CHARACTERIZATION OF JUNCTION TRANSPORT MECHANISMS IN CADMIUM TELLURIDE - CADMIUM SULFIDE THIN FILM PHOTOVOLTAIC DEVICES

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DEDICATION

To my wife Laurie and my daughter Lili.

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by

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ABSTRACT

CdTe-CdS thin-film heterojunction photovoltaic devices fabricated at three different laboratories by close-space sublimation (CSS) have been characterized using electrical and optical techniques. Capacitance versus voltage (C-V) measurements were performed in the dark at temperatures between 200 Kelvin and 350 Kelvin. The current density versus voltage (J-V) characteristics of the cells were measured at temperatures between 200 Kelvin and 350 Kelvin in the dark and under broad-spectrum illumination intensities of approximately 100mW/cm^2 through 100μW/cm^2. J-V characteristics were also studied using infrared (IR) illumination of various wavelengths. An analysis of the steady-state current settling time after a change in forward bias was performed. Additionally, dc quantum efficiency measurements were performed.

C-V data indicates the existence of a nearly intrinsic CdTe layer near the junction. C-V analysis and settling time measurements show that at least one and possibly many deep trap levels with large time constants in the CdTe layer affect the operational characteristics of the cells.

The J-V versus temperature and intensity data for the cells was fit to a parallel diode model that includes series and shunt resistance. Analyses of the extracted diode parameters reveal the existence of two junction transport mechanisms. The first is a depletion region recombination process that is independent of illumination intensity and active at high bias levels under low illumination intensities. The second mechanism is an intensity-dependent quantum mechanical tunneling transport mechanism that is active at

low bias levels and is significant under high illumination intensities. Quantum efficiency measurements and IR J-V analysis confirm that this tunneling transport is not active when the incident optical radiation is of energy less than the bandgap of CdTe.

A model of the CdTe-CdS solar cell as a p-i-n structure with a trap level in the CdTe layer is presented and analyzed. The C-V and settling time measurements agree well with predicted characteristics of the model. However, the p-i-n model cannot explain the observed tunneling transport characteristics.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

A photovoltaic device, or solar cell, is a semiconductor device that converts solar radiation directly into electricity. Because of the depletion rate of fossil fuels and the expense and safety concerns associated with nuclear power sources, cleaner renewable energy sources will be needed in the future to meet the world's growing energy needs [1]. Solar cells are being extensively researched because of the virtually limitless supply of solar energy, the achievement of high conversion efficiency, low operating cost, and almost pollution-free operation. Currently, solar cells are used for a variety of scientific and commercial applications, including power generation for spacecraft and satellites, commercial power generation in remote areas where the cost of installing power generation and transmission lines is prohibitive, and power for handheld consumer electronics.

The single-crystal silicon solar cell has been extensively used for a variety of applications, but the production costs associated with this type of device limits its application for widespread commercial use. Low cost alternatives, such as thin-film and polycrystalline devices, promise a more cost-effective alternative [1,2]. Thin-film Cadmium Telluride (CdTe)-Cadmium Sulfide (CdS) heterojunction solar cells have been studied for years [3-18] because of the nearly ideal bandgap energy of CdTe for solar absorption and the lower production costs promised by thin film devices [3].

The solar spectral radiation reaching the earth near the equator at midday is referred to as "one sun" illumination and has a power density of approximately 100mW/cm^2 [2]. The spectral intensity of this radiation can be approximated by a 5800K blackbody, although the earth's atmosphere attenuates certain wavelengths. A semiconductor is transparent to radiation of lower energy than the semiconductor's bandgap ($hc/\lambda < E_g$) [1]. Additionally, the open-circuit voltage of a solar cell is limited by several factors, including bandgap energy. Assuming ideal conversion efficiency, the optimum bandgap for a semiconductor solar cell is about 1.5eV [1,2]. This makes CdTe ($E_g \approx 1.5$eV, direct) [2] a nearly ideal semiconductor for absorption of solar radiation.

