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Electronic Structure of Electrodeposited Thin Film CdTe Solar Cells

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ABSTRACT

Independent experimental verification done at four research laboratories, namely, Ametek, Colorado State University (CSU), Institute of Energy Conversion (IEC), and Solar Energy Research Institute (SERI) confirm the n-i-p model proposed by Ametek. The experiments done for the verification of the n-i-p structure are the high frequency capacitance-voltage, light and voltage bias quantum efficiency, and EBIC measurements. All experimental evidence suggests that the n-i-p model is appropriate for the existing n-CdS/i-CdTe/p-ZnTe cell structure. From the C-V measurements, the depletion width has been estimated at 1.7-2.0 μm and corresponds to the thickness of the CdTe film. This unique thin film device design has resulted in improved stability and a SERI-verified world record single-junction total area AM1.5 global efficiency of 11%. Further refinements in device design and cell processing should result in 12-13% efficiencies for thin-film CdTe solar cells in the not-too-distant future.

INTRODUCTION

One of the major problems encountered in the thin-film CdTe solar cell technology has been contact degradation. Reproducible and uniform p-type doping of thin-film CdTe has normally resulted in non-uniform and inconsistent p-type CdTe films, with high resistivity. Ametek has circumvented this problem by designing the solar cell structure such that the CdTe is always intrinsic in the final device design. The intrinsic CdTe film with a resistivity of $>10^7$ ohm-cm is sandwiched between the n-type CdS and p-type ZnTe to complete the device structure.

SOLAR CELL FABRICATION

The n-i-p cell structure shown in Fig. 1 is Glass/SnO_2/CdS/CdTe/ZnTe/Metal. Low cost soda-lime glass is coated with about 0.4 µm of fluorine doped tin oxide. The typical transmission is > 80% and sheet resistance is about 10 ohms/square. Undoped CdS is deposited in a narrow-gap reactor at 450^0C by spray pyrolysis. The film thickness of the CdS is 0.15 µm. The next step in the process is the deposition of 2 µm of thin-film CdTe by electrodeposition at 80^0C. The CdTe is then heat treated at 400^0C for about 20 mins. causing significant change in morphology (Fig. 2, A. Mason at SERI), which is the key to high process yields. During this treatment, the microcrystalline grains at the CdS-CdTe interface are believed to coalesce or fuse, thus greatly reducing the density of grain boundary states. Recrystallization and growth occurs over the entire thickness of the CdTe film. The cell fabrication is completed by depositing Cu doped ZnTe by thermal vacuum evaporation. The ZnTe is about 0.1 µm thick and has a resistivity of 1 ohm-cm. Metal contact is also deposited by thermal vacuum evaporation.

RESULTS AND DISCUSSION

Figure 3 is an idealized band diagram of the n-i-p cell structure. The bandgap of the CdS, CdTe and ZnTe is 2.42, 1.45, and 2.23 eV respectively. The 1.45 eV bandgap of CdTe is an ideal match for the solar spectrum. Solar cells with this structure have been analyzed by various laboratories. Their experimental evidence suggests that an n-i-p model is appropriate for this unique device design. Figure 4 is a plot of the (capacitance)$^{-2}$ versus voltage at 10^5 Hz for a solar cell that is over 10% efficient. The data was taken by J. Sites at CSU. Numerically this capacitance is consistent with an insulating layer of thickness equal to 1.7 μm, which corresponds roughly to the film thickness of the CdTe layer. The resistivity for the CdTe film has been calculated to be 10^7 ohm-cm. The acceptor density depth profile for a high efficiency cell is shown in Fig. 5. The depletion width at zero bias is 2.0 μm, and increases to 2.15 μm at a reverse bias of 1 volt. The range of the acceptor density is about 2×10^{15} cm^{-3}. The sharp increase in the acceptor density for the larger depth is due to high conductivity of the Cu-doped ZnTe layer. The depletion width estimated from the C-V measurements done by R. Ahrenkiel at SERI is also 2.0 μm and is consistent with the Ametek results. Figure 6 is a quantum efficiency plot under light and voltage bias conditions. The data is taken by J. Phillips at IEC. The increase in the response at 1 volt reverse bias is 5% of the zero bias value. This is the same order by which the depletion width increases. For a heterojunction device, one would expect to see a larger increase in the response in the near infrared region as the depletion width extends into the

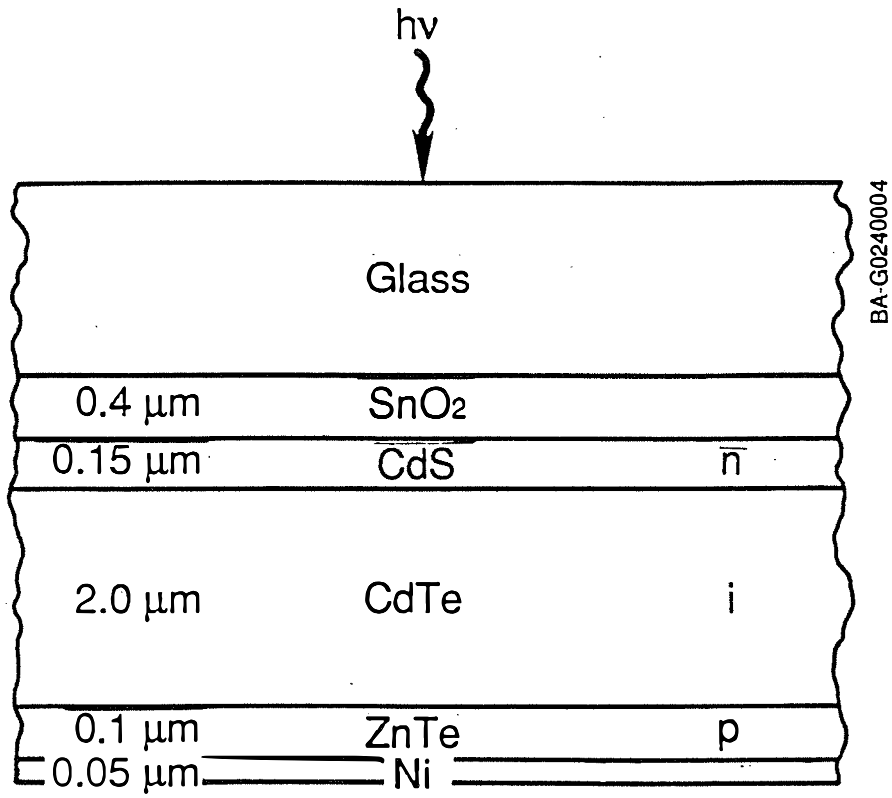
CdTe. In the present case, however, the CdTe is fully depleted even under zero bias conditions. SERI's EBIC scans (R. Matson) of the cleaved cross section shown in Fig. 7 indicate that current collection occurs over the entire thin-film CdTe layer. The depletion width under normal condition is of the order of the CdTe film thickness. The above data suggests that a n-i-p model is appropriate for the thin-film n-CdS/i-CdTe/p-ZnTe solar cell. This thin film device has resulted in a SERI-verified world record single-junction total area efficiency of 11%. The cell parameters are J_{SC} = 20.09 mA/cm^2, V_{OC} = 0.763 volt, and FF = 0.72. The light I-V curve is shown in Fig. 8. The cells have been tested for stability for 3000 hours under 1 SUN illumination and load at 70^{0}C. No change in device performance has been observed over this extended period of testing.

SUMMARY

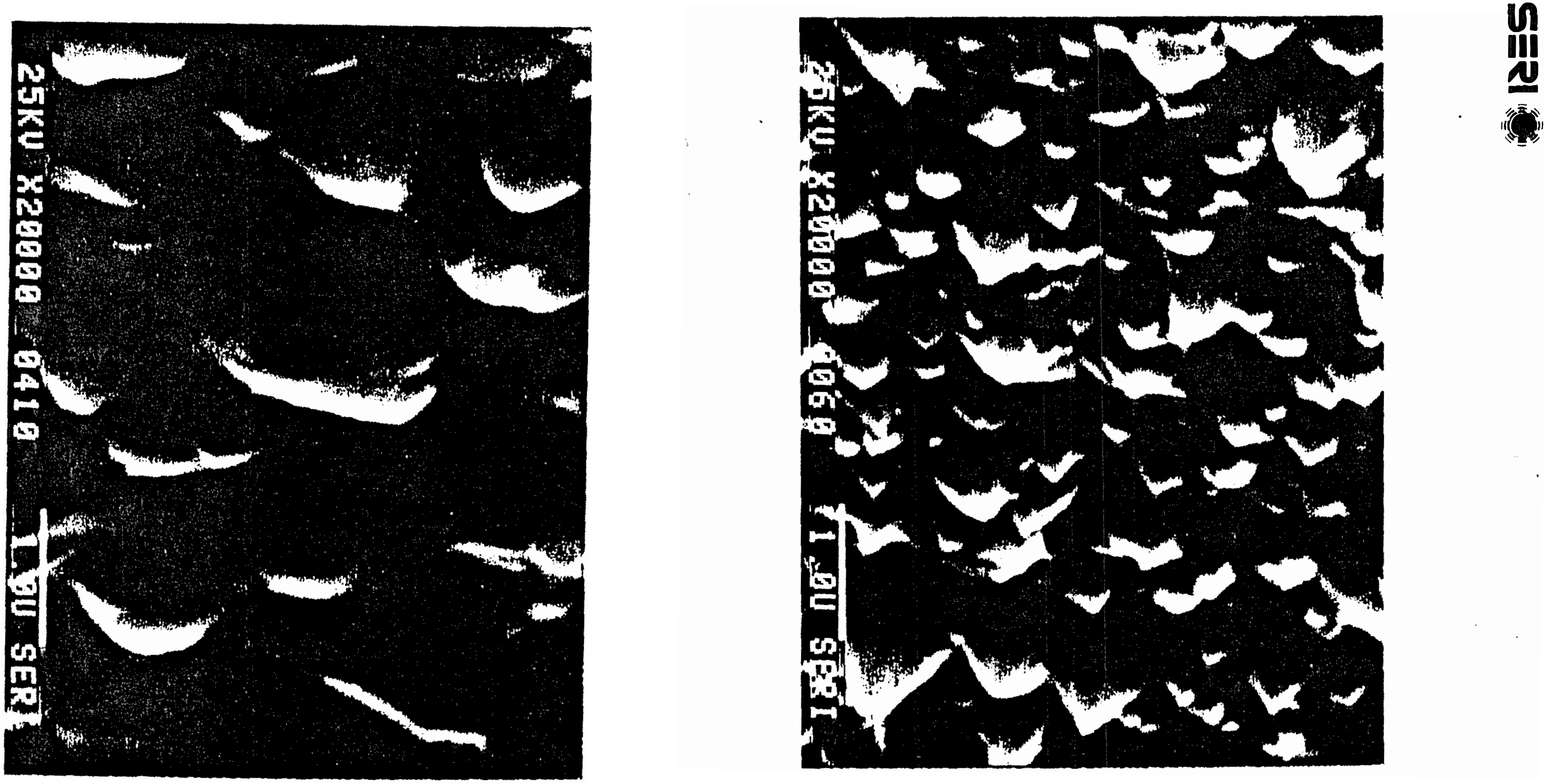
Four independent research laboratories, namely Ametek, Colorado State University, Institute of Energy Conversion, and Solar Energy Research Institute have experimentally verified the n-i-p model proposed by Ametek. The experiments used in the study was the high frequency $(\text{capacitance})^{-2}$ versus voltage, light and voltage bias quantum efficiency, and EBIC measurements. From the C-V measurements, the depletion width was estimated at 1.7 - 2.0 μm. This corresponds to the thickness of the CdTe layer, suggesting that the intrinsic film is fully depleted. The n-i-p thin film device has resulted in a SERI verified world record single-junction, total area global efficiency of 11%. Further refinements in cell processing and device design should result in efficiencies for thin-film CdTe solar cells of 12-13% in the near future.

