Parameter Extraction of Solar Cells using Genetic Algorithm

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In this talk:

- Genetic Algorithm (GA).
- Solar cells: working principles, theoretical models.
- Using GA to model Solar Cells.
- How GA aids in developing new theoretical models.

Primer to Solar Cells

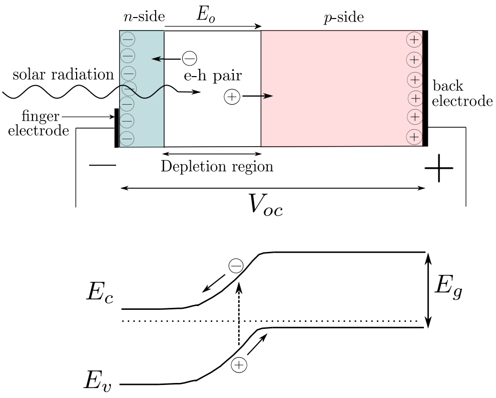


Figure 1: Basic principle behind solar cell operation illustrated.

- A photo-voltaic device. Solar Energy $\rightarrow$ Electrical energy.
- 2 step process:
  - Harness carriers,
  - Drive the carriers to constitute a current.

Solar Cell as a current generator

Solar cell: an unbiased *pn* diode under illumination. A current generator.

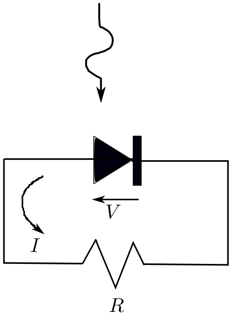
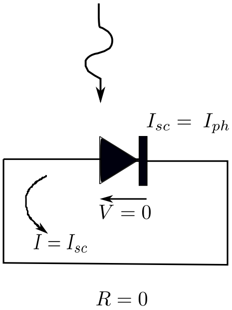


Figure 2: Solar cell represented by the diode, connected to a load R.

Solar Cell as a current generator

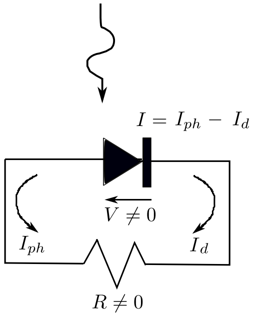
Consider a shorted load.



- $I = I_{sc} = I_{ph}$. Maximum current.
- $V = 0$.

Solar Cell as a current generator

Consider finite load, $R \neq 0$.



- V_{load} reduces E_o in the diode, hence the charge separation ability.
- Holes (electrons) migrate to $n(p)$-side (*Minority Carrier Injection*).
- Forward diode current I_d.

Single diode equation for Solar Cell

- I_d, from Shockley diode equation:

$$I_d = I_o[\exp(\frac{qV}{\eta k_b T}) - 1] \tag{1}$$

  I_o: *Reverse saturation current*
  η: ideality factor. $1 < \eta < 2$.

- Thus, total I through the solar cell is,

$$I = I_{sc} - I_o[\exp(\frac{qV}{\eta k_b T}) - 1] \tag{2}$$

  The *single-diode equation* (SDE).

$V - I$ of a Solar Cell

$V - I$ of solar cell: *pn* diode $V - I$ flipped and shifted.

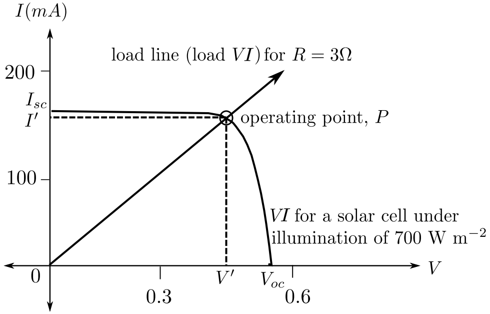


Figure 3: $V - I$ of a typical Si solar cell and load driven by the solar cell. The intersection point is the operating point of the circuit. From *Principles of Electronic Materials and devices* by S. Kassap [1]

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Power delivered to the load $= V'I'$.

