INVESTIGATION OF JUNCTION PROPERTIES OF CdS/CdTe SOLAR CELLS AND THEIR CORRELATION TO DEVICE PROPERTIES

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Objective - Junction Studies

• Understand the nature of the junction in the CdTe/CdS device
• Correlate the device fabrication parameters to the junction formation
• Develop a self consistent device model to explain the device properties

Detailed analysis of CdS/CdTe and SnO$_2$/CdTe devices prepared using CSS CdTe.
Glass
SnO₂
Buffer layer
CdS-
CBD
CdS/CdTe Interface
CdTe
Contact - doped graphite, Cu/Au
CdTe
CdS/CdTe Interface
CdS- CBD
Buffer layer
SnO₂
Glass

CdTe Device Structure

National Renewable Energy Laboratory
n\textsuperscript{+}-p device model for CdS/CdTe device (6/95)-based on blue QE loss:

- One sided junction with depletion width entirely in CdTe.
- Only field assisted collection.
Problems with the n⁺-p model

• Phenomenological Model – can explain the device performance but without physical basis.

• CBD CdS has carrier concentration around $10^{13}$/cm$^3$ which is even less than CdTe

Here we present our interface/junction analysis using Secondary Ion Mass Spectrometry (SIMS), Modulated reflectance techniques and Electron Beam Induced Current (EBIC) to elucidate the junction properties.
SIMS Results

- Roughness of the samples (RMS – 0.5 μm) makes it impossible to resolve the features at CdS/CdTe interface.
- NREL SIMS and Microscopy groups developed sample preparation with polishing to improve the interface resolution.
Observations

- Interdiffusion at CdS/CdTe interface increases with $T_{\text{sub}}$ and CdCl$_2$ HT
- Accumulation of Cl at CdS/CdTe interface after CdCl$_2$ HT. Level of Cl increases with level of HT
- Cl is a n-type dopant in both CdS and CdTe; also in the intermixed alloy
Photo- or Electro-Modulated Reflectance (PR or ER)

CdTe/CdS Solar Cell

Modulated Laser

DC Light

Detector

$\Delta R/R$

AC voltage
Reflectance modulation

\[ R = \left| \frac{n - n_a}{n + n_a} \right| \]

\[ n^2 = \varepsilon_1 + i \varepsilon_2, \quad n_a^2 = \varepsilon_a \text{ (real)} \]

Near band-gap \( \Rightarrow \) major contribution is from \( \Delta \varepsilon_1 \):

\[ \frac{\Delta R}{R} \approx \alpha \Delta \varepsilon_1 \]
Fitting Modulation Reflectance Spectrum

\[ \Delta \varepsilon_1 = \frac{2e^2 \hbar^2}{m^2 (\hbar \omega)^2} \left| \vec{e} \cdot \vec{P}_{cv} \right|^2 \left( \frac{2\mu_0}{\hbar^2} \right)^{3/2} \sqrt{\hbar \Omega_0} \left( G \left( \frac{E_g - \hbar \omega}{\hbar \Omega_0} \right) - \sqrt{\frac{E_g - \hbar \omega}{\hbar \Omega_0}} F \left( \frac{E_g - \hbar \omega}{\hbar \Omega_0} \right) \right) \]

\[ F(\eta) = \pi [A_i^2(\eta) - \eta A_i^2(\eta)] \]

\[ G(\eta) = \pi [A_i'(\eta)B_i'(\eta) - \eta A_i(\eta)B_i(\eta)] \]

Photo-reflectance

From Data fitting:
\[ E_{\text{max}} = 31.9 \text{ kV/cm} \]
\[ E_g = 1.448 \text{ eV} \]
From Data fitting:

$E_{\text{max}} = 34.6 \text{ kV/cm}$

$E_g = 1.4482 \text{ eV}$

CdTe-A1
300 K  100 mV P-P

$E_g = 1.4482 \text{ eV}$

$F = 34.6 \text{ kV/cm}$
Effect of CdCl$_2$ treatment (by PR)

![Graph showing the effect of CdCl$_2$ treatment on CdTe materials.](image-url)

- **CdTe, as deposited**
- **CdTe, CdCl treated**

Energy (eV)

- 1.2
- 1.3
- 1.4
- 1.5
- 1.6
- 1.7

Wavelength (nm)

- 750
- 800
- 850
- 900
- 950
- 1000

$\Delta R/R \times 10^6$

- 0
- 1
- 2
- 3
- 4
- 5
- 6

1.505 eV for CdTe 300 K 532nm
Modulated Reflectance

- Modulated electro-reflectance and photo-reflectance studies identify a region of high electric field (~32-35 kV/cm) for high efficiency CdS/CdTe devices. The field is present in the region of 1.45 eV material.
- SnO$_2$/CdTe devices do not show high field region

The high field region corresponds to Te-rich CdSTe alloy.
CdTe\(_{1-x}\) S\(_x\) alloy Bandgaps

Optical Bandgap, eV

Composition Parameter, x

Zinc-blende

Wurtzite

D. Albin, et al.
Ohata, et al.,
From $E_{\text{max}} = 32 \text{ kV}$ and depletion width on p-side = 3 $\mu$m (base on C-V and EBIC results)

Using $E_{\text{max}} = qN_A X_p / \varepsilon_s$
Gives $N_A = 5.5 \times 10^{14} \text{ cm}^{-3}$

Evaluation of $N_D$ based on SIMS and EBIC results
EBIC

- SEM and HR-EBIC measurements performed on high $V_{oc}$ (835 mV) device.
- Measurements on the cross-section of the device. Shows EBIC response close to CdS/CdTe interface.
substrate
SnO$_2$
Cds
CdTe

e-h
$R_e$
e-beam

picoamp
Electron-beam-induced-current

HREBIC

200 nm

CdS
CdTe
SnO₂
Device model

SnO$_2$  CdTe

SnO$_2$  CdS  CdS$_x$Te$_{1-x}$  CdTe

Hetero  Quasi-homo

$V_{oc}$, mV

600  750  n-p

850  890  n$^+$-p
<table>
<thead>
<tr>
<th>Device structure</th>
<th>$V_{oc}$, mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$/CdTe</td>
<td>600-650</td>
</tr>
<tr>
<td>CdS/CdTe as dep</td>
<td>720-750</td>
</tr>
<tr>
<td>CdS/CdTe w/ CdCl$_2$</td>
<td>840-850</td>
</tr>
</tbody>
</table>

- Lower $V_{oc}$ devices are true hetero-junctions, whereas the devices with CdCl$_2$ treatment have a junction between n$^+$ Te-rich CdSTe alloy (doped with Cl) and p-type CdTe with compatible cubic structure i.e. quasi-homojunction.

- A true hetero-junction CdS/CdTe device performance will be dominated by interface defects at the hetero-interface which will be within the depletion region. This may be the case for as deposited devices fabricated at lower temperatures and SnO$_2$/CdTe devices giving low Voc.

- Role of CdS is mainly to produce Te rich alloy layer that gets doped to n-type during CdCl$_2$ process and passivation of the surface.