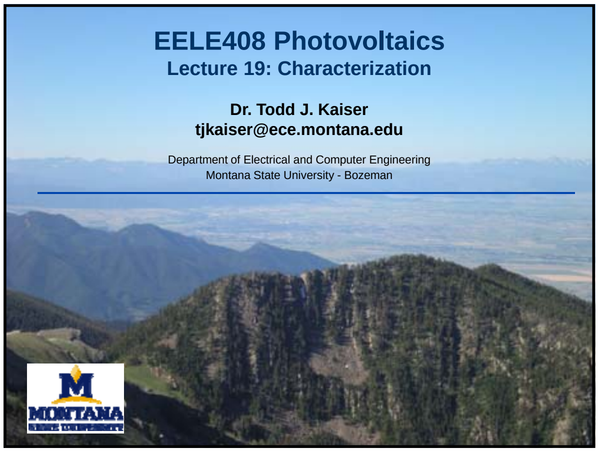

EELE408 Photovoltaics

Lecture 19: Characterization

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Electrical Characterization

- 3 basic techniques
  - Illuminated IV: the cell is illuminated at one sun and basic cell parameters are measured
  - Dark IV: cell is in the dark and the cell IV are traced
  - Jsc Voc: Jsc and Voc are measured at different illumination levels

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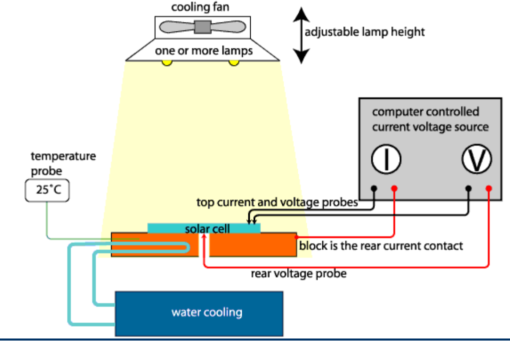
Measurement of Solar Cell Efficiency

- Air Mass 1.5 for terrestrial cells and AM0 for space cells
- Intensity of $100\text{mW/cm}^2 = 1\text{kW/m}^2$ (one sun)
- Cell temperature of 25°C (not 300K)
- 4-point probe to remove effect of contact resistance

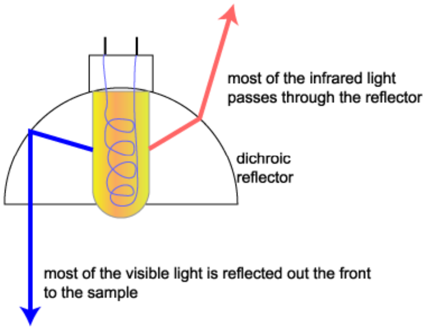
Basic Structure for IV Testing



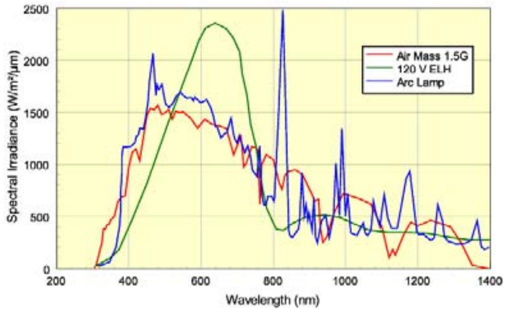
Illumination Sources

- The intensity as well as the spectrum must be matched to sun light
- Ideal artificial source features
  - Spatial nonuniformity of less than 1%
  - Variation in total irradiance with time less than 1%
  - Filtered for a given reference mismatch of 1%
  - Gives an accuracy of 2%
  - Cost: <$100,000