Non Idealities: Series and Shunt resistance

- Series resistance (R_s): resistance faced by flowing carriers in the semiconductor (SC), ohmic resistance of metal electrodes, contact resistance b/w SC and metal.
  Broadens the $V - I$, reduces maximum possible power delivered to the load.
- Shunt resistance (R_{sh}): manifests as carriers flowing through grain boundaries in polycrystalline SC, away from load. Reduces V_{oc}.
- These parasitic resistance cause loss of solar cell efficiency.
  Low R_s and high R_{sh} is desired.

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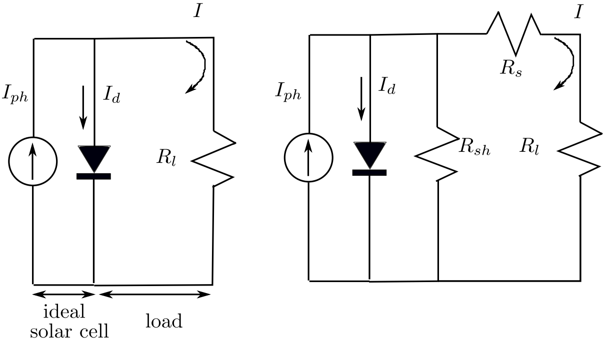


Figure 4: Circuit equivalent representation of (a) an ideal solar cell connected to load (b) single-diode model with the parasitic series and shunt resistance.

Modified single-diode equation:

$$I = I_{sc} - I_o[\exp(\frac{q(V+IR_s)}{\eta k_b T}) - 1] - \frac{V+IR_s}{R_{sh}} \quad (3)$$

Double diode equation of a Solar Cell

- At low illumination, recombination of the generated carriers occurs in the space charge region. Therefore, recombination current term is added to SDE

$$I = I_{sc} - I_{o1}[\exp(\frac{q(V + IR_s)}{\eta_1 k_b T}) - 1] - I_{o2}[\exp(\frac{q(V + IR_s)}{\eta_2 k_b T}) - 1] - \frac{V + IR_s}{R_{sh}} \quad (4)$$

The *double diode equation* (DDE).
I_{o1} and I_{o2} : diffusion and recombination components of the reverse saturation current respectively.
η_1 and η_2 : ideality factors for the two processes (around 1 and 2 respectively).

Modelling the Solar Cell

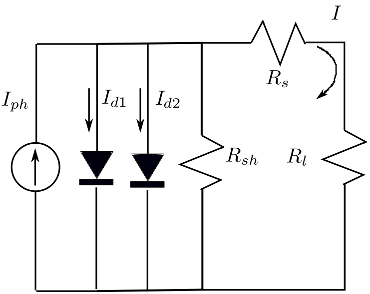


Figure 5: Circuit equivalent representation of the double-diode model with the two diodes representing diffusion and recombination reverse current respectively.

- Theoretical models : SDE and DDE, useful in simulation during production and testing phase. Give insight on the physical processes inside the solar cell.
- The parameters ($I_{sc}, I_o, R_s, R_{sh}, \eta$ for SDE, $I_{sc}, I_{o1}, I_{o2}, R_s, R_{sh}, \eta_1, \eta_2$ for DDE) cannot be measured experimentally.

Determining the parameters

- Two principle methods:
  - Analytical,
  - Heuristic.
- DDE: a non-linear, implicit, transcendental equation - difficult to solve.
  Analytical approach till date involves arbitrary omission of one or more parameters [4, 5, 6, 7].
- Computational heuristic methods are more promising.
  Multi-parameter optimization methods sample the parameter space and yields a solution which minimizes the “error” [8, 9].

Determining the parameters

- In this work we use Genetic Algorithm (GA) to extract optimal parameter values from raw $V - I$ data of a Solar Cell (single-junction, multi-junction)

Genetic Algorithm (GA) 101

- A multi-parameter search-and-optimize procedure inspired from theory of natural selection and survival of the fittest.
- A pool of potential solutions is created. GA iteratively weeds out the unfit solutions while sampling newer sets of the solution space using biological operators like reproduction and mutation [2, 3].
- Gives sub-optimal solution. Requires less computation.