ACKNOWLEDGMENT

The author would like to express his sincere appreciation to the following researchers for their experimental input. Drs. P. Meyers and V. Ramanathan of Ametek for the C-V measurements, Prof. J. Sites of CSU for the C-V measurements, Dr. J. Phillips of IEC, University of Delaware for the C-V and quantum efficiency measurements, and K. Emery (light I-V), A. Mason (SEM), R. Matson (EBIC) and Dr. R. Ahrenkiel (C-V) of SERI. The many stimulating discussions with Ken Zweibel are also acknowledged.



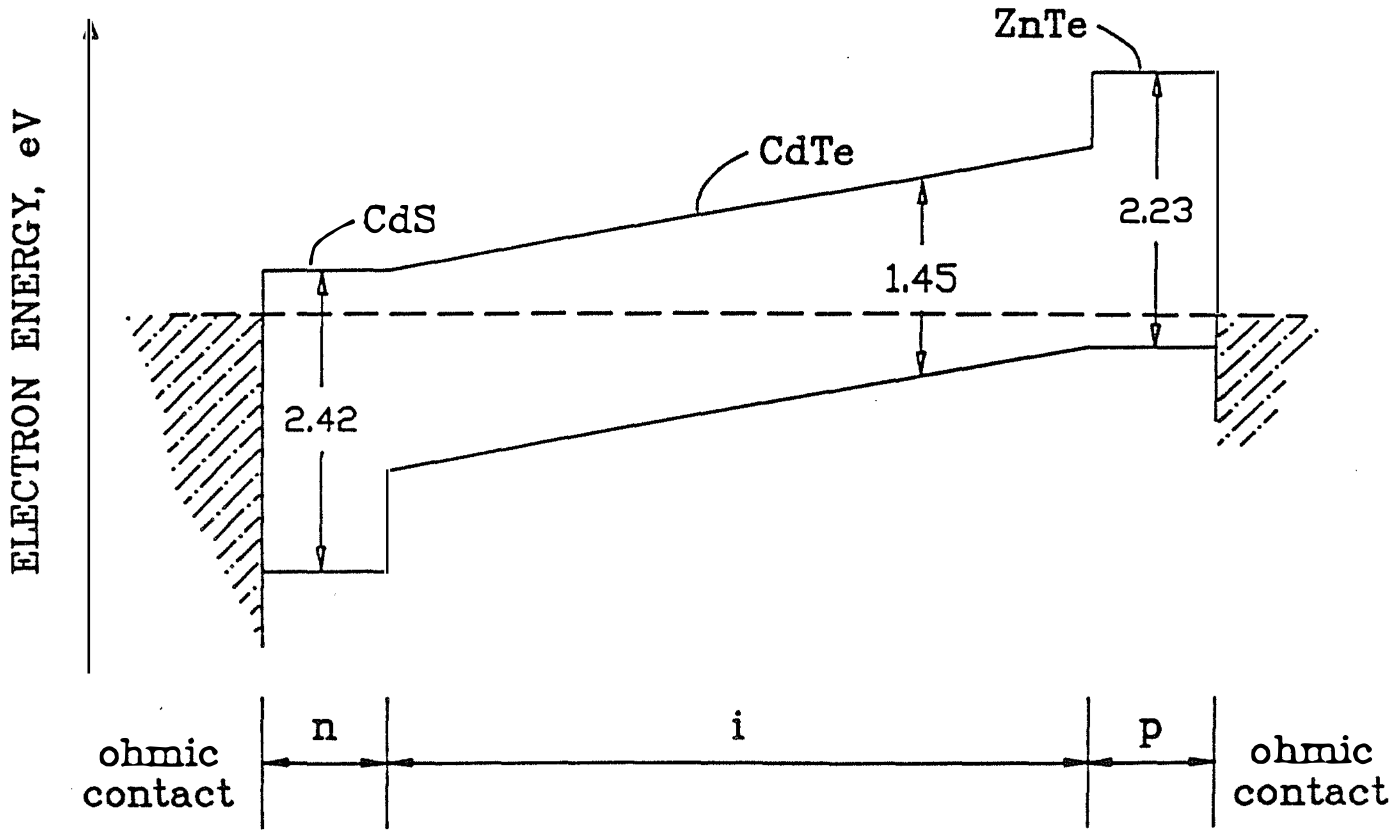
1. Cell structure of glass/SnO_2/CdS/CdTe/ZnTe/Metal for a n-i-p thin film solar cell