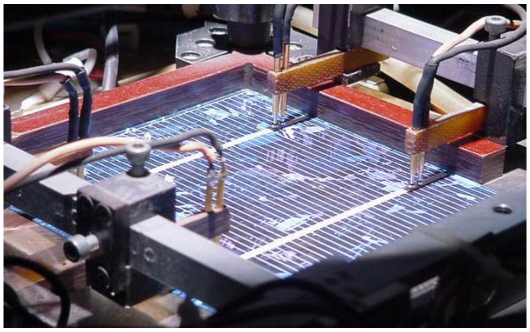
Halogen Lamp with Dichroic Reflector



Spectrums from typical solar simulator sources



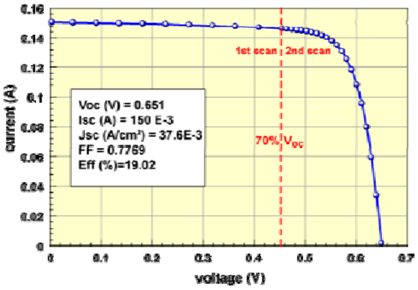
Probing



Errors

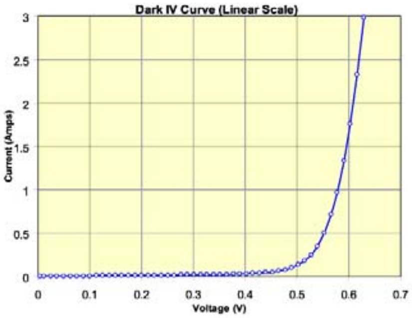
- Difficult to exactly match solar spectrum
  - Deviations in AM1.5 causes errors in J_{sc}
- One-sun illumination is quite intense and heats the cell
  - Poor temperature control introduces errors in V_{oc}
- Contact errors in probing
  - Probing errors primarily cause Fill Factor errors but can also cause J_{sc} and V_{oc} errors

Automated Electronics

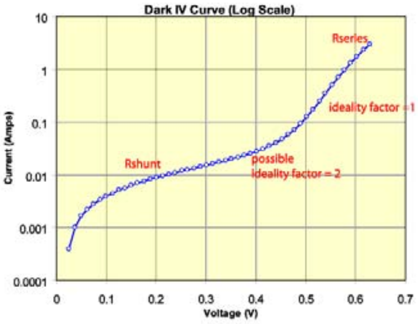


Two sweeps 0-70% of Voc then 70%-100% of Voc in smaller increments

IV Dark (linear)



IV Dark (semilog)

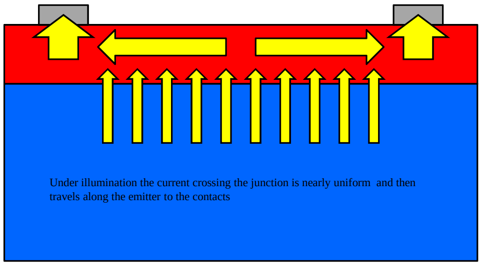


Semilog IV plot reveals more information about the diode. Different regions of the IV curve are dominated by different loss mechanisms

Limitations of Dark IV Measurements

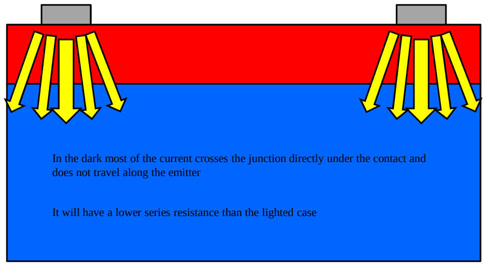
- Assumes the light IV curve is just the dark IV curve shifted by the photogenerated current
  - Not always true, if has high series resistance
  - Or if carrier lifetime is a function of voltage in some multicrystal materials
- Measures the diode with current in the opposite direction

Current Comparison (Light)



Under illumination the current crossing the junction is nearly uniform and then travels along the emitter to the contacts

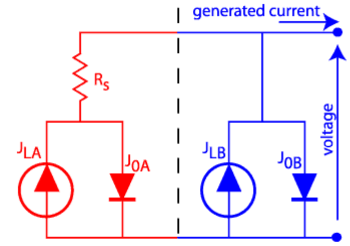
Current Comparison (Dark)



In the dark most of the current crosses the junction directly under the contact and does not travel along the emitter

It will have a lower series resistance than the lighted case

Model for Effect of Series Resistance on Part of the Solar Cell



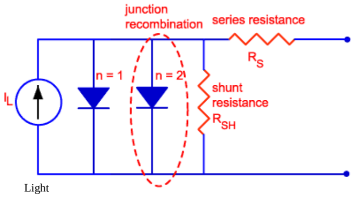
Portion of cell with high series resistance, region A. Area = C

Portion of cell with no series resistance, region B. Area = 1 - C

Double Diode Model

- Single diode model assumes a single value for the ideality factor
- In reality the ideality factor is a function of the voltage across the device
- High voltage
  - Recombination dominated by surface and bulk recombination ➔ n → 2
- Low voltage
  - Recombination in the junction dominates ➔ n → 1