Although high efficiencies have been achieved with CdTe-CdS thin film solar cells [12,13,15], higher efficiencies are at least theoretically possible [15]. Improvements in efficiency will undoubtedly come about with a deeper understanding of the non-ideal behavior of these devices, partially caused by interface states and deep trap levels associated with polycrystalline semiconductors.

The purpose of this work is to characterize the dark current transport mechanisms in several CdTe-CdS photovoltaic devices with various efficiencies, fabricated by different methods at different laboratories. An attempt is made to explain the operational characteristics in terms of existing physical models, and modify those models where appropriate to account for observed behaviors.

CHAPTER 2

THEORY

2.1 Ideal CdTe-CdS heterojunction

A heterojunction is formed when two dissimilar semiconductors are brought into contact. Heterojunction theory is based on the work of Anderson [19], and is described elsewhere [2]. Figure 2.1 depicts the energy band diagram of a p-CdTe/n-CdS heterojunction with no deep trap levels, or interface states before and after joining. In the diagram, χ is the electron affinity of the semiconductor, E_g is the bandgap energy of the semiconductor, and ΔE_C and ΔE_V are the conduction band and valence band discontinuities, respectively, given by:

$$\Delta E_C = \chi_p - \chi_n \tag{2.1}$$

$$\Delta E_V = E_{gn} - E_{gp} - \Delta E_C \tag{2.2}$$

If ΔE_C is positive or ΔE_V is negative then spikes in the conduction or valance band may be present which would impede the flow of charge across the junction. For the ideal CdTe-CdS heterojunction described here, ΔE_C = -0.22eV and ΔE_V = 1.2eV so there should be no spikes present in the CdTe-CdS junction. The diffusion potential at the junction is given as

$$V_d = V_{dn} + V_{dp} = \frac{1}{q}\left(E_{gp} - \delta_p - \delta_p + \Delta E_C\right). \tag{2.3}$$