The Algorithm

Preliminary requirements:

- **Genetic Representation**: the solution domain is encoded in binary.
- **Fitness function**: to grade the solution domain.

In our case:

- An array of $16 \times m$ bits represents one chromosome. A sector of 16 bits represents one trait (parameter). Total m parameters.

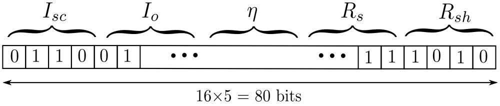


Figure 6: A chromosome representing a set of the five parameter values (for SDE).

- Cost function f

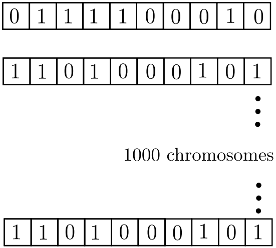
$$f = \sqrt{\frac{1}{n} \sum_{j=0}^{n} \frac{(I_j(measured) - I(V_j))^2}{I_j(measured)^2}} \tag{5}$$

is 0 when all parameters are exactly deduced.

The Algorithm

- **Initialization**: a population set is randomly created and ranked fitness-wise.

In our case, the pool is made of 1000 chromosomes.



The Algorithm

- **Selection**: constructing the next, fitter generation.
  - The top 5 fittest are directly sent to the next generation.
  - **Crossover**: Parents from the top 30 % of the population are crossed to give birth to offspring for the next generation.
  - **Mutation**: A randomly selected bit is flipped with some probability. Allows for more diversity.

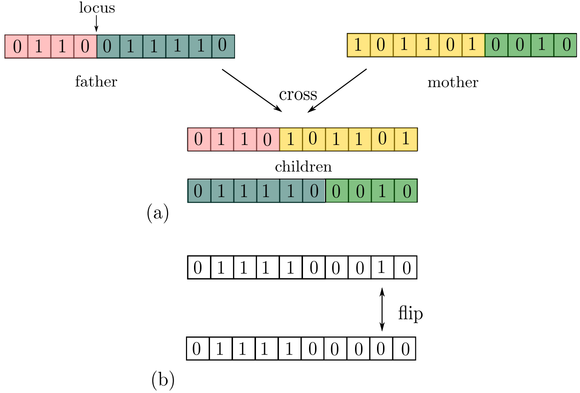
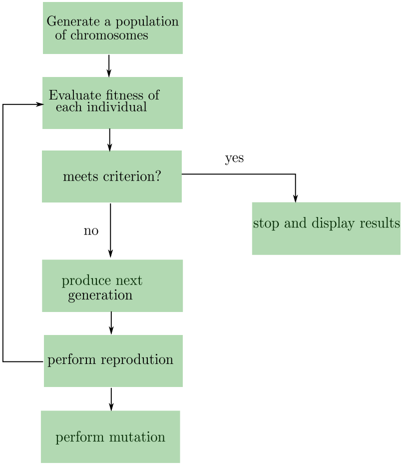


Figure 7: (a) Single point crossover reproduction (b) Mutation

The Algorithm

- **Termination** when the maximum number of generations is reached or when the solution converges i.e. error in the best solution is under prescribed tolerance.

GA in a nutshell



Implementing GA

- The GA is implemented to extract the 5 parameters of SDE ($I_{sc}, I_o, \eta, R_s, R_{sh}$), DDE ($I_{sc}, I_{o1}, I_{o2}, , R_s, R_{sh}$; η_1 and η_2: 1 and 2 respectively)
- Before calling GA, a search range for every parameter is determined (through visual inspection or preliminary direct search methods), by ± 5 to 100 %.
- GA runs for $\approx$ 100 generations.
- Operating temperature: 300 K

Results and Analysis - DDE

Sanity check for developed program on a test cell under the DDE formulation.

Table 1: Testing GA for a test Si solar cell. $f = 0.000125723$

Parameter	Actual	Acquired from GA
I_{sc}	1.0 A	1.00055 A
I_{o1}	1×10^{-10} A	9.775×10^{-11} A
I_{o2}	5×10^{-7} A	7.276×10^{-7} A
R_s	0.025 Ω	0.02458 Ω
R_{sh}	1000 Ω	1999.97 Ω

- The extracted parameters closely reproduce the original $V - I$.

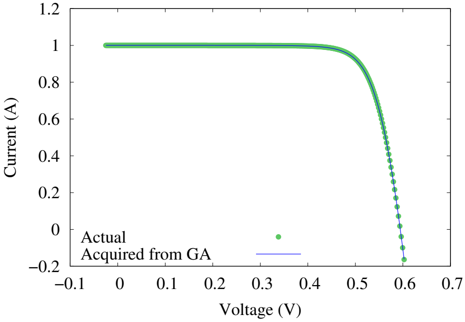


Figure 8: Comparing the actual $V - I$ with $V - I$ evaluated using parameters yielded by the GA. The curves have been calculated using DDE.

Single junction solar cells

GA implemented on measured data of individual GaInP, (In)GaAs and Ge solar cells.

Table 2: Extracted (and measured) Parameters for GaInP, (In)GaAs, Ge solar cells using double-diode GA.

Parameter	GaInP	(In)GaAs	Ge
I_{sc}(measured)	0.505 A	0.550 A	0.86 A
V_{oc}(measured)	1.396 V	1.030 V	0.247 V
I_{sc}	0.4971 A	0.5326 A	0.8744 A
I_{o1}	4.188×10^{-26} A	2.846×10^{-19} A	8.033×10^{-6} A
I_{o2}	1.040×10^{-12} A	1.147×10^{-9} A	0.004221 A
R_s	0.0325 Ω	0.01 Ω	0.0282 Ω
R_{sh}	102.696 Ω	10960.8 Ω	1288.28 Ω

- Measured I_{sc} and calculated I_{sc} are in agreement.

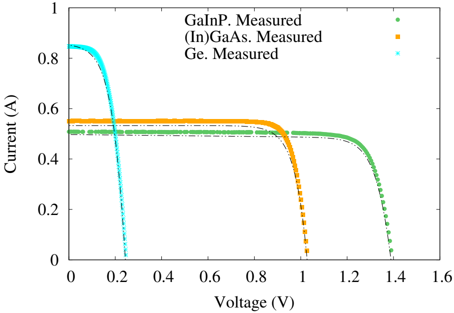
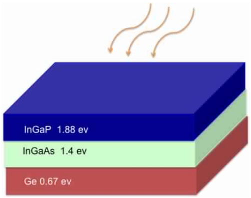


Figure 9: Comparing the measured $V - I$ of the solar cells (dots) with $V - I$ (dashed curves) evaluated using parameters yielded by the GA in table 2, calculated using DDE.

Single junction solar cells in series

Table 3: Extracted parameters for the effective cell

Parameter	Value acquired from GA
I_{sc}	0.5041 A
I_{o1}	1×10^{-35} A
I_{o2}	1.597×10^{-11} A
R_s	0.08571 Ω
R_{sh}	9931.08 Ω



- The double-diode equation had to be modified to yield accurate ideality parameters of the combined cell: $\eta_1 \approx 2, \eta_2 \approx 4$.
- I_{o1} value is not practical. Resort to SDE.

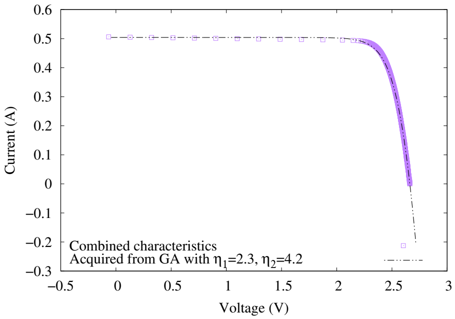


Figure 10: Scatter plot shows the $V - I$ evaluated for a solar cell composed of GaInP, (In)GaAs, Ge cells in series. The dashed plot represents the reproduced characteristics obtained by plugging extracted parameters (table 3) from the scatter plot into modified DDE.

Single junction solar cell - SDE

Table 4: Extracted (and measured) Parameters for GaInP, (In)GaAs, Ge solar cells using single-diode GA.