Double Diode Equations



Small fluctuations in the light intensity overwhelm the effects of the second diode. More common to use the double diode equation in the dark

Light

$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT} - 1\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT} - 1\right) - \frac{V+JR_s}{R_{shunt}}$$

Dark

$$J = -J_{01}\exp\left(\frac{q(V+JR_s)}{kT} - 1\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT} - 1\right) - \frac{V+JR_s}{R_{shunt}}$$

Ideality Factor Measurements

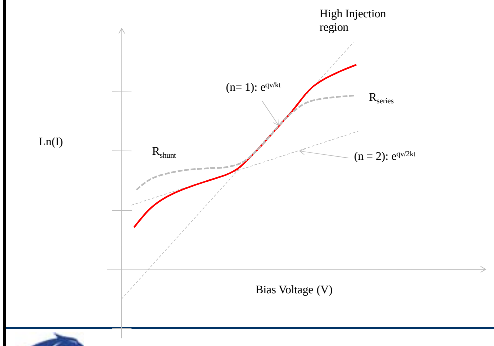
$$I = I_0\left(\exp\left(\frac{qV}{nkT}\right)-1\right)$$

$$I \approx I_0 \exp\left(\frac{qV}{nkT}\right)$$

$$\ln(I) \approx \ln(I_0)+\left(\frac{q}{nkT}\right)V$$

Plot the natural log of the current vs the voltage gives a slope proportional to q/nkT and an intercept at the $\ln(I_0)$

Semilog plot of Dark Current-Voltage



Problems Measuring the Ideality Factor

- At low voltages the shunt resistances dominates the device performance and causes a large peak (can not be compensated for)
- At high voltages the series resistances dominate causes a large peak in the ideality factor
- Ideality factor comes from a difference of signals and is prone to noise
- Temperature changes during measurement introduce errors

Carrier Lifetime

- Carrier lifetime in the bulk is composed of various recombination mechanisms
  - Band to Band or Radiation Recombination
  - Auger Recombination
  - Shockley-Read-Hall (SRH) Recombination via traps

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_A} + \frac{1}{\tau_{SRH}}$$

For indirect bandgap materials such as silicon the τ_{rad} is very large and usually neglected

Surface Lifetime

- Includes the surface recombination and surface lifetimes
- Function of Surface Recombination Velocity (S), the minority carrier Diffusivity (D), and width of the wafer (W)

$$\tau_s = \frac{W}{2S} + \frac{1}{D}\left(\frac{W}{\pi}\right)^2 \qquad : \text{Identical Surfaces } S = S_1 = S_2$$

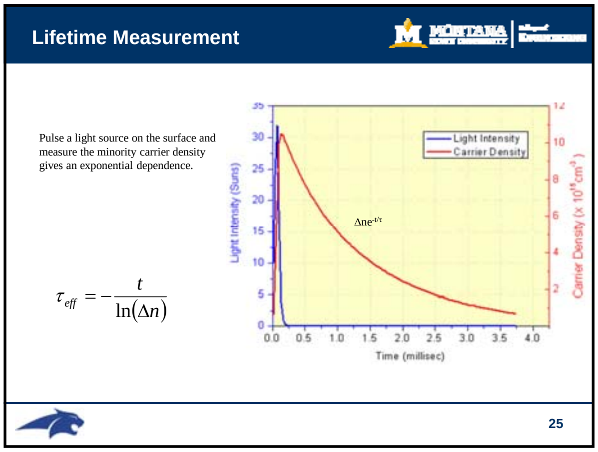
$$\tau_s = \infty \qquad : \text{Perfectly Passivated } S_1 = S_2 = 0$$

$$\tau_s = \frac{1}{D}\left(\frac{W}{\pi}\right)^2 \qquad : \text{High Recombination} \rightarrow \text{Large } S = S_1 = S_2$$

Effective Lifetime

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surface}}$$

- Combination of bulk lifetime and surface lifetime
- If correctly passivated surfaces then $\tau_{eff} = \tau_{bulk}$
- If high bulk lifetimes then effective is dominated by the surface: $\tau_{eff} = \tau_{surface}$



Lifetime Measurement

Pulse a light source on the surface and measure the minority carrier density gives an exponential dependence.

$$\tau_{eff} = -\frac{t}{\ln(\Delta n)}$$

$\Delta n e^{-t/\tau}$