Modeling Approaches for CIGS and CdTe Solar Cells: Focus on Uniformity

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With help from a large number of students, especially Galym Koishiyev

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Advantages and Problems for CIGS and CdTe

ADVANTAGES:
(1) Fabrication of large areas is relatively inexpensive (technology similar to optical coatings on glass).
(2) Materials utilization much smaller when dealing with micron thicknesses.
(3) Energy pay-back time is low (less than one year).
(4) Entire structures can be deposited on flexible, low-weight substrates.
(5) High tolerance to additional defects and impurities.

PROBLEMS:
(a) Thin-film cells are generally composed of heterojunctions which may have band offsets and interfacial states.
(b) Thin-film thickness and composition may not be uniform.
(c) Grain boundaries are potential recombination sites and diffusion paths.
(d) Thin-films tend to have compensating donor and acceptor levels and hence lower carrier densities.
Approach (1): Numerical Simulation

Three software packages

Variation with recombination lifetime

QE as a function of absorber thickness

Simulation reproduces general features, but not the details.

Experimental Data

Numerical Simulation

From Univ. Toledo

From Jun Pan
Approach (2): The Diode Equation

CurVA
by Markus Gloeckler
[based on Hegedus and Shafarman, Prog. in PV 12, 155, (2004)]

Applied here to high-efficiency CIGS cell

Assumes \( J = J_0 \exp[q(V-J_R)/AkT] + GV - J_L \)

(1) Plot data four ways
(2) Select data to fit
(3) Adjust fit with sliders
(4) Fitting parameters appear on screen

Note: (c) linearizes the diode equation above:
\( \frac{dV}{dJ} = R + \frac{AkT}{J+J_L} \)
when \( G = 0 \)
Approach (3): Circuit Modeling

(3a) Distributed Series Resistance

Circuit Equivalent (light source not shown)
Note: voltage across cell may not be uniform.

Monolithic integration without grids implies large series resistance

Pspice™ works well for analysis
Single alteration to circuit element: (will return to the shunt)

Lumped series resistance approximation likely to fail
Distributed Series Resistance

Big difference between distributed and lumped series resistance

Approximate universal relationship of how fill-factor is impacted

Koishiyev and Sites, SOLMAT 93, 350 (2009)
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CIGS and CdTe Device Structure (Light Above)

Similar crystallite sizes and shapes; color artificial

Slide from R. Noufi (NREL)
(3b) Circuit Modeling of Non-Uniformities

Circuit Equivalent

Single alteration to circuit element:
Shunt shown, could be a weak diode

Physical Picture

Glass superstrate
TCO
CdS
CdTe
Back contact

Weak diode
Shunt path

From G. Koishiyev
Experimental Uniformity Tools

Light-beam-induced current (LBIC)
- Measures Local Photocurrent Directly
- 1-µm resolution
- LBIC from CIGS cell

Electroluminescence (EL)
- Very Fast; Good Industrially
- 5-µm resolution
- EL from CdTe module

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Window Layer Uniformity

Vary Thickness

Low-Resolution LBIC

From Alan Davies
Small LBIC Defect

High-Resolution LBIC

E_{\text{photon}} > E_g(\text{CdS})

E_{\text{photon}} < E_g(\text{CdS})

Feature size ~ 20 µm

From Russell Geisthardt

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Modeling Workshop – Jim Sites
EL Variations with Open-Circuit Voltage

Nine CdTe cells on same substrate with varying voltage and EL response (non-uniform CdCl$_2$ responsible)

Well-behaved relation between voltage and EL response
EL: Two Types of Shunt

Module from before

Shunt in the lower cell

Diameter of affected area ~ 3 mm

Shunt between two cells

Lower-cell current transferred to upper cell

Raguse et al, PVSC-38 (2012)
Shunt Effect Using Circuit Modeling

Shunts can be distinguished from dust or weak diode areas

Impacted area (about 3 mm here also) depends on TCO sheet resistance

Reduced voltage from shunt superimposed on background

No shunt: voltage drop across cell.

PSpice simulation by Galym Koishiyev
Extension to Multiple Shunts

*current sources are not shown
Extension to Multiple Shunts

(1) Now combine subcells, some fraction of which are non-uniform, but most of which are uniform, into cells (1-D, parallel).
(2) Then combine cells into a module (1-D, series).


*current sources are not shown
Distribution of Shunts in a Module

A – Shunts spread over many cells
B – Intermediate
C – Shunts in one or two cells preferred for shunts (or weak diodes)

Shunts mainly affect fill-factor

Shunts mitigated by higher TCO sheet resistance

(1) Several different types of PV modeling; each has value for specific types of problems.

(2) Uniformity modeling is particularly important for CIGS and CdTe, BUT analysis is relatively immature.

(3) Always helpful to have direct comparisons with experimental data, and if at all possible give credible physical interpretation of modeling results.

(4) Modeling failures can sometimes be as illuminating as successes.