The relative voltage supported in each semiconductor is

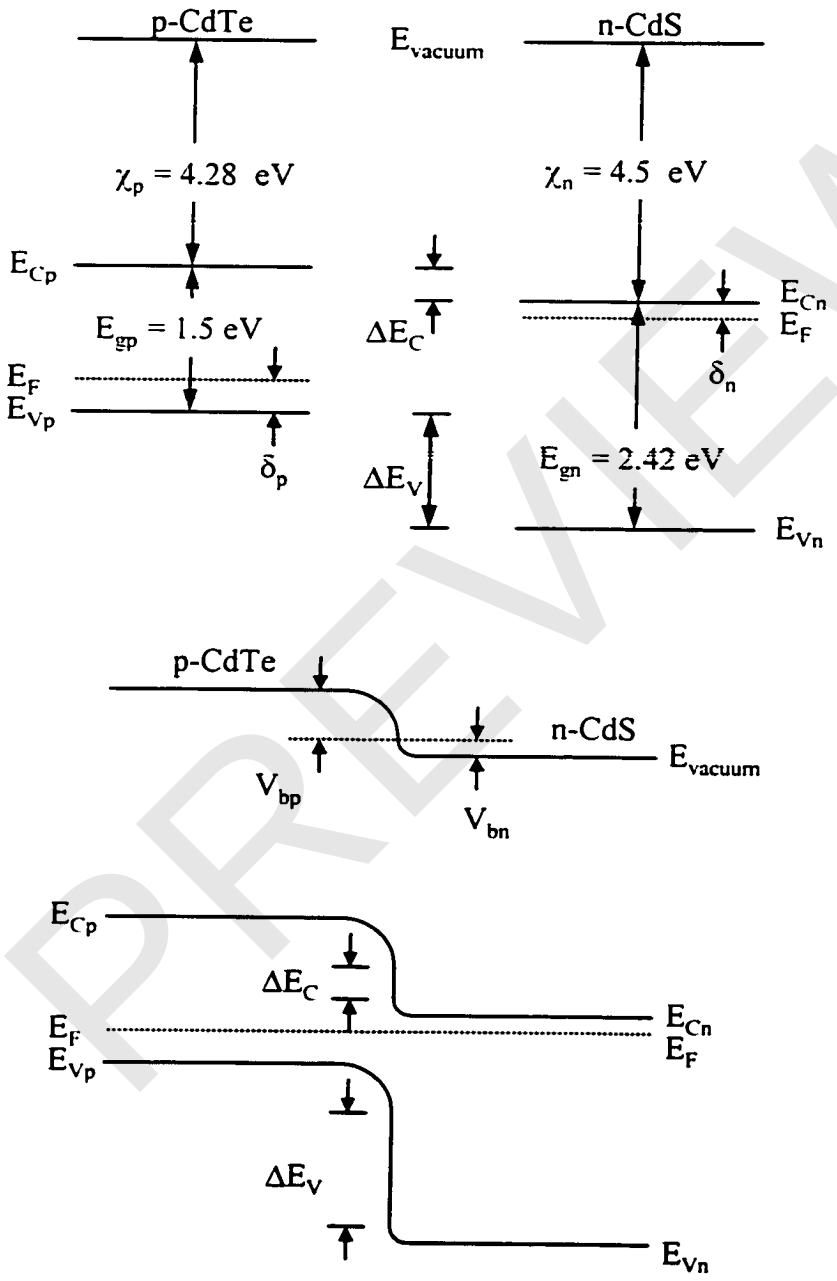

Figure 2.1 Energy band diagram of ideal CdTe-CdS heterojunction before and after joining.

$$\frac{V_{dn}}{V_{dp}} = \frac{V_n}{V_p} = \frac{N_A \varepsilon_p}{N_D \varepsilon_n}, \qquad (2.4)$$

where $V = V_n + V_p$ is the applied voltage across the semiconductor and V_p and V_n are the portions of the applied voltage dropped on the p-side and n-side of the junction, respectively.

2.2 Ideal solar cell theory.

2.2.1 Energy band model for ideal solar cell.

A solar cell is a semiconductor p-n junction that is optimized for conversion of solar radiation into electricity. For the ideal solar cell presented here, the device is assumed to be an abrupt p-n homojunction. A brief description of the device operation is given here, and a more thorough treatment of the subject is given in the literature [1,2].

Figure 2.2 depicts the energy band diagram of an ideal solar cell under illumination at $V = 0$ (short circuit) (Fig. 2.2a) and at $V = V_{OC}$ (open circuit) (Fig. 2.2b). When an ideal solar cell is illuminated, photons with energy greater than the bandgap energy E_g are absorbed creating electron-hole pairs. If the electron-hole pairs are created within a diffusion length of the junction, the minority carriers (electrons in the p-type material and holes in the n-type material) will diffuse to the space charge region before recombining and will be swept across the junction by the electric field. This light-generated current (J_L) is assumed to be independent of bias voltage. When the junction is forward biased, the potential barrier is lowered, enabling minority carriers to diffuse across the junction. The resulting current is the sum of the electron forward current and

