Frequency and Voltage Dependence of Series Resistance in a Solar Cell

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Abstract

While admittance measurements of solar cells are typically conducted in reverse or at zero bias, and analyzed using the depletion approximation, the operating point of the solar cell is in forward bias, and the series resistance is often estimated using IV curves with a high forward current. In this mode, the device is no longer in the depletion regime, and the large number of injected minority carriers alters the transport properties significantly. In our Cu(In,Ga)Se_2 devices, we measure negative values of capacitance at high forward bias, which may be linked to injected minority carriers and carrier transport limitations, although our calculations of capacitance may also be influenced by series resistance.

In this study, we compare AC and DC measurements of voltage dependent series resistance to try to better understand the negative capacitance signal.

Introduction

Solar cells:

- Imperfect → need to understand carrier trapping, recombination and transport better

Admittance Spectroscopy:

- Useful tool to characterize electronic properties
- Weird → shows negative capacitance

Negative Capacitance:

- Shows up at $V > V_{bi}$
- Not inductive
- Predicted by model including $R_s(V)$, where $R_s(V)$ decreases rapidly with bias
- Need to measure $R_s(V)$
- Extract device parameters
- Then we can better understand device performance

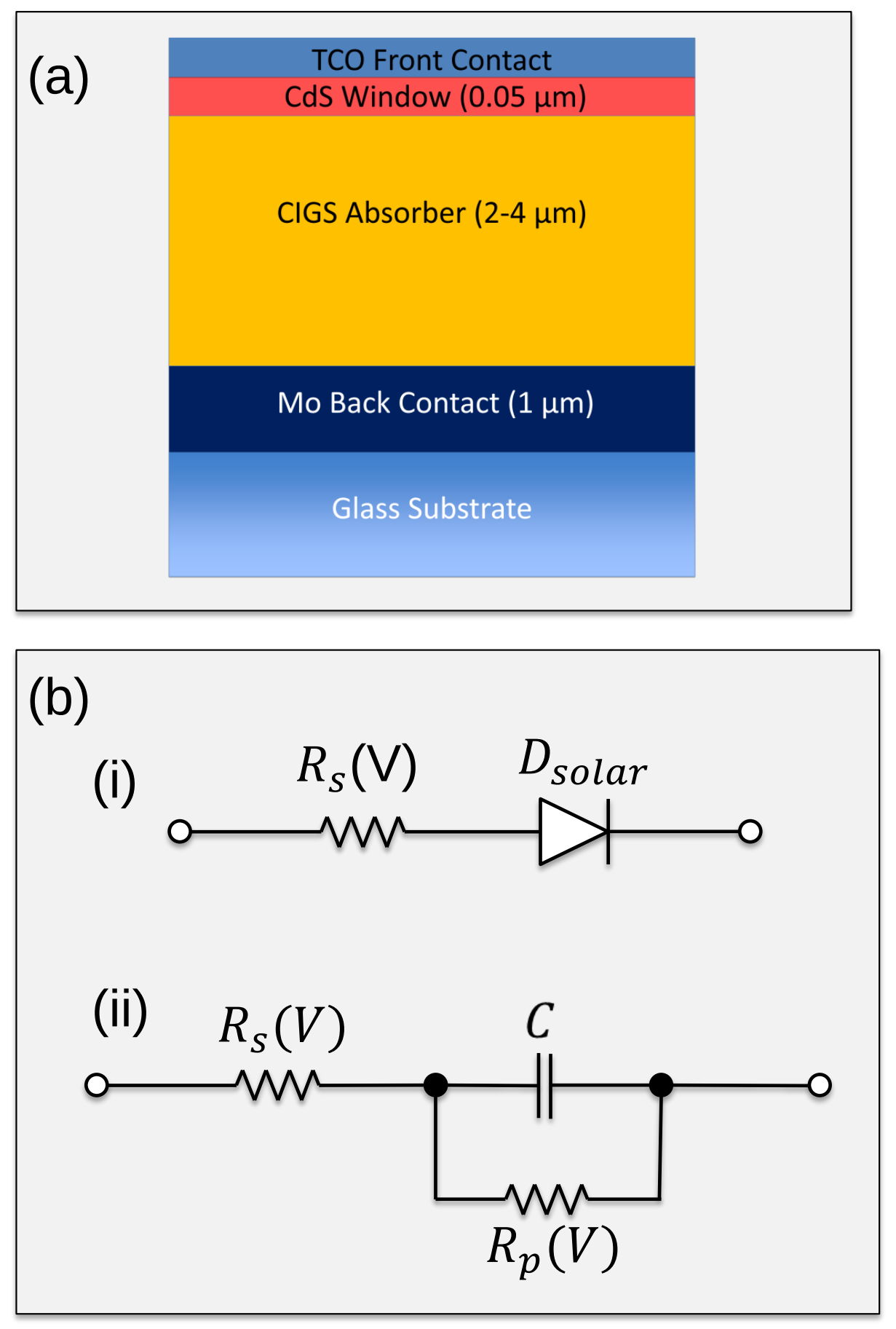

Figure 1: **(a)** Structure of CIGS solar cell and **(b)** the circuit diagram for a **(i)** traditional single-diode model of a solar cell and **(ii)** the model accounting for negative capacitance.[1]

Capacitance Voltage/Frequency Data

High forward bias:

- Injection of minority carriers
- Appearance of negative capacitance

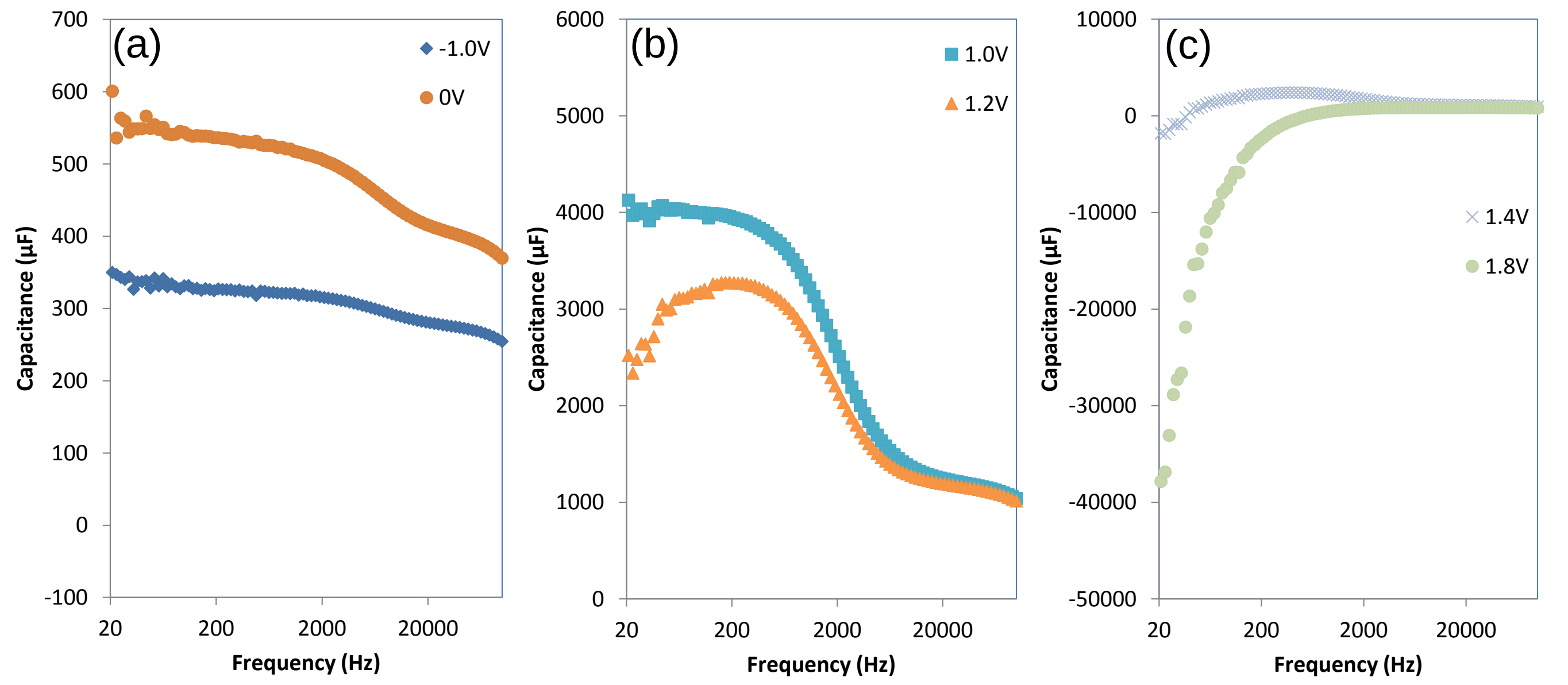

Figure 2: Capacitance-frequency data for **(a)** reverse and zero bias **(b)** forward bias before the negative capacitance phenomenon and **(c)** high forward bias, where the capacitance goes significantly negative.

R_s from Double-Light Method (DLM)

Double-Light Method (DLM)[2]:

$$R_s = \frac{V^{(1)} - V^{(2)}}{J^{(1)} - J^{(2)}}$$

where $V^{(1)}$ and $J^{(1)}$ represent the point on the less illuminated curve corresponding to ΔJ greater than the illumination current, $J_{L1.}$ $V^{(2)}$ and $J^{(2)}$ represent the point on the more illuminated curve corresponding to ΔJ greater than the illumination current, $J_{L2.}$

