well has a stepped structure for relatively thick interlayer, whereas it has a

rectangular line-up in the absence of inter-layers. The proposed design principle can be summarized into the following three points:

- InGaAs wells should be made thinner and deeper for a given band-gap in order to achieve both a higher absorption coefficient for 1e-1hh transitions, and to reduce the compressive strain accumulation.
- GaAs inter-layers with thicknesses of just a few nanometers can effectively extend the absorption edge to longer wavelengths without introducing compressive strain, and can also suppress lattice relaxation during growth.
- GaAsP barriers should be thinner than 3 nm to facilitate tunneling transport, and their phosphorus content should be minimized while avoiding detrimental lattice relaxation.

Multi-junction Solar Cell has been proved to be highly promising for utilization of solar power. The InGaAs/GaAsP strain-compensated multiple quantum wells (MQWs) are promising narrow-band gap materials that can be pseudo-lattice-matched to Ge or GaAs[10]. By alternately growing InGaAs absorber layers with compressive strain and GaAsP strain-balancing layers with tensile strain on nanometer-scale, a large number of MQWs can be epitaxially grown on GaAs. The targeted band gap of 1.20–1.25 eV, including quantum confinement effects, can be obtained by adjusting the composition and the thickness of each layer. Incorporation of such MQWs or super-lattice structures has been proposed not only for current-matched tandem solar cells but also for high-efficiency single-junction solar cells[11].

Although the potential of InGaAs/GaAsP MQW solar cells has been experimentally demonstrated in terms of improvement in device performance, understanding of physics in quantum structures, and implementation of MQW into tandem devices [12], challenges still exist from the viewpoints of both crystal growth and structural design toward practical application. The growth challenge is primarily attributed to the difficulty in controlling the strain balance, especially in crystals with high indium and phosphorus contents, where lattice relaxation gradually occurs during formation of the hetero-interface between the two oppositely strained layers. This results in severe crystal degradation as a large number of layers are grown, even though, in theory, MQWs can be epitaxially stacked infinitely if the compressive and tensile strain completely balance each other out [13].

The difficulty in achieving a suitable structural design is due to the trade-off between light absorption and carrier collection, which is a general challenge not only for InGaAs/GaAsP MQWs but also other material systems[14]. For complete absorption of photons with energies above the effective band gap of the MQW, the excitations involving ground-state electrons and holes, that is, 1e-1h transitions, must be sufficiently large. This necessity, however, requires a large number of wells to be stacked, which imposes more difficulty in extracting carriers through the MQW regions

because of the weakened electric field in the thickened i-region. To overcome this transport problem, various strategies based on MQW structural design have been proposed. These include using a superlattice with ultra-thin barriers to facilitate tunneling, limiting the number of thick wells to suppress non-radiative recombination, using step-designed MQWs for efficient thermionic carrier escape, and performing quick carrier extraction from deep wells via resonant-tunneling-assisted processes[15]. A comparison of Multi-junction solar technology with other technology is given in table 3.

Table 3 Comparison of Multi-junction solar technology with other technology[16].

Technology	η (%)	V_{OC} (V)	I_{SC} (A)	W/m²	t (μm)
u c-Si	24.7	0.5	0.8	63	100
p c-Si	20.3	0.615	8.35	211	200
a-Si	11.1	6.3	0.0089	33	1
CdTe	16.5	0.86	0.029	–	5
CIGS	19.5	–	–	–	1
MJ	40.7	2.6	1.81	476	140

4. CONCENTRATING PHOTOVOLTAIC TECHNOLOGY

Concentrating photovoltaic technology is another promising field of development. Instead of simply collecting and converting a portion of whatever sunlight just happens to shine down and be converted into electricity, concentrating PV systems use the addition of optical equipment like lenses and mirrors to focus greater amounts of solar energy onto highly efficient solar cells. Although these systems are characteristics material dependent and generally pricier to manufacture, they have a number of advantages over conventional solar panel setups and encourage further research and development efforts[16].

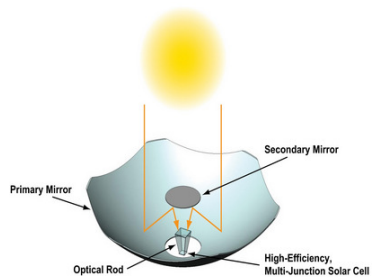

Fig.3 Concentrating photovoltaic Technology: The sun's rays are concentrated before hitting the solar cells producing a greater output. Heat sinks have to be provided to dissipate the increased heat and the panels work best in sunny weather.

5. SUMMARY

This paper analyze the role of functional materials in enhancing the solar energy conversion. The technological advancement in solar photovoltaic materials with enhanced conversion efficiency is promising. More research and development is needed in Multi-junction solar Photovoltaic Technology and Concentrating Photovoltaic Technology to make it more efficient and economical to meet our future energy needs.

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