Capacitance Measurements of Defects in Solar Cells: Checking the Model Assumptions

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Abstract

Capacitance measurements of solar cells are able to detect minute changes in charge of the material. For that reason, capacitance is used in many methods to electrically characterize devices. Standard interpretations of capacitance rely on many assumptions, which, if wrong, can skew the results. We have focused on a non-ideal back contact and the additional capacitance it adds to the cell. We work to distinguish the influence of a back contact from that of a thermally activated trap state on capacitance data. We find the DLCP method most clearly distinguishes between the contributions of the trap state and the back contact barrier.

Introduction

Solar Cells are composed of semiconductor material which converts solar energy into electrical energy. Thin film cells, including those we have analyzed, are relatively cheap to make in terms of time, energy, and materials. However, thin film materials have many imperfections, or defects, which can trap charge. We study these traps using differential capacitance. Capacitance, which is sensitive to minute changes in charge in the material, allows us to determine the origin and location of trap states in the bandgap. However, other non-ideal device responses can also behave as trap states. For example, the series resistance and capacitance can combine to make a low pass filter. Or, a non-ideal interface can create a thermally activated barrier at the back contact.

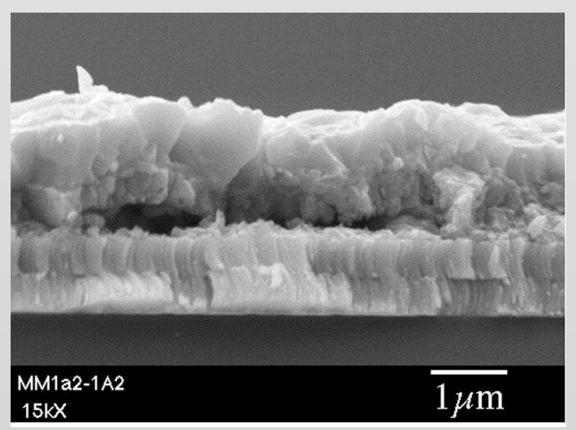


Figure 1. Cross-section of a thin film $Cu(In,Ga)Se_2$ solar cell. Reproduced from [1].

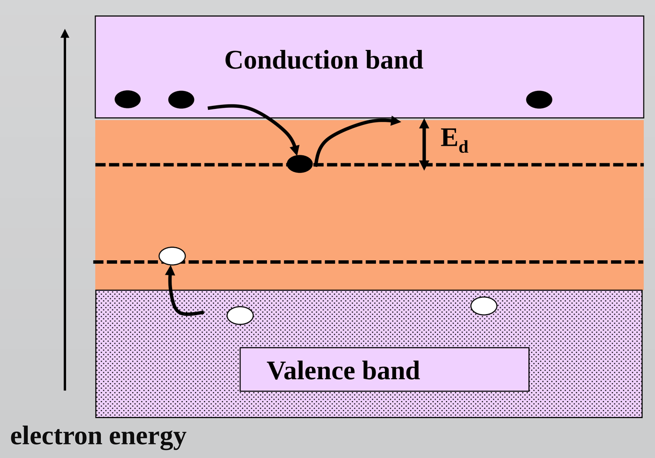
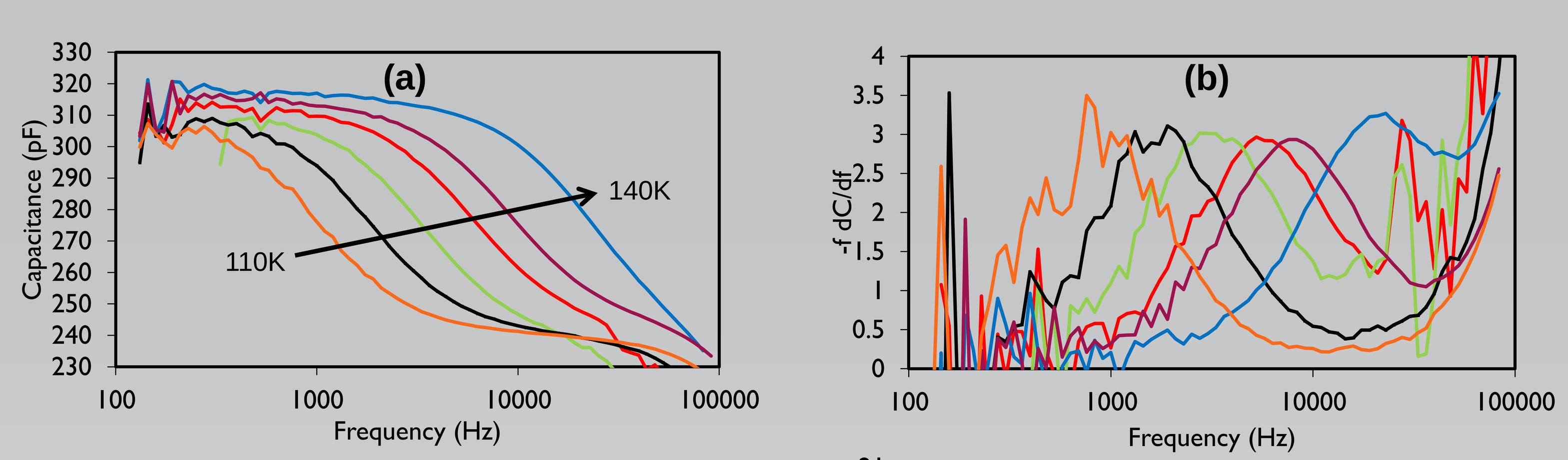