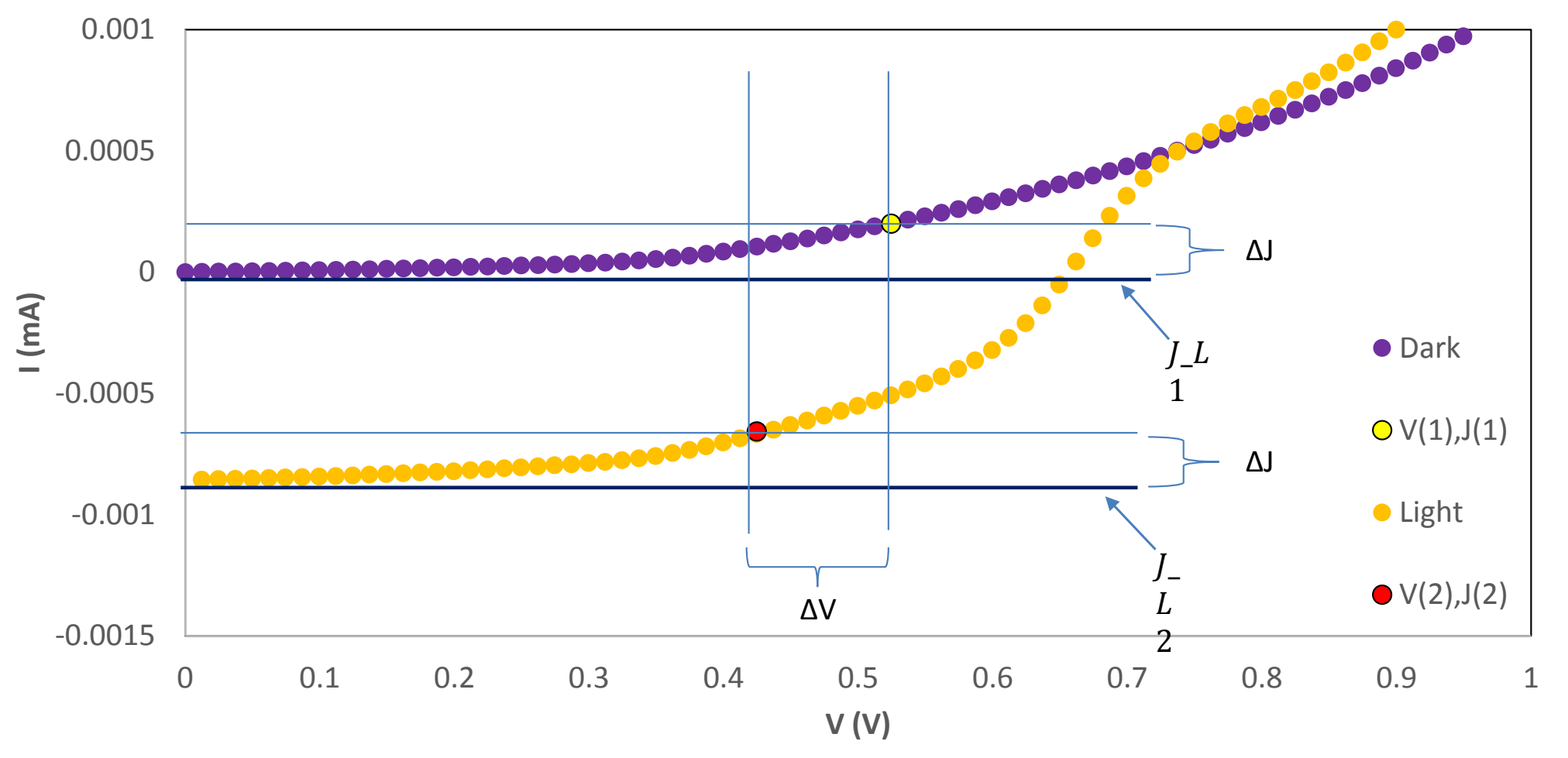

Figure 3: IV curves for the CIGS sample collected at $T = 140K$ in the dark and with illumination from a halogen light source at $\sim 0.5\, {}^{W}/_{cm^2}$.

R_s From Differential Resistance Analysis

Differential resistance is determined by finding the inverse of the slope between consecutive points on the IV curve. In the regime where our R_p is negligible, we can say:

$$R_{s,i} = \frac{V^{(i+1)} - V^{(i)}}{J^{(i+1)} - J^{(i)}}$$

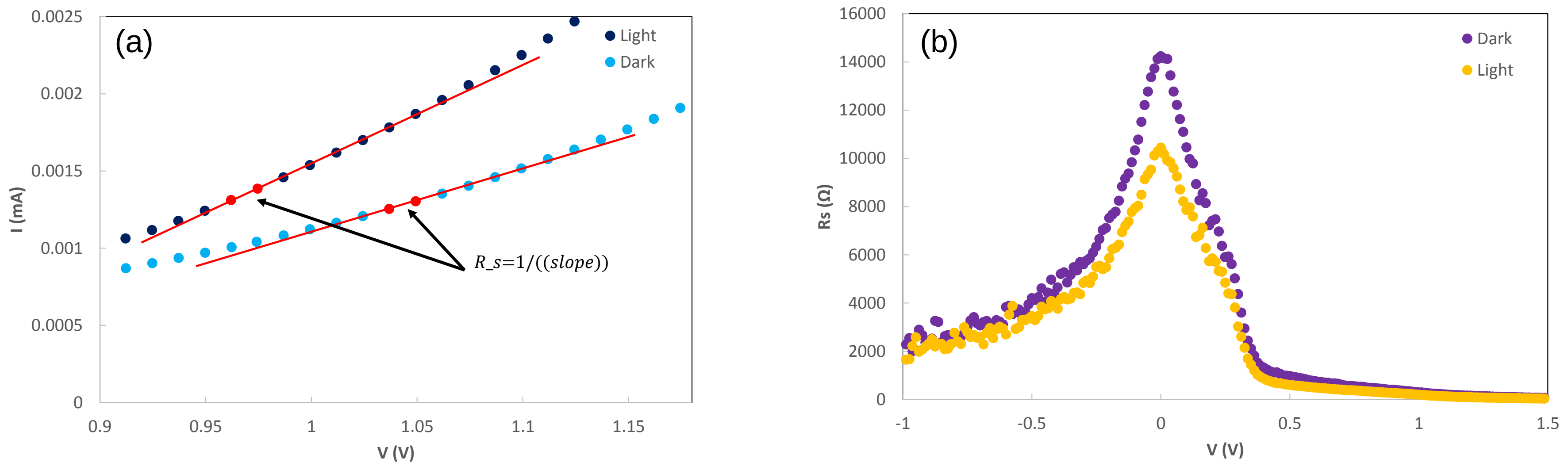

Figure 4: **(a)** An example of how the differential resistance is calculated. The inverse of the slope between two consecutive points is found. **(b)** Differential resistance data for IV curves taken at $T = 140K$ in the dark and with illumination from a halogen light source at $\sim 0.5\, {}^{W}/_{cm^2}$.

