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)Se2 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 lead to understand carrier trapping, recombination and transport better
- We need to understand device performance

Negative Capacitance:
- Shows up at \( V > V_n \)
- Not inductive
- Predicted by model including \( R_s(V) \)

Admittance Spectroscopy:
- Useful tool to characterize electronic properties
- Weird shows negative capacitance

Capacitance Voltage/Frequency Data

High forward bias:
- Injection of minority carriers
- Appearance of negative capacitance

Rs from Double-Light Method (DLM)

DC double-light method (DLM) [2]:
\[
R_s = \frac{V(1) - V(2)}{I(1) - I(2)}
\]

where \( V(1) \) and \( I(1) \) represent the point on the less illuminated curve corresponding to \( \Delta I \) greater than the illumination current, \( J_{s1} \). \( V(2) \) and \( I(2) \) represent the point on the more illuminated curve corresponding to \( \Delta I \) greater than the illumination current, \( J_{s2} \).

Rs from Impedance 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:
\[
R_s = \frac{V(x+1) - V(x)}{I(x+1) - I(x)}
\]

Rs from Impedance Measurements

AC Resistsances:
- 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]

Comparisons
- 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

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References: