Electrical, Mechanical, and Thermal Modeling of Photovoltaic Modules

An Overview

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Note: This is the first version of this presentation, and an updated version will be available in the future. If you are reading this after March 2010, please check http://steelandsilicon.com/pubs/ for an updated version.

Overview

The presentation surveys a broad range of topics relevant to modeling of PV modules, based on experience doing modeling for a number of PV companies and technologies (conventional front-contact, rear-contact, CPV).

The hope is that this will be useful not only to people who do modeling, but also to people who work on teams with modeling experts, or make decisions about which areas to explore through modeling or testing.

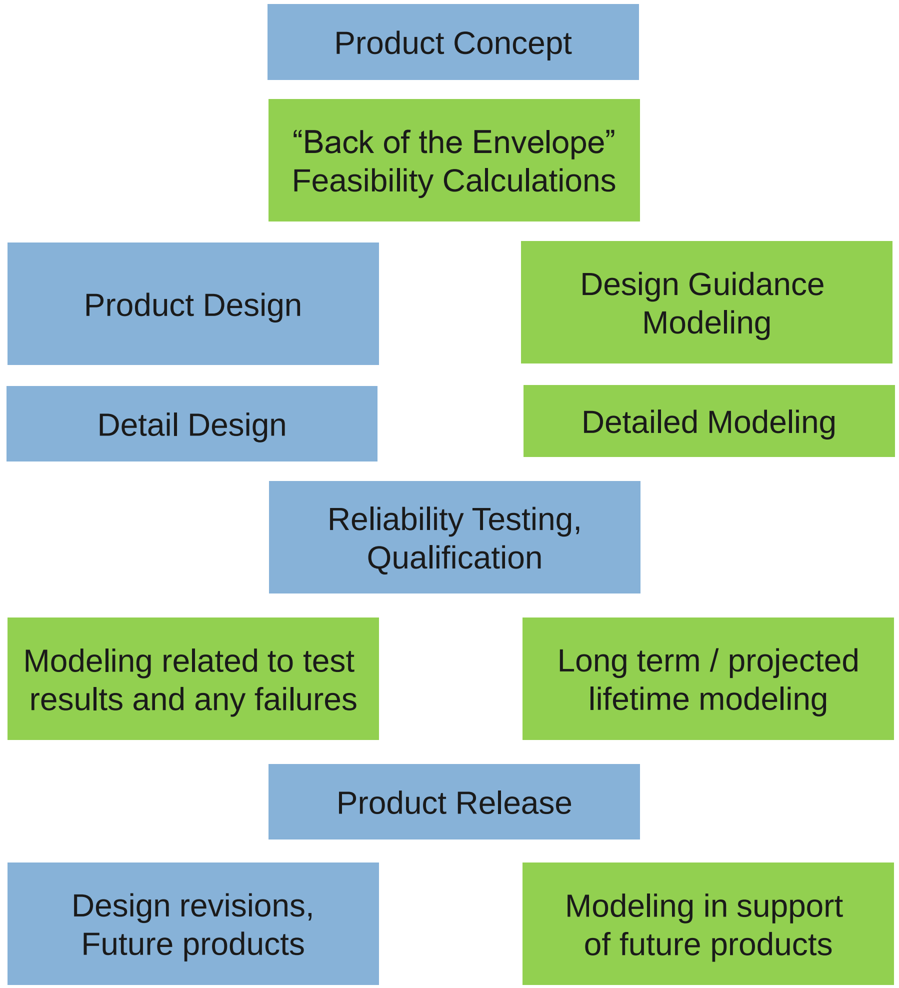
Outline

- Modeling Overview
- Material Properties and Testing
- Electrical Modeling
- Mechanical-Thermal Modeling

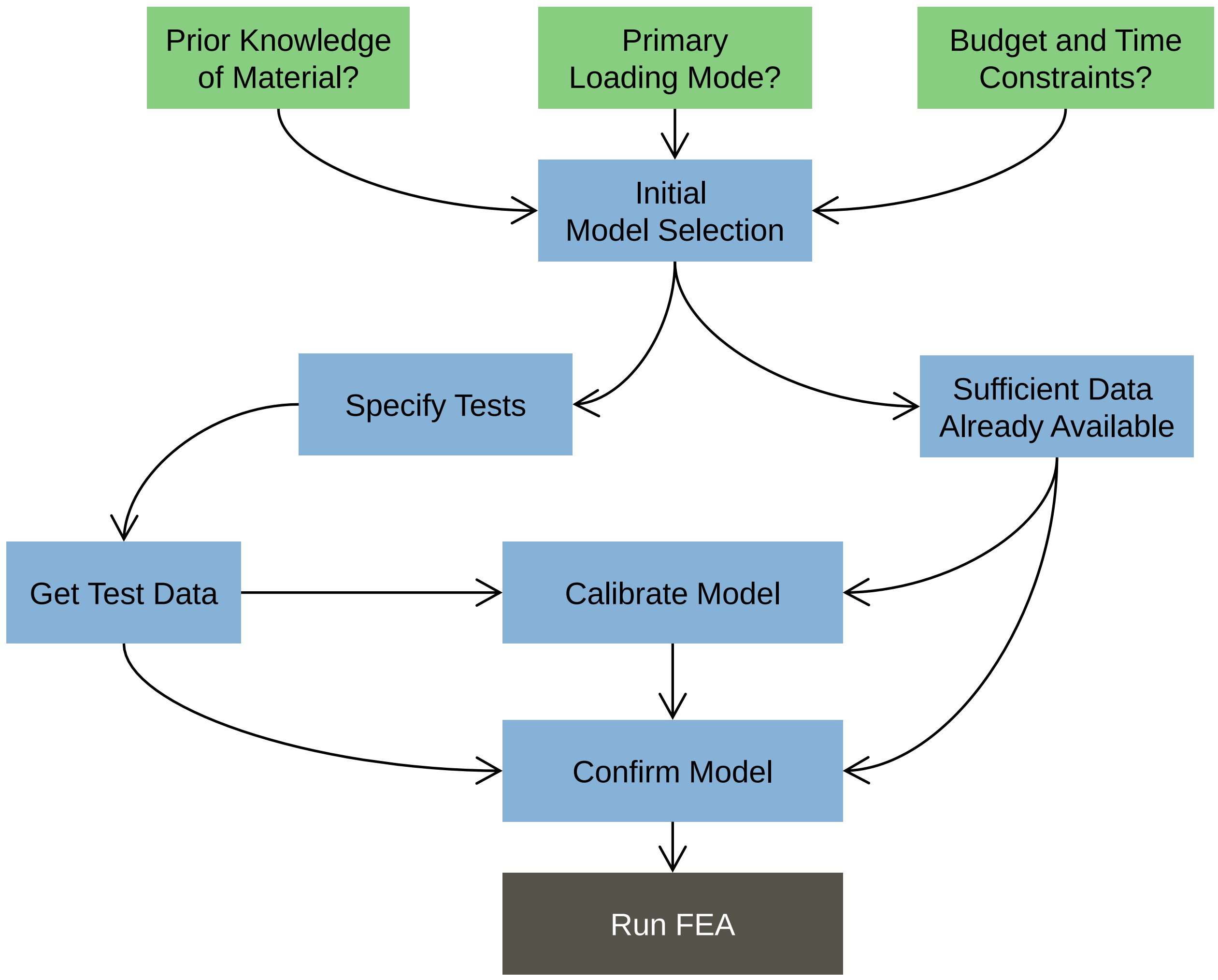
Note that there are a number of other important reliability-related areas (moisture, UV, acceleration factors, statistics, and so on) that are not covered here.

Modeling Process

Modeling in the Development Process



Material Testing/FEA Flow Diagram



Credit: John Lawler,
GreenMountain Engineering

When to Model?

PV is growing up!

Prototype

Observe failure
↓
Identify mechanism
↓
Develop test
↓
Mitigate problem
↓
Identify next failure

Mature product

Failure analysis
↓
Identify mechanism ← (and build model for mechanism)
↓
Develop (ALT) test
↓
Measure acceleration
↓
Predict performance ← (via models)

When do we move from focus on mitigation to focus on prediction?

Slide Source: Sarah Kurtz, NREL

Limits of Modeling

"All models are wrong; some models are useful."

--attributed to George Box, 1979

To model every aspect of a complex material's behavior, in detail, can be a PhD-thesis-level effort.

However, many aspects of a material's behavior may have only modest impact on the overall model conclusions.

Benchmarking against test data, sensitivity analysis, and relative modeling all help.

Despite the fact that this is a modeling presentation, I will say: modeling is not a substitute for testing.

Material Properties & Testing

Material Models

Hand calculations and basic models typically assume linear elastic material properties.

More complex models can give better accuracy but take more effort to develop and benchmark.

Material	Typical Models
Glass	Elastic
Silicon	Elastic
Encapsulant	Viscoelastic, or hyperelastic(?), or temperature-dependent elastic
Backsheet	Elastic or temperature-dependent elastic
Copper	Elastic-Plastic
Solder or Adhesive	Elastic-Plastic or viscoelastic

Material Properties

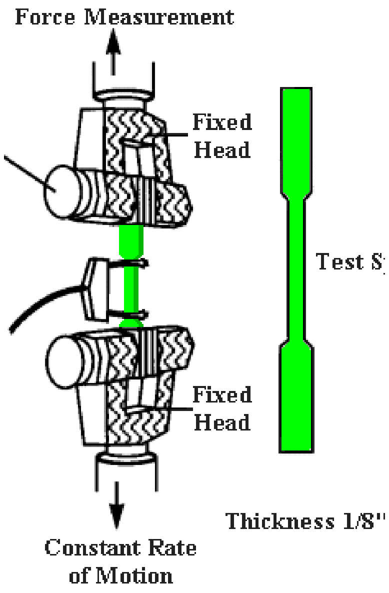
Some key material properties for modeling (not including failure criteria):

Property	Symbols	Typ. Units
Modulus (stiffness)	E, G	Pa
Poisson's ratio	v	None
Plastic Deformation	σ_y, E_t	Pa
Viscoelasticity	T_g, E_s, E_l, $E_{1..n}$, $\tau_{1..n}$	Pa, s
Thermal expansion	c_{te}, α	ppm/ºK
Thermal conductivity	K	W/m-ºK
Electrical resistivity	ρ	Ω-cm

Material Testing

There are numerous labs that can test materials to extract model parameters, at a moderate cost ($500 - $5k).

Description	Sample ASTM test standards
Modulus	E8, D638 (full stress-strain curves) D5026 (polymer modulus as a function of temperature)
Poisson's ratio	see above
Plasticity	see above
Viscoelasticity	D2990/2991 for creep D5279, D5026 for DMA
Thermal expansion	E228, E831, D696 (polymers)
Thermal conductivity	E1225, D5930 (polymers)
Electrical resistivity	B193 (w/ four-point probe)

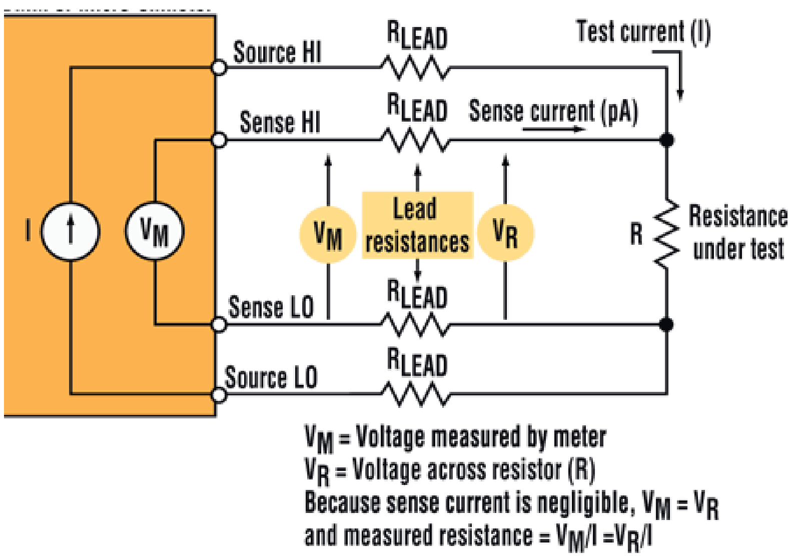


Source: Matweb

Example: Resistance Testing

Measuring the electrical resistance of conductors is not trivial, as the resistance of the measurement system can introduce errors.

Various four-point measurement methods are useful.



Semiconductor industry Kelvin structure for measuring contact resistance

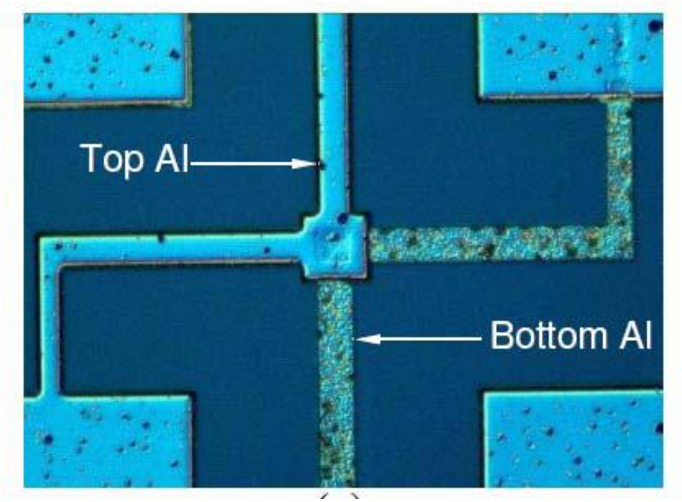


Image Source: H.Lin, An Evaluation of Test Structures for Measuring the Contact Resistance of 3-D Bonded Interconnects

Custom Test Example: Fatigue

With sufficient cyclic fatigue, solders and electrically conductive adhesives can exhibit some resistance degradation (at stresses and strains below what would cause cohesive mechanical failure or delamination).

Some publications detail custom methods for testing this resistance degradation over time.

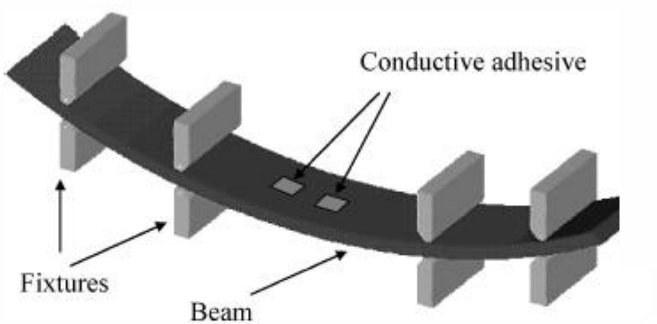


Figure 1. Schematic illustration of the four-point beam bending test.

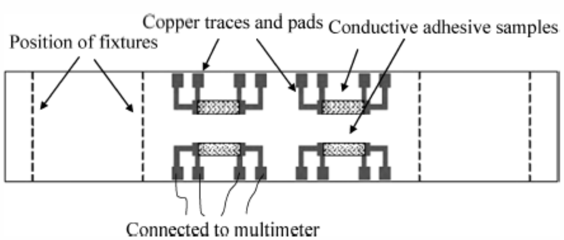


Figure 6. The layout of the upper surface of the PCB beam.

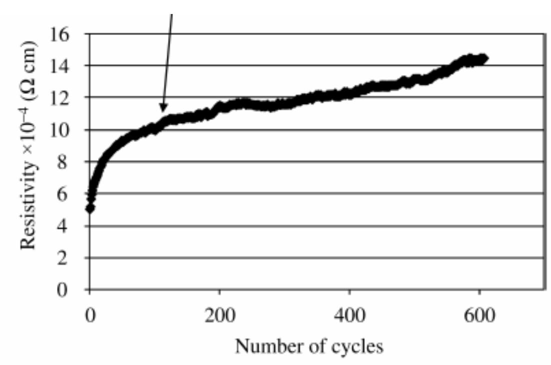


Figure 10. Resistivity of a conductive adhesive sample in fatigue test.

Source: PhD Thesis, Bin Su
[more detailed citation to be added]

Electrical Modeling

Applications

- Cell effective series resistance
  - Metallization, emitter, contacts, current distribution
- Metallization pattern optimization
- Bypass diodes
- Power losses in series strings
  - Cell-to-cell variation, binning
  - Shading
  - Irradiance variation (especially in CPV)
  - Interconnect and cell failures
- Contact fatigue and resistance degradation
- Semiconductor cell models (not covered here)

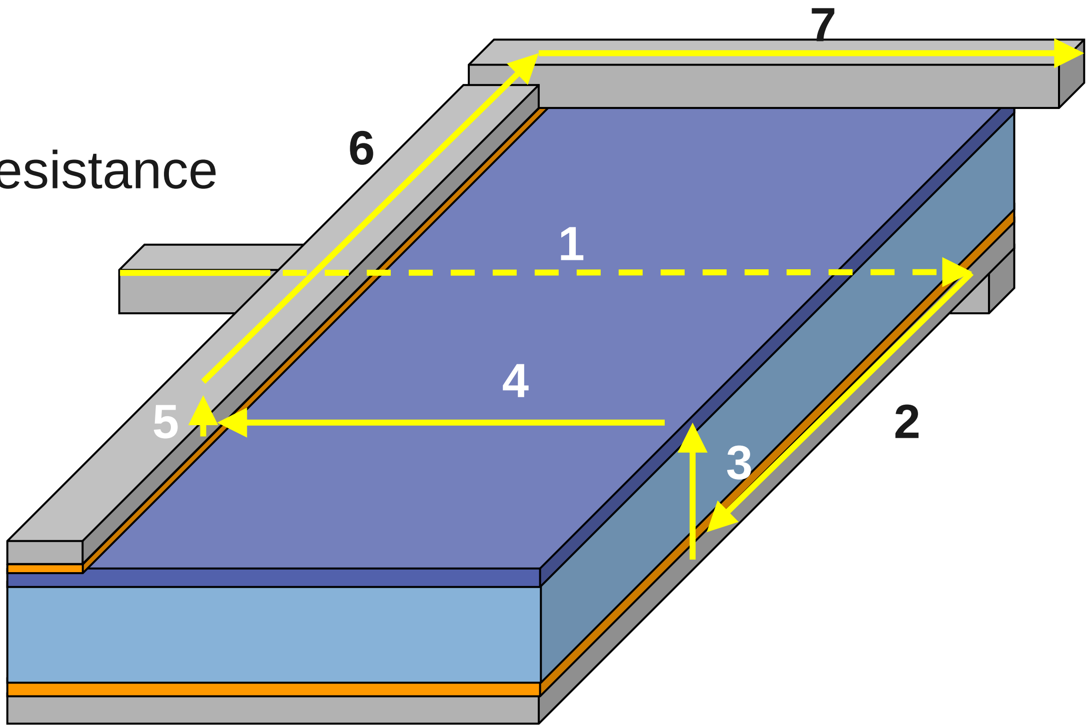
Physics and Tools

- Basic series resistance and power calculations can often be done "by hand" (or using spreadsheets, MATLAB, or similar software) without need for FEA
- SPICE is useful for circuit models
- Semiconductor models using PC1D, Sentaurus, etc.
- For 2D and 3D current distribution calculations, FEA tools are useful (especially in rear-contact or point-contact cells with significant 2D transport)

Series Resistance Components

In conventional front-contact cells, most current flow can be considered to be linear within each layer, to allow simpler, non-FEA modeling of series resistance losses.

1. Bottom bus resistance
2. Rear metallization resistance
3a. Rear metallization contact resistance
3b. Bulk resistance
4. Emitter sheet resistance
5. Finger contact resistance
6. Finger resistance
7. Top bus resistance



Electrical: Scaling Laws, Rules of Thumb

Resistance of a conductor scales linearly with geometric parameters (cross-section, length): $R=\rho*L/A$

Voltage drop is also linear with resistance and current: $I*R$

Power loss in a resistance scales with current squared: I^2R

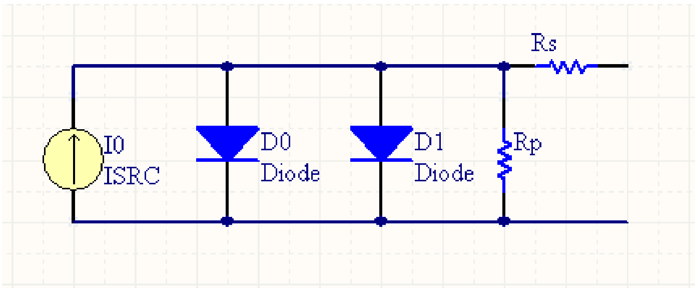
Therefore, if you reduce the current in a conductor by 2x, power loss goes down by 4x (or the conductor can be made 4x smaller with the same power loss).

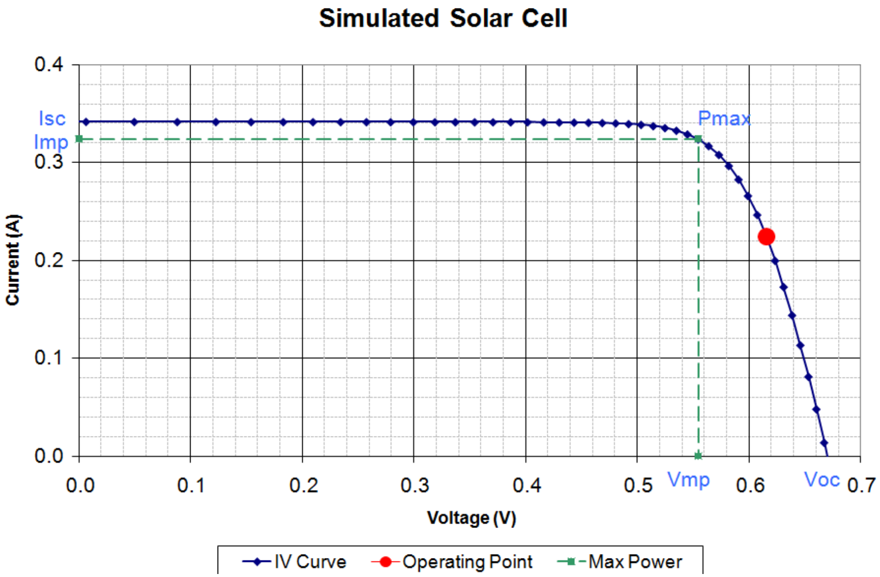
This is relevant in metallization optimization, and is also part of what drives various electrical system designs towards higher voltage and lower current.

Solar Cell Circuit Model

A circuit model* combining a current source, one or two diodes, and two resistances can simulate the I-V curve of a solar cell fairly accurately.

Using SPICE-based modeling tools, this model can then be parameterized and used to study the behavior of strings and modules, cell-to-cell variation, and other factors.



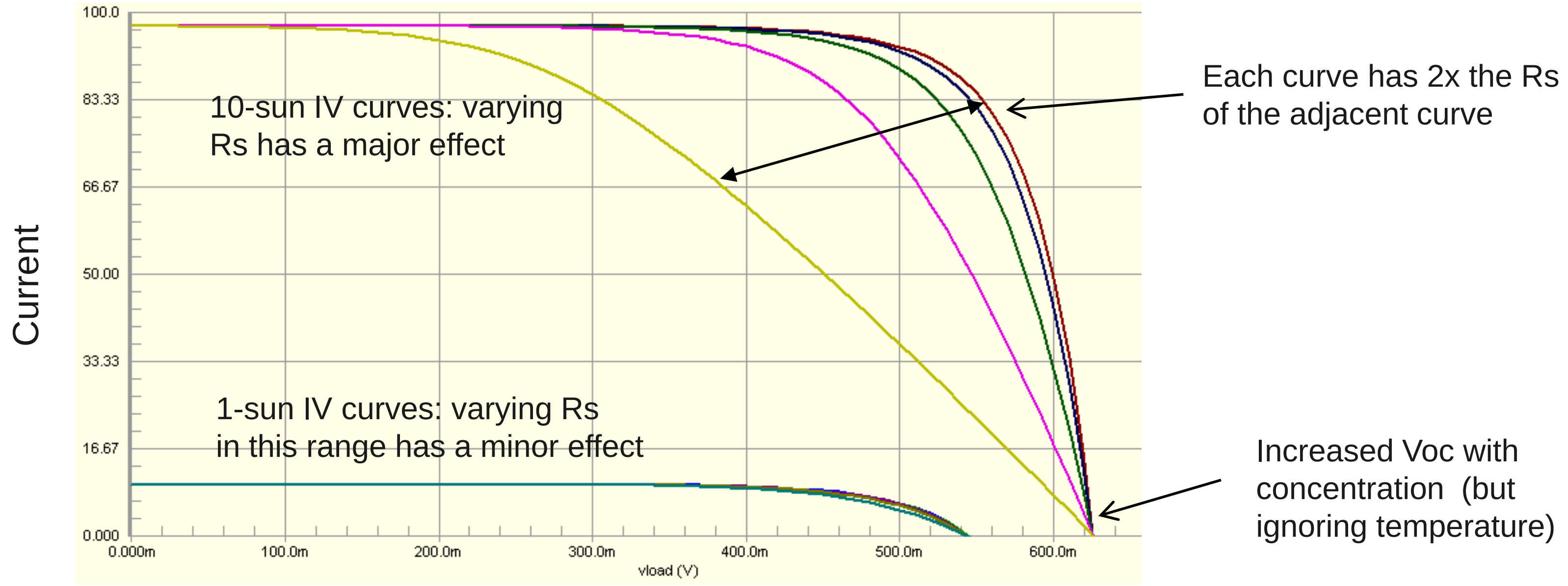


* I've implemented and benchmarked a simple, parametric SPICE subcircuit model for solar cell modeling: contact me if you want a copy of it.

Series Resistance and CPV

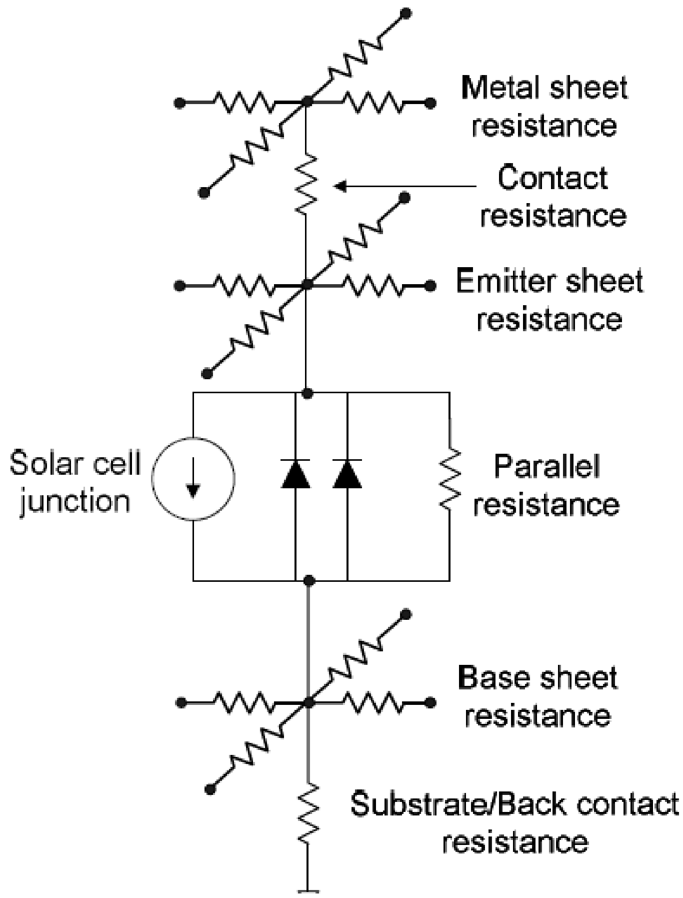
Unless cell series resistance is low, it can be a significant source of efficiency loss for concentrating photovoltaics.

SPICE-simulated IV curves



Note that Voc,efficiency increase under concentration, but efficiency decreases w/ heating or nonuniform illumination.

Distributed Resistance

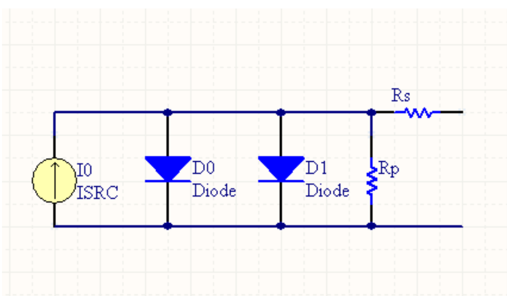


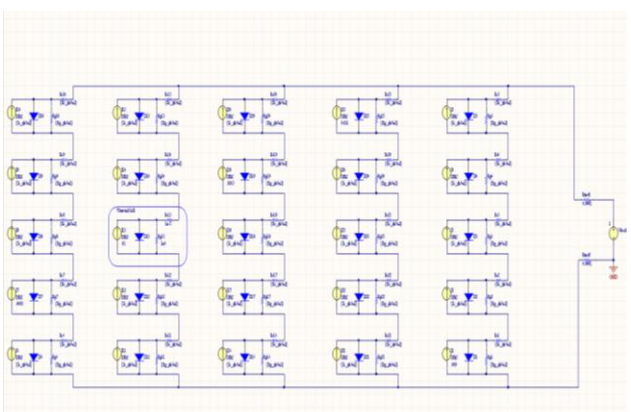
A solar cell can more accurately be modeled as a distributed network of unit cells and resistances (especially important if non-uniform illumination will be modeled).

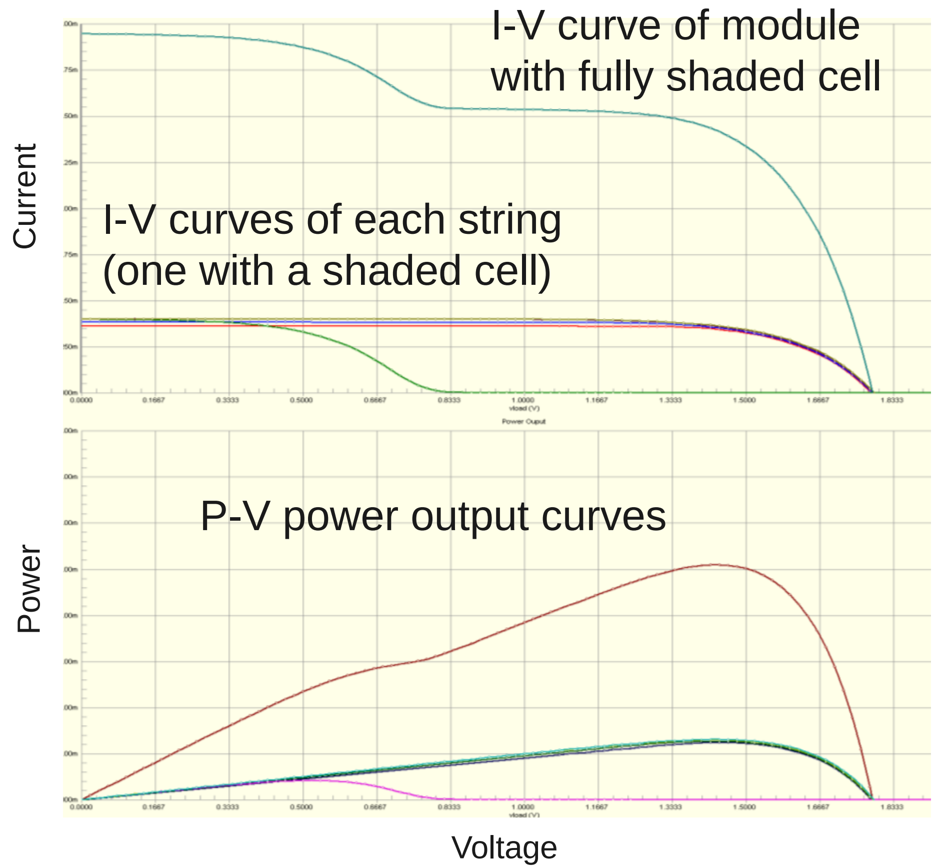
SPICE can be used to simulate this network, though a separate script may be used to generate the circuit.

Series / Parallel Array Modeling

SPICE models can also be used to examine shading, bypass diodes, and changes in cell operating points.







Electrical: Advanced issues

- Metal-semiconductor contacts can be non-ohmic (nonlinear resistance) if doping is low.
- Current crowding: higher effective resistance.
- Each diode in the circuit model represents a combination of several different physical phenomena / types of recombination.
- Under high concentration, a three-diode model (with N=2/3 for the third diode) may be helpful to model Auger recombination.
- Some conductors may show resistance degradation prior to mechanical failure.

Mechanical & Thermal Modeling

Outline

- Modeling applications
- Core physics
  - Stress and strain
  - Thermal expansion
  - Fatigue
  - Creep and viscoelasticity
- Scaling Factors
- Examples

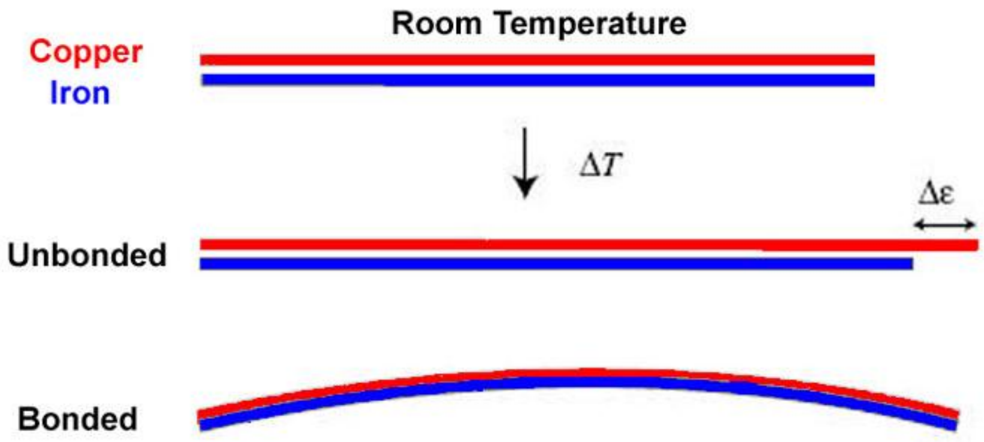
PV Applications

- Stress in glass and cells in physical loading (wind, snow)
- Stress in cells and interconnects due to thermal expansion (both during the initial cool-down from lamination, and thermal cycling)
- Stress in cells from local heating (soldering during manufacturing, irradiance variation in CPV)
- Crack propagation in cells (damage initiated during handling in manufacturing, stresses applied later)
- Failure / delamination of solder joints, encapsulant
- Low-cycle fatigue of copper, solder, adhesives

Thermal Expansion

In PV modules, the most relevant causes are:

- Cooling from lamination to room temperature
- Thermal cycling (in testing, in the field)
- Temperature gradients (especially in CPV)



[image source: electrical-forensics.com]

Note that thermal expansion does not cause stress in a simple, unconstrained material.

Stiffness: higher is not always better

People sometimes confuse a material's 'strength' (yield stress, for example) with its stiffness (modulus).

- High stiffness: low deflection for a given force
- Low stiffness: low stress for a given deflection

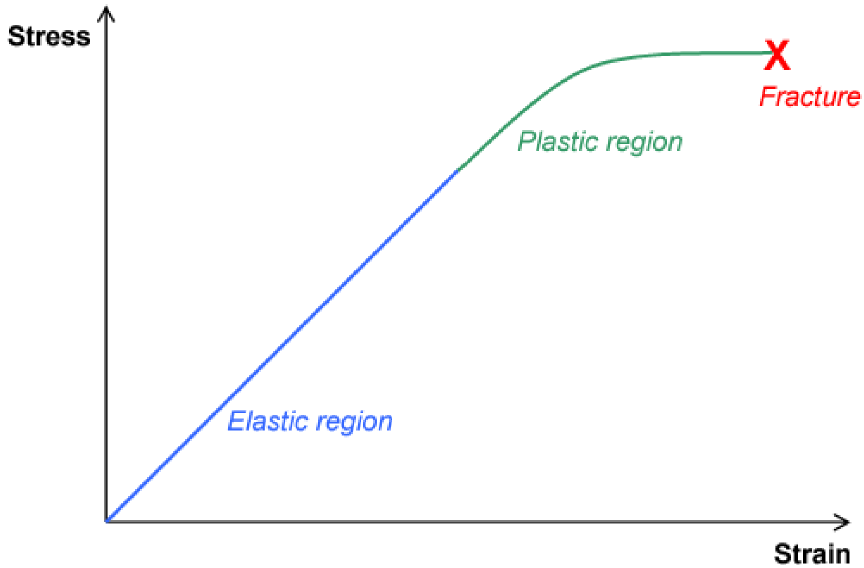
Source: Wikimedia Commons, Rich Niewiroski Jr.

Source: Wikimedia Commons

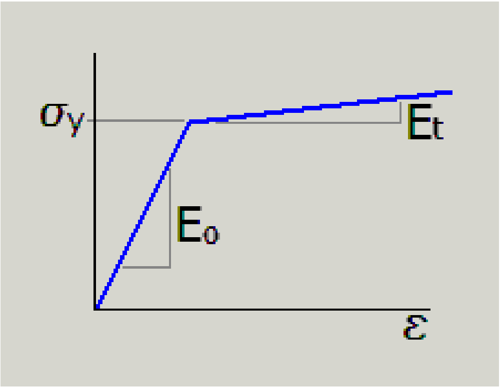
For example, processes like tempering affect a metal's strength but not its stiffness.

Plastic Deformation

Plastic deformation is irreversible strain in a material that is loaded beyond its yield stress (think of bending a paper clip). In PV modules, it can be important in modeling copper and solder joints under cycling loading.



A typical elasto-plastic modeling approximation:



Source: Beaufort Analysis

Fatigue

High-Cycle Fatigue: low stress over many cycles (but... PV modules only see 13k day-night thermal cycles in 20 years)

Low-Cycle Fatigue: cyclic plastic deformation to failure (think bending a paper clip). Relevant to solder, adhesives, and copper in solar modules, and can be modeled.

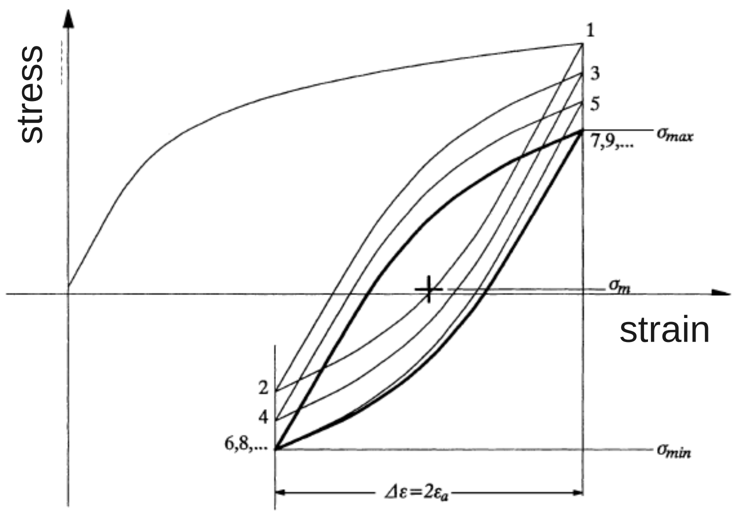


FIG. 5.45 Stress relaxation during a mean strain axial fatigue test.

[Source: Rothbart, *Mechanical Design Handbook 2nd Edition*]

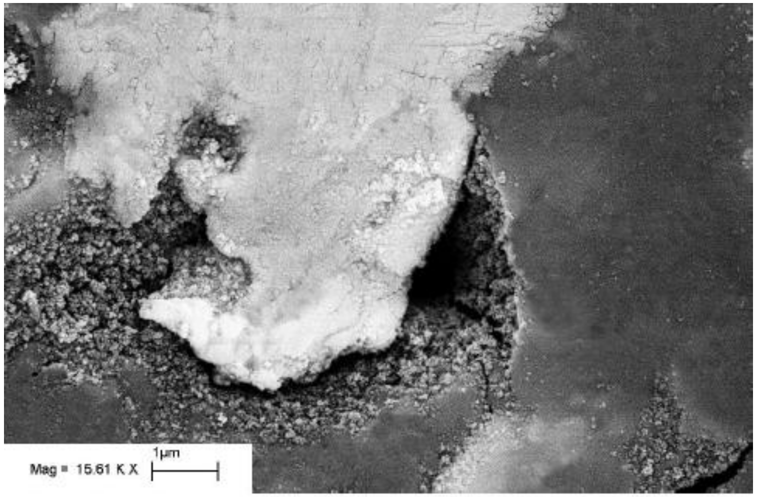


Figure 64. A silver flake in a conductive adhesive sample after fatigue test

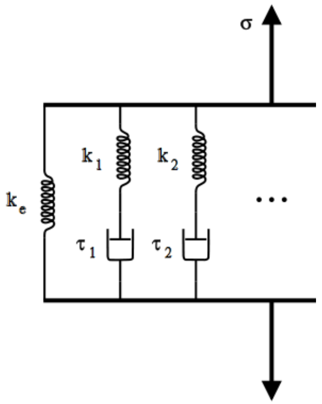
[Source: Bin Su J. Adh Science, citation details to be added]

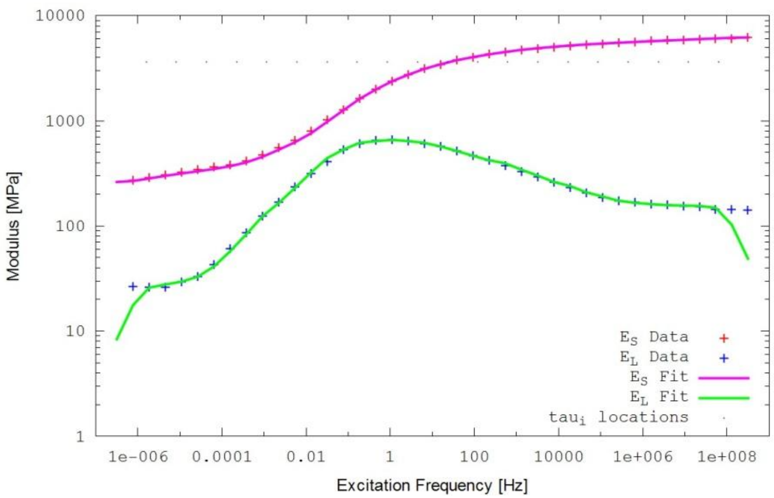
Viscoelasticity

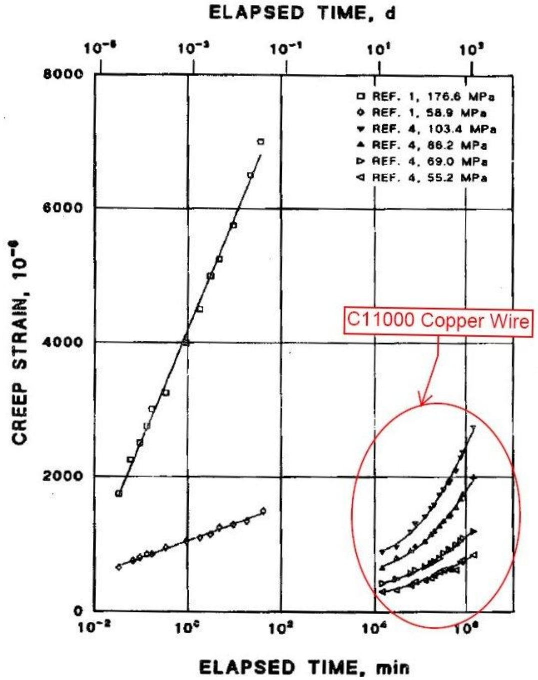
Encapsulants, adhesives, and solders can exhibit creep and viscoelasticity (e.g. stress relaxation over time).

These effects can change by many orders of magnitude over reasonable temperature ranges.

Material models can take this into account, with enough characterization (see Appendix).

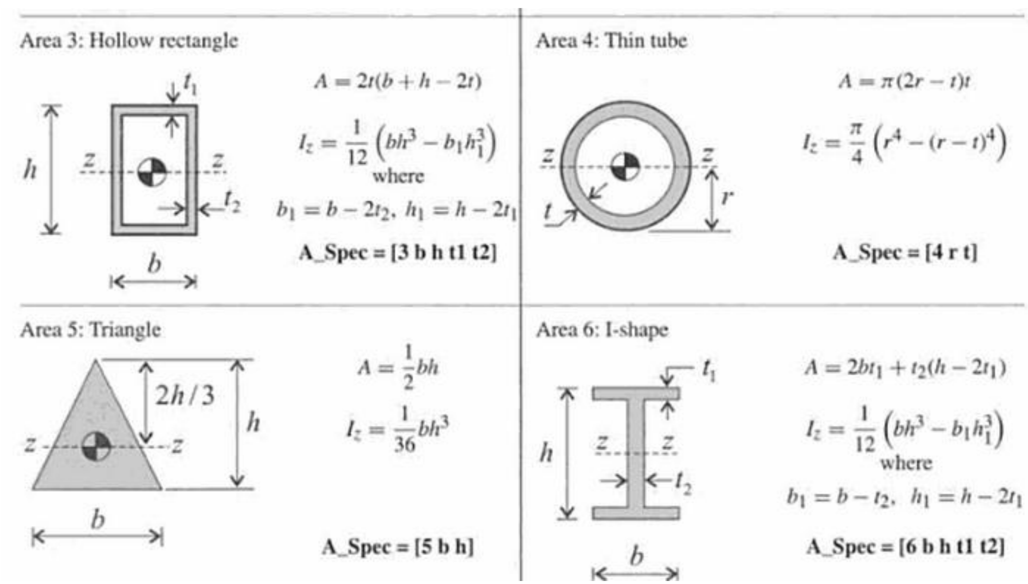






Scaling Laws, Rules of Thumb

- Beam bending stiffness scales with thickness^3, while tensile stiffness and many other properties scale linearly with thickness.



Source: B. Yang, Stress, Strain, and Structural Dynamics

- Optimizing the aspect ratios of components such as cell interconnects can significantly reduce stresses.

Scaling Laws, Rules of Thumb

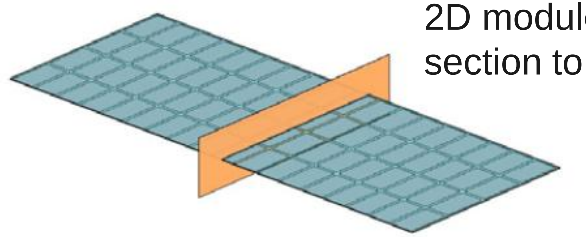
- The product of E * t * c_{te} of various layers in a module can be compared to get a general feeling for which layers will dominate thermal expansion effects.

Material	E (GPa)	t (mm)	C_{te} (ppm)	E * t * c_{te}
Glass	73	4.0	9	~2600
EVA	0.006	0.4	400	1
Backsheet	2.7	0.35	100	~100

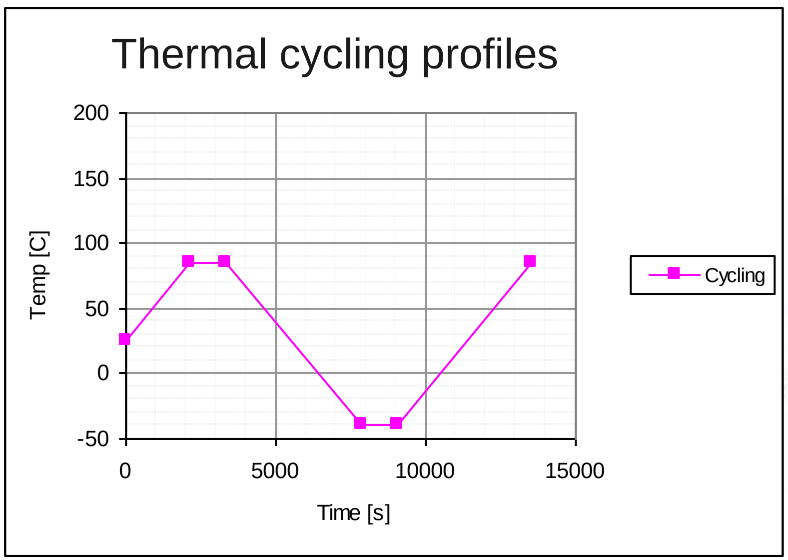
- This is especially useful for non-standard module or CPV designs.

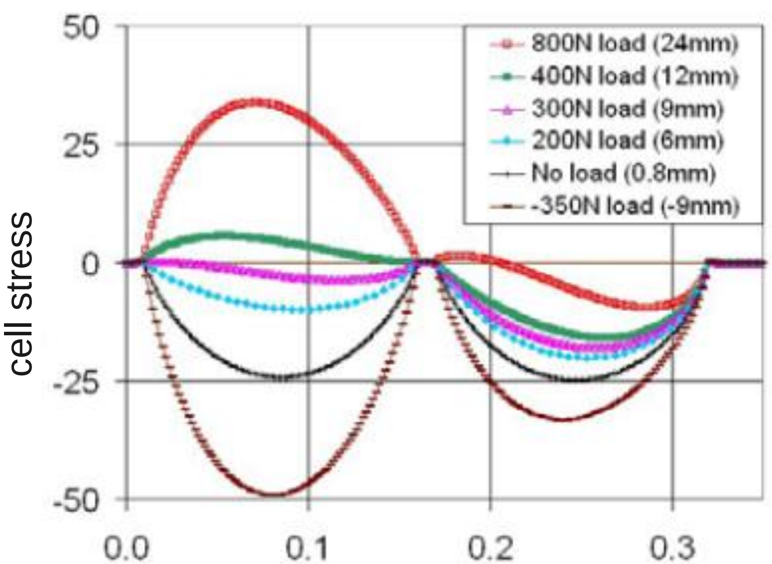
Cell Stress Modeling

A common useful model examines stress in cells and interconnects in a PV module due to either thermal expansion or weight/wind loading.



2D module cross-section to plot





Source: Evergreen Solar / GreenMountain Engineering, EUPVSEC 2007, and other sources

Global-Local Modeling

- FEA is still limited by computational power: Analyzing full-module, complex 3D models with accurate results at every small feature is not practical.
- Model the global system coarsely, use those results to determine constraints and assumptions for detailed 2D/3D models of certain regions.

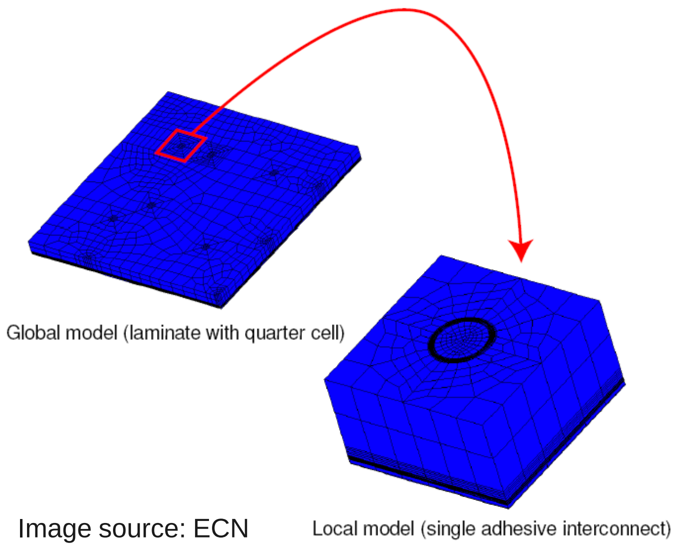