Figure 2. Schematic for a trap level in the bulk material.

Admittance Spectroscopy

- C(f,T) → Trapping time, energy: $e_n = \gamma \sigma_{na} T^2 exp[-\frac{E_{na}}{kT}]$
- Measuring C: Apply V_{ac}, measure I_{ac}
- $C = \frac{dQ}{dV} \rightarrow C\frac{dV_{ac}}{dt} = I_{ac}$
- Defects that release charge fast enough contribute to C.



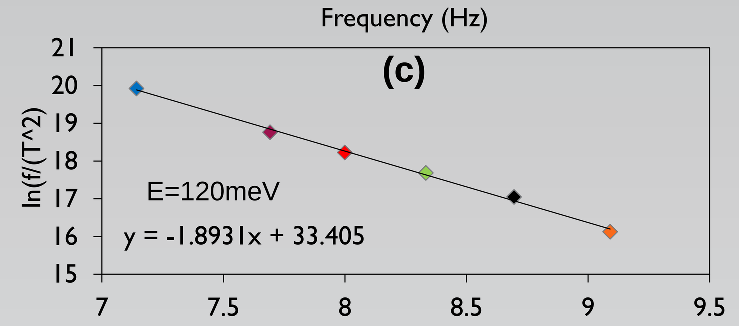


***Figure 3. (a)** Typical Admittance Spectroscopy; results. **(b)** Derivatives of C-f data, clearly showing the transition frequency. **(c)** Arrhenius plot of peak frequencies from (b). These data are consistent with a thermally activated trap at 120 meV.*

CV Profiling

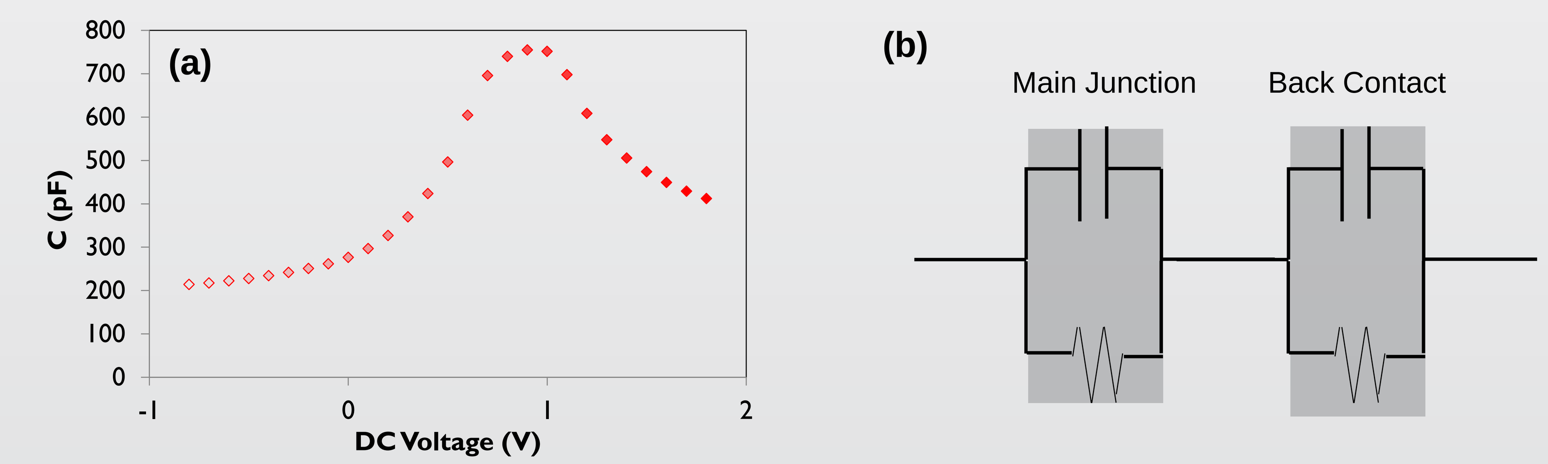


*Figure 4. **(a)** Graph of CV data. Capacitance response rolls over in forward bias, indicating a back contact barrier. **(b)** Equivalent circuit diagram of a solar cell with a back contact.*

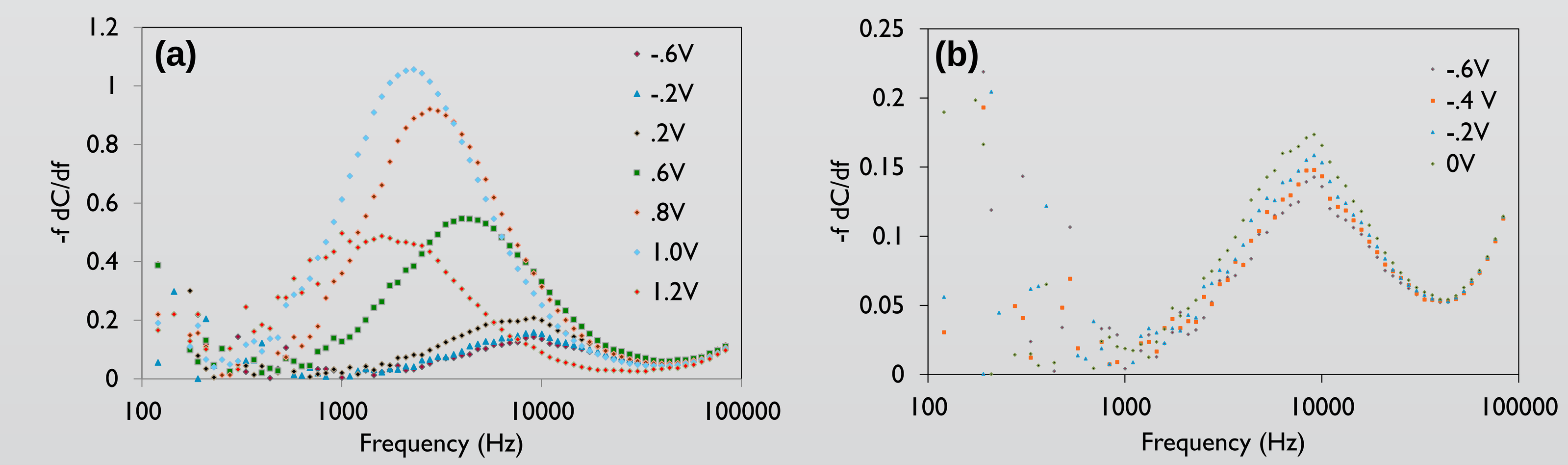


*Figure 5. Effect of DC Bias on AC response for the CIGS cell in Figure 4. The emission frequency seems to shift to lower energies in forward bias **(a)** Data for AS across a full range of DC bias values. **(b)** Focus in on reverse bias data, which show a constant AS peak position.*