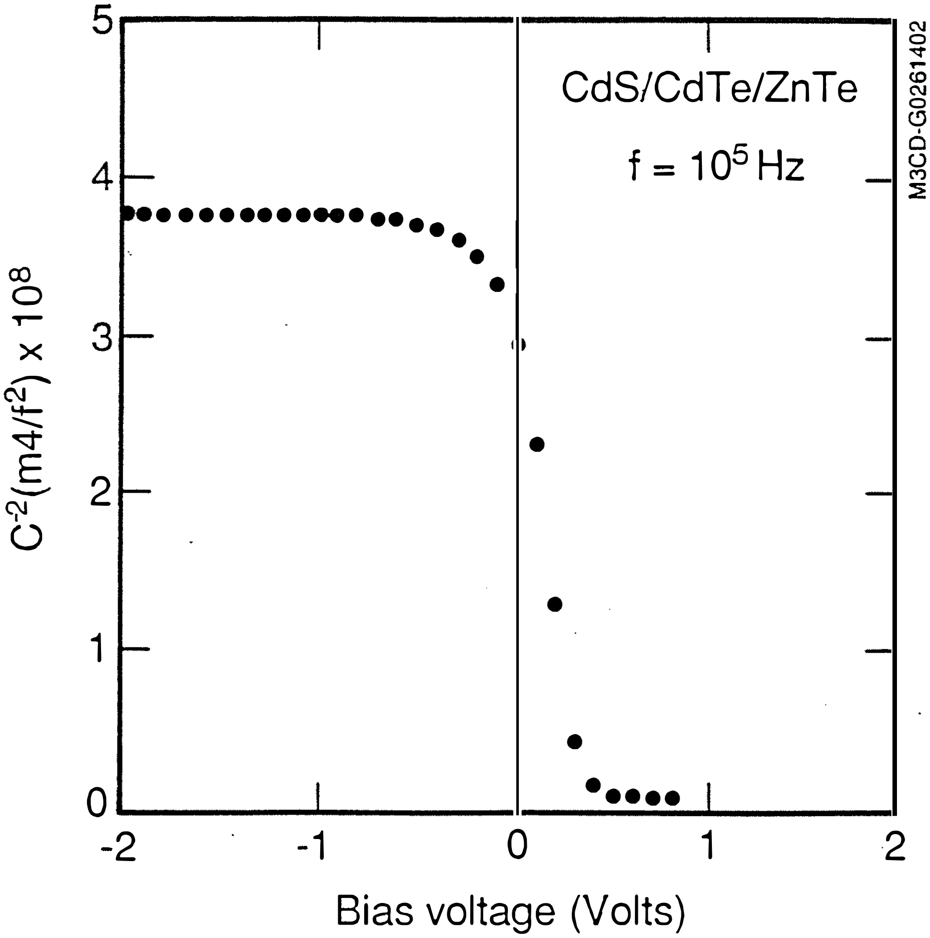
MW60A 410^{o}C annealed

MW60A unnannealed

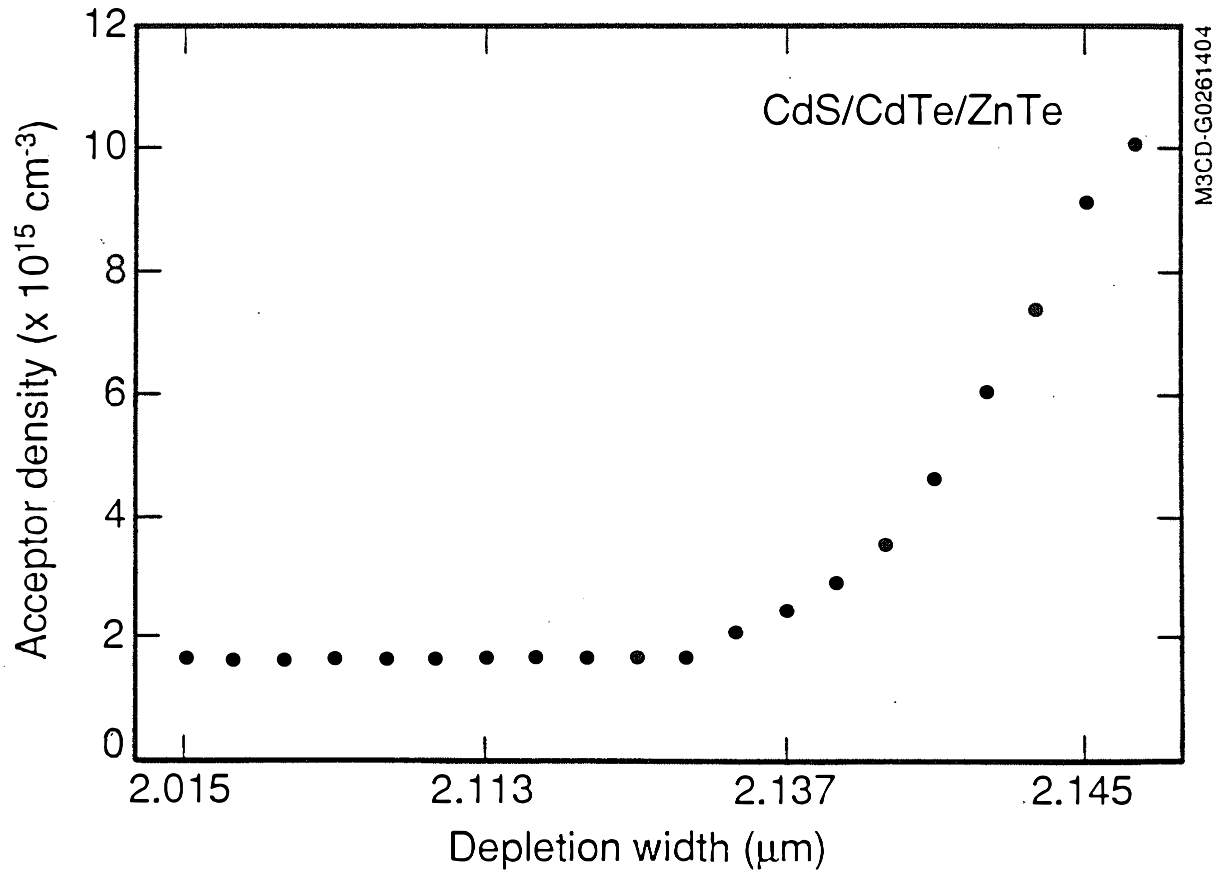
2. SEM micrographs of the thin film CdTe morphology before and after heat treatment



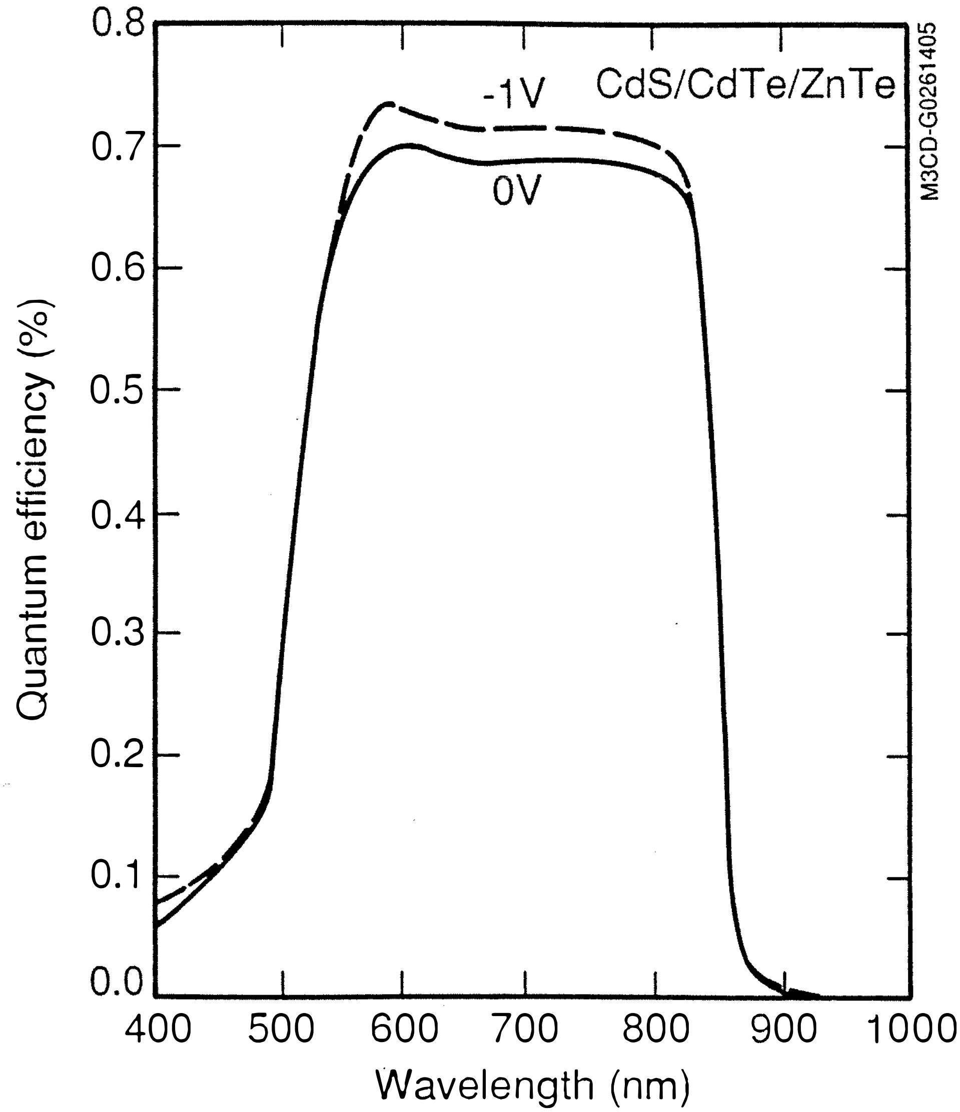
3. Idealized band diagram for a n-i-p thin film CdTe solar cell