R_s from Impedance Measurements

AC Resistances:

- Plot real and imaginary parts of impedance (from admittance spectroscopy data)
- Fit to an equation for a circle
- Extract AC series and parallel resistances [3]

$$Z = \frac{1}{Y} = Z' + iZ'' = R_s + \frac{R_p}{1 + (\omega R_p C)^2} - i\frac{\omega C {R_p}^2}{1 + (\omega R_p C)^2}$$

$$(x-h)^2 + (y-k)^2 = r^2$$

$$Z''^2 + + [(Z' - R_s) - \frac{R_p}{2}]^2 = \frac{{R_p}^2}{4}$$

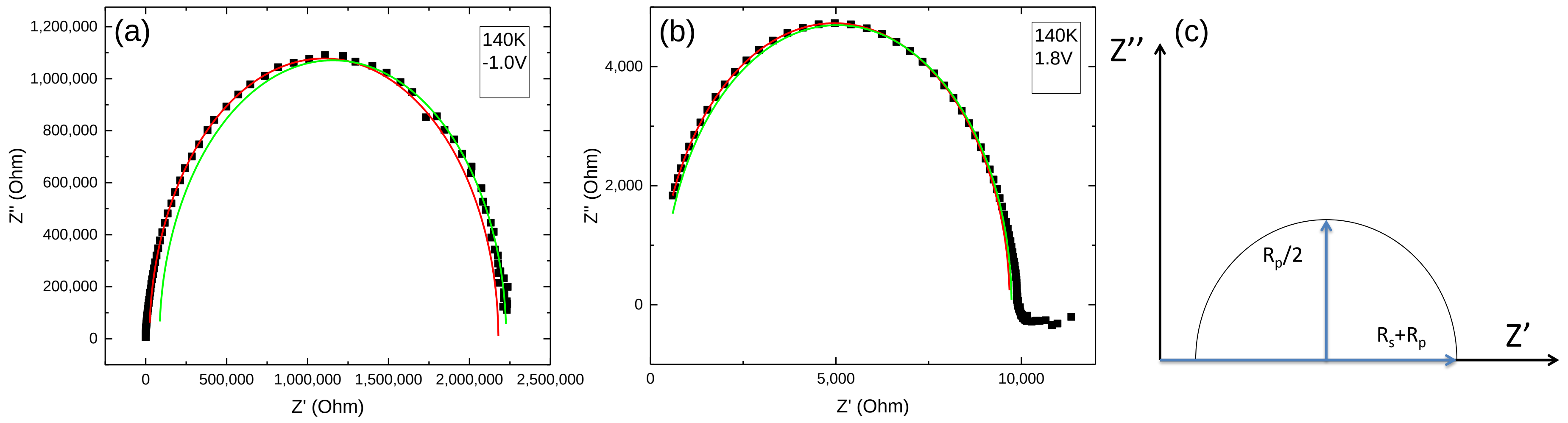

Figure 5: **(a)** Impedance curve at negative bias and **(b)** impedance curve at high forward bias. **(c)** Theoretical impedance curve showing how series and parallel resistances are extracted. Both impedance curves are fitted for the left (fit 1, high frequency) and right (fit 2, low frequency) sides of the circle.