Back Contact Modeling

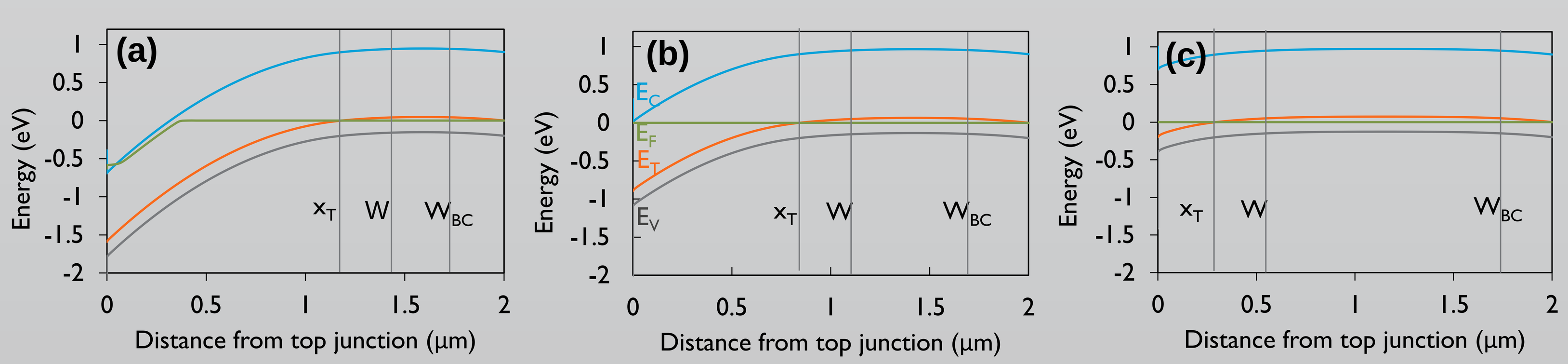


***Figure 6.** Band diagrams created using the expected parameters for our samples. Created using SCAPS [2] to solve Poisson's equation for the device. The trap state stays a constant value from the edge of the depletion width as the DC bias is varied. **(a)** At -0.7V reverse bias. **(b)** At 0V bias. **(c)** At 0.7V forward bias.*

Drive Level Capacitance Profiling

- Technique which determines carrier and trap density from a purely AC measurement: $N_{DL} = -\frac{C_0^3}{2q\epsilon A^2 C_1} = p + \int_{E_F}^{E_V+E_e} g(E,x)dx$

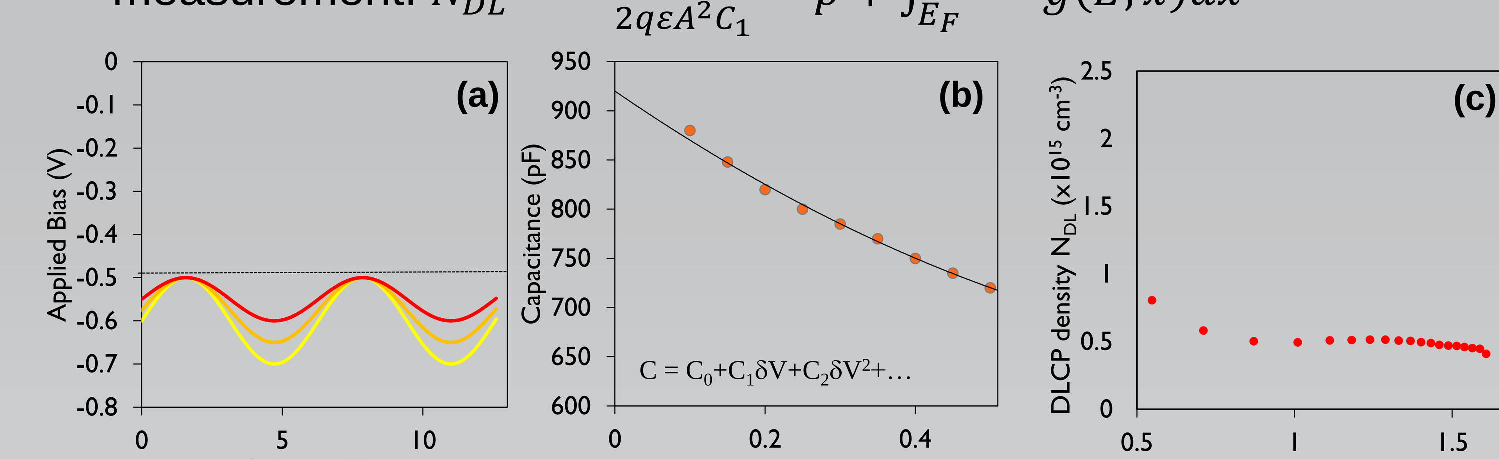


***Figure 7. (a)** Method of varying V_{ac} during the DLCP measurement so the measurement location remains constant. **(b)** Capacitance dependence on $|V_{ac}|$. C_0 and C_1 are used to find N_{DL}. **(c)** Variation of N_{DL} with average measurement location <x>.*