Parameter	GaInP	(In)GaAs	Ge
I_{sc}(measured)	0.505 A	0.550 A	0.86 A
V_{oc}(measured)	1.396 V	1.030 V	0.247 V
I_{sc}	0.505 A	0.556 A	0.883 A
I_o	7.128×10^{-11} A	9.849×10^{-10} A	0.006312 A
η	2.269	1.965	1.914
R_s	0.0125 Ω	0.0159 Ω	0.01072 Ω
R_{sh}	147.42 Ω	1000 Ω	804.991 Ω

- Measured I_{sc} and calculated I_{sc} are in agreement.
- From DDE analysis we infer $I_o = I_{o2}$ with $\eta = \eta_2 \approx 2.$ for single junction cell.

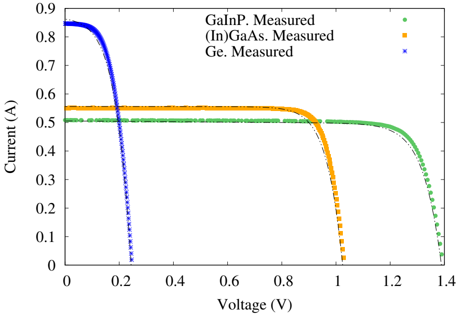


Figure 11: Comparing the measured $V - I$ of the solar cells (dots) with $V - I$ (dashed) evaluated using parameters yielded by the GA in table 4, calculated using SDE .

Triple junction solar cell - SDE

The GA for SDE was fed with measured data from the manufacturer for a triple junction solar cell.

Table 5: Extracted parameters for an Azure triple-junction solar cell

Parameter	Value acquired from GA
I_{sc}	0.515916
I_o	7.6303×10^{-12} A
η	4.14874
R_s	0.08 Ω
R_{sh}	29999.7 Ω

- SDE is a more viable formulation in this case.
- Again from DDE analysis we infer $I_o = I_{o2}$ with $\eta = \eta_2 \approx 4$ for triple junction cell.

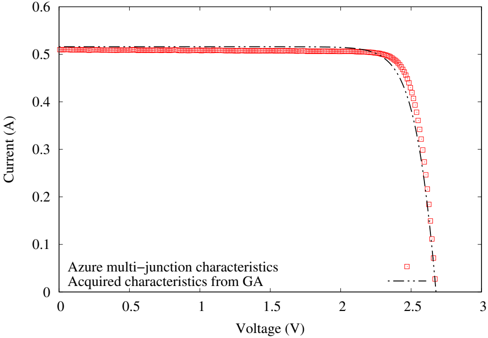


Figure 12: Comparing *Azure* triple-junction solar cell $V - I$ provided by the manufacturer to the reproduced $V - I$

Quadruple junction solar cell - SDE

The GA for SDE was fed with measured data from the manufacturer for a quadruple junction solar cell.

Table 6: Extracted parameters for a quadruple junction solar cell

Parameter	Value acquired from GA
I_{sc}	0.6868
I_o	2.747×10^{-9} A
η	7.85287
R_s	0.02293 Ω
R_{sh}	19999.7 Ω

- Here for a four-junction solar cell, $\eta \approx 8$

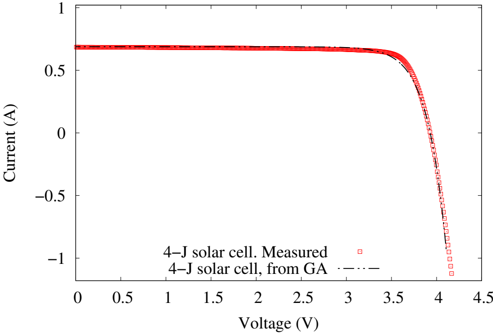


Figure 13: Comparing quadruple-junction solar cell $V - I$ provided by the manufacturer to the reproduced $V - I$.

Conclusions and Outlook

- Genetic Algorithm is a reliable and fast method to predict $V - I$ characteristics of single and triple junction solar cells.
- Single junction GA have been studied in literature [8, 9]. We extended the study to multi junction solar cells. GA aids in delineating patterns that can aid in building models for multi junction cells.
- Remains to be tested for n junction solar cells where $n > 4$.

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Thank You