Comparisons

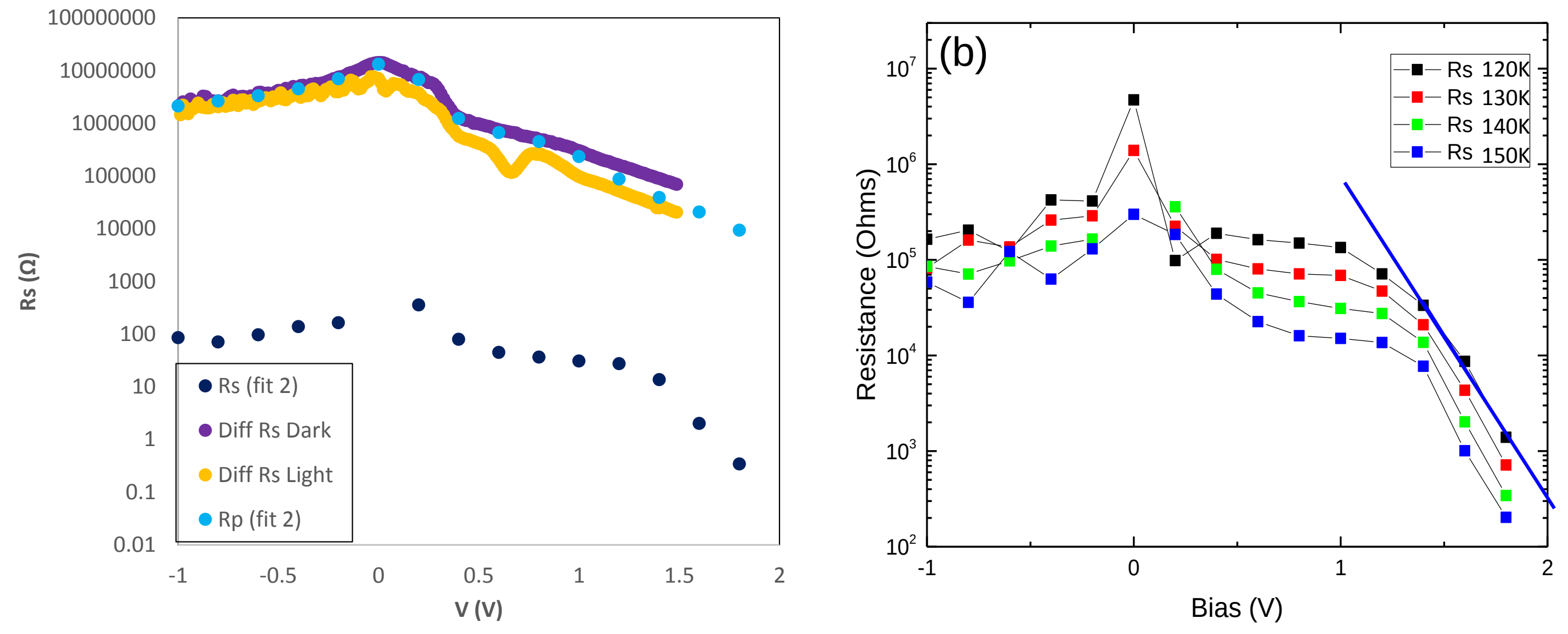

Figure 6: **(a)** DC differential resistance and impedance AC series resistance from fit 2. **(b)** Series resistances for varying temperatures from impedance measurements.

- Differential R_s and impedance derived R_p agree; as expected, R_p dominates the total resistance that a DC current would pass through
- R_s from DLM surprisingly large; needs further investigation
- Photoconductivity or phototransistor effects may significantly influence results [4]
- R_s from impedance is significant and falls off exponentially in far forward bias

Conclusions

- Significant R_s seems to be present in devices which also exhibit negative capacitance phenomenon
- $R_s(V)$ behavior is consistent with a model predicting negative capacitance
- Impedance measurements seem to give the best estimate of differential R_s. DLM may be affected by photoconductivity or phototransistor effects. Differential resistance always shows the total resistance, $R_s + R_p$.

Moving Forward:

- Use series resistance data to correct IV and CV curves
- Obtain fundamental values for main diode of solar cell
- Better understand limitations to device performance

Acknowledgements

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References:

[1] Barna, Arpad A., Transactions on Circuit Theory **18**:233-240 (1971).
[2] Fong, Kean C., et al., Progress in Photovoltaics: Research and Applications; **21**:490-499 (2013).
[3] Jonscher, AK, *Dielectric Relaxation in Solids;* Chelsea Dielectrics Press Ltd.(1983).
[4] Rockett., A., et al., Solar Energy Materials & Solar Cells **118**:141-148 (2013).