Model Analysis

What can cause a thermally activated step in capacitance?

$$C=\frac{\epsilon A}{<x>} \qquad <x> = \frac{\int_0^\infty x\delta\rho(x)dx}{\int_0^\infty \delta\rho(x)dx}$$

- Series resistance, such as a low pass RC filter [3]
  - Series resistance determined from IV data.
  - Not at the correct f for this step.
- Back contact barrier [4]
  - Capacitance step due to depletion region at back (W_B).
  - At low frequencies, carriers can travel over the barrier; measured energy E_B; $<x>_{HF} - <x>_{LF} = W_B$
- Trap state
  - $<x>_{HF} - <x>_{LF}$ is constant as V is varied; Depends on N_T.
  - N_{DL} is larger at low frequencies, when traps add to the response.

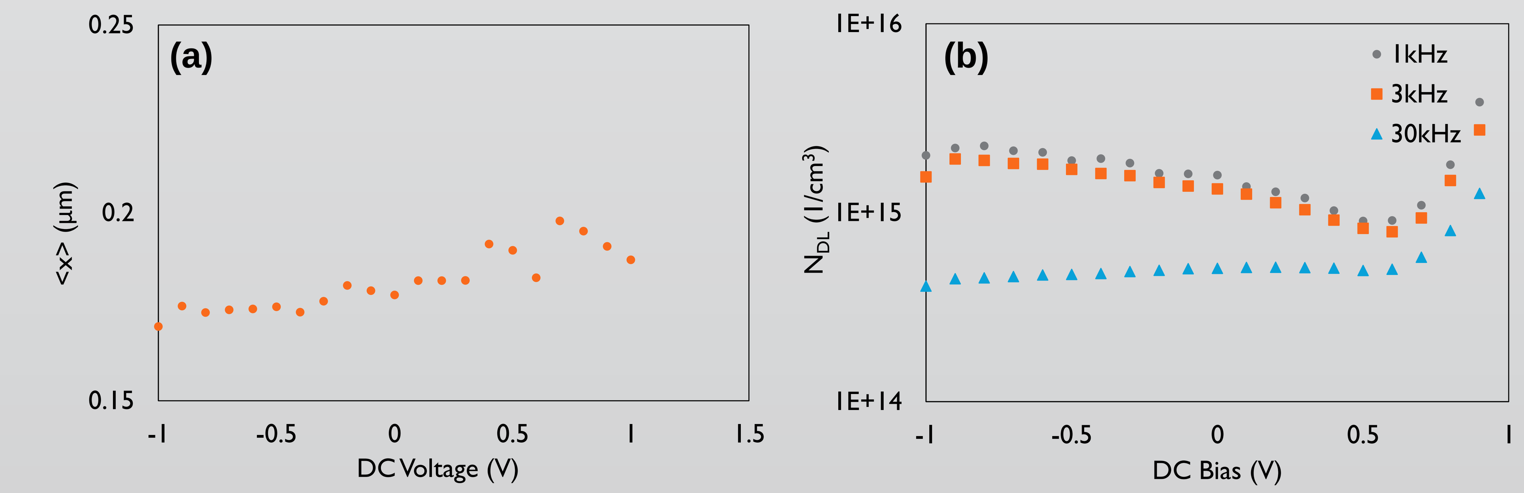


***Figure 8. (a)** The first moment of charge response <x> does not change significantly with DC bias, consistent with both the back contact barrier and the trap state models. **(b)** Increased N_{DL} at low frequencies indicates the presence of a trap state.*

Conclusions

- Samples clearly show both a bad back contact and a trap in the bulk material.
- DLCP allows the capacitance step to be associated with a trap state.
- Shift in E with DC bias suggests a non uniform density of states, a shift in trap energy as the quasi-Fermi energy moves, or overlap between the trap energy and back barrier energy.
- Numerical models of DLCP would be useful for further analysis.

Acknowledgements

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References:

[1] Rockett, et al., Thin Solid Films **372**, 212 (2000).
[2] M. Burgelman, et al., *Thin Solid Films*, **361**, 527 (2000).
[3] T Weiss, et al.,Appl Phys. Lett. **102,** 202106 (2013)
[4] T. Eisenbarth, et al., J. Appl. Phys. **107**, 034509 (2010).

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