4. Capacitance - voltage plot for a n-i-p thin film CdTe solar cell at 10^5 Hz



5. Acceptor density versus width for a n-i-p thin film CdTe solar cell



6. Quantum efficiency versus wavelength plot for a n-i-p thin film CdTe solar cell

Operator:
RM

Date:
2/9/88

Device/ Material:
/ Glass / / /

SiO_2	450 Å
SnO_2	4000 Å
CdS	1500 Å
CdTe	2 μm
ZnTe	800 Å
Au	200 Å

Sample No.:
EF 176 BL8

Source:
Ametek

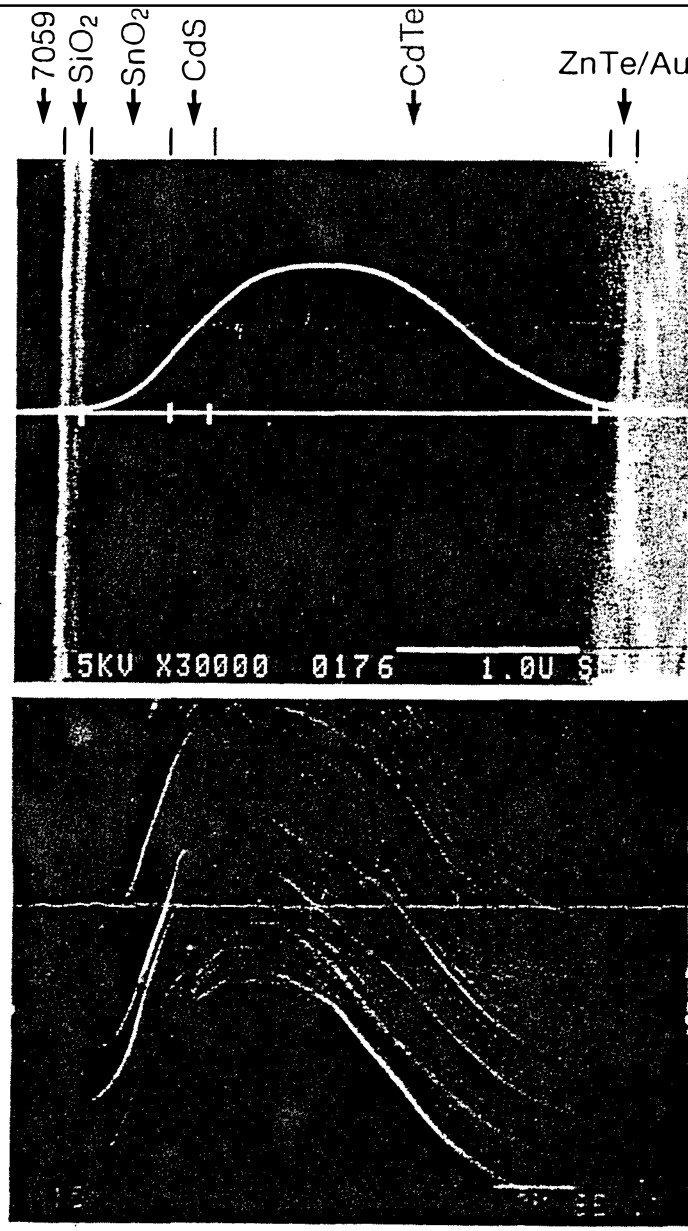
SEM:
35° C

E_b (kV):
R_e = 1.6 μm
15 kV

I_b:
~ 30 pA

MAG:
30 kX

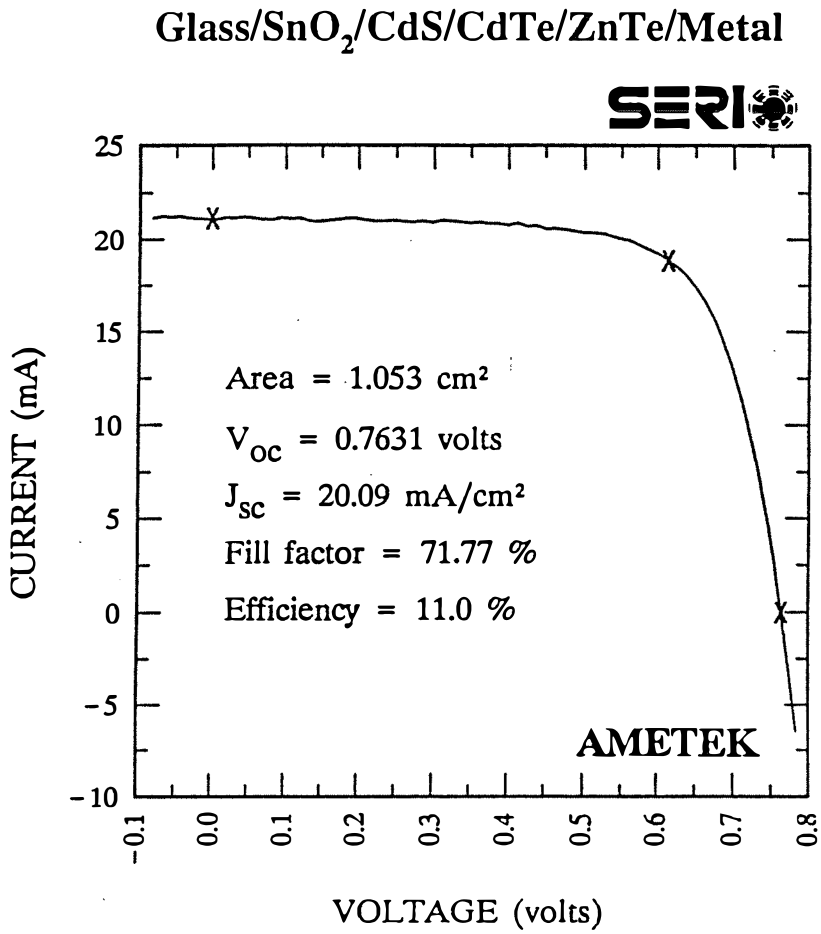
Tilt:
90°



Notes:
Ametek Cell

Y-modulated EBIC map of above area

7. EBIC micrograph for a n-i-p thin film CdTe solar cell



8. Light I-V plot of 11% efficient, 1.05 cm^2 n-i-p thin film CdTe solar cell