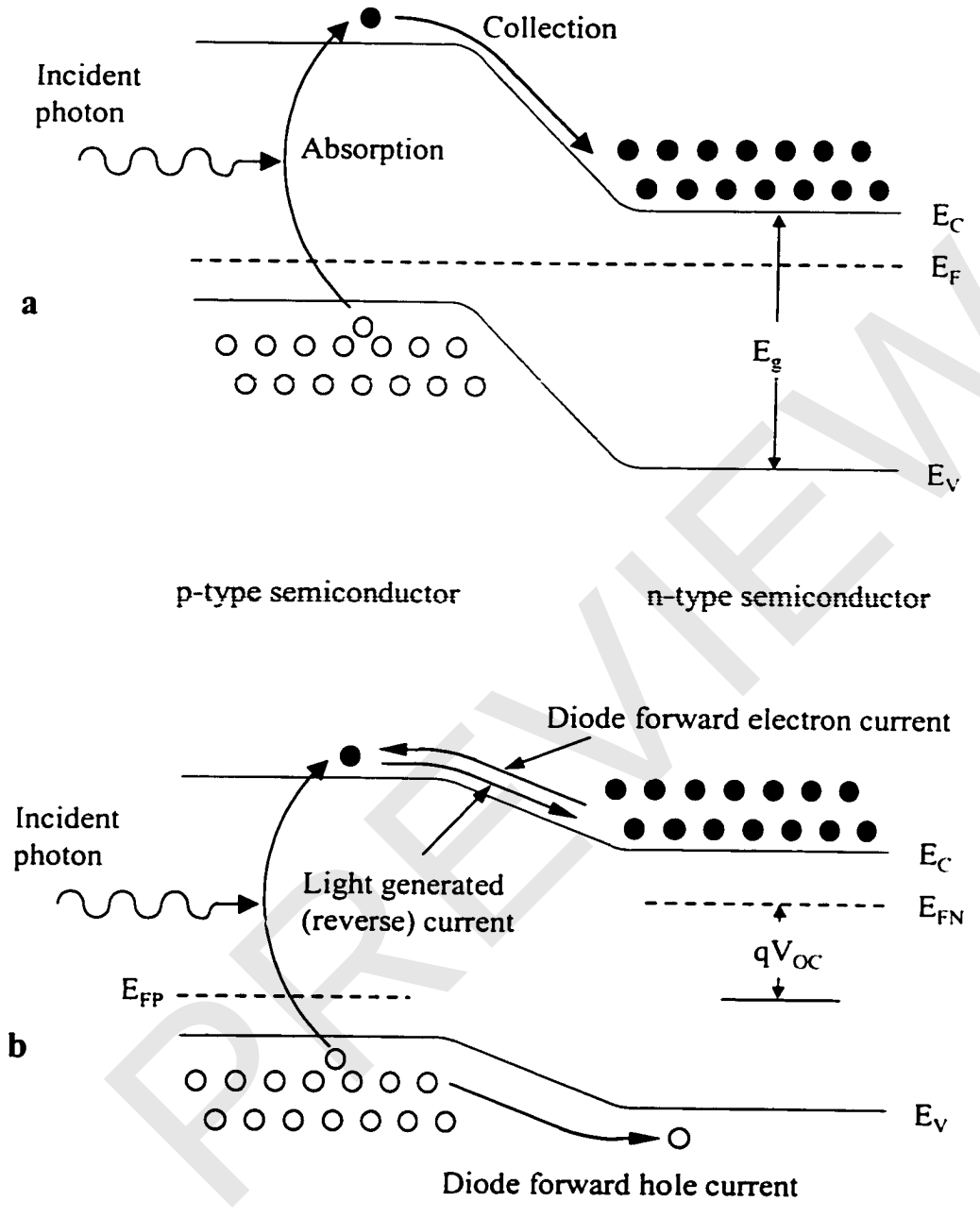

Figure 2.2 Energy band diagram showing ideal solar cell operation in (a) short circuit condition ($V_F = 0V$), and (b) open circuit condition ($V_F = V_{OC}$).

the hole forward current and flows in the opposite direction to the light-generated current. This diode current is called the dark current (J_D) and is described by [1]

$$J_D = J_0\left[\exp\left(\frac{qV}{kT}\right)-1\right], \tag{2.5}$$

where q is the electron charge, k is Boltzman's constant, and T is the temperature in Kelvin. J_0 is the diode reverse saturation current density and is given as

$$J_0 = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}, \tag{2.6}$$

where n_{p0} (p_{n0}) is the equilibrium minority electron (hole) concentration, D_n (D_p) is the electron (hole) diffusion coefficient, and L_n (L_p) is the electron (hole) diffusion length. The temperature dependence of the reverse saturation current density may be approximated by [1]

$$J_0 \approx J_{00}\exp\left(\frac{-E_g}{kT}\right), \tag{2.7}$$

where J_{00} is weakly temperature dependent.

For the ideal device, superposition holds and the resulting current versus voltage (J-V) characteristics are shown graphically in Fig. 2.3 for the device in the dark and under illumination. Note that, for the ideal case, the two curves are identical except for the vertical shift caused by the light-generated current.

If the illuminated cell is biased at a point occurring in quadrant four, power can be extracted from the device. The bias point at which delivered power is maximized is known as the maximum power point where $V=V_{MP}$ and $J=J_{MP}$. These points are depicted

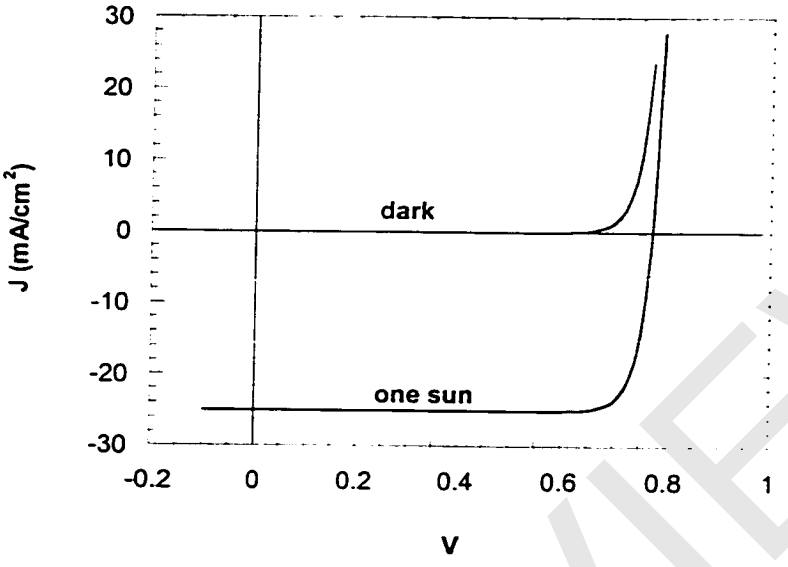

Figure 2.3 J versus V characteristics for ideal solar cell.

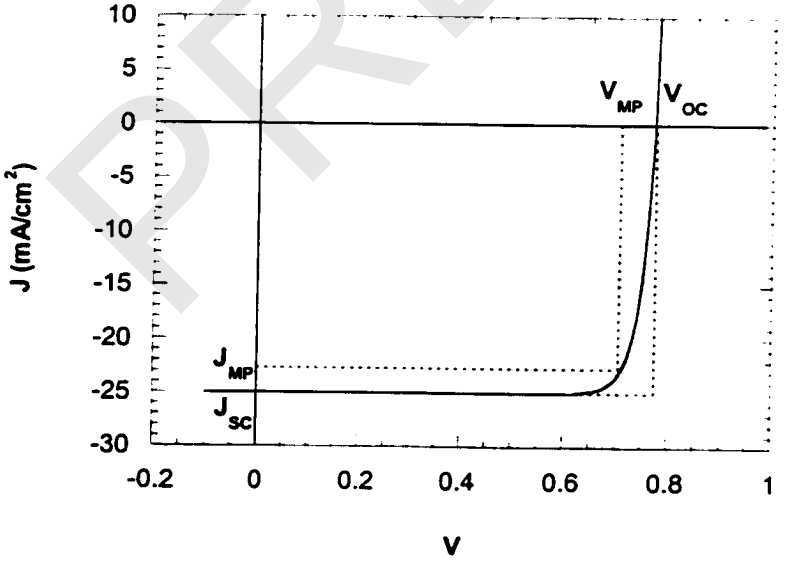

Figure 2.4 V_{OC}, J_{SC}, V_{MP}, and J_{MP} for ideal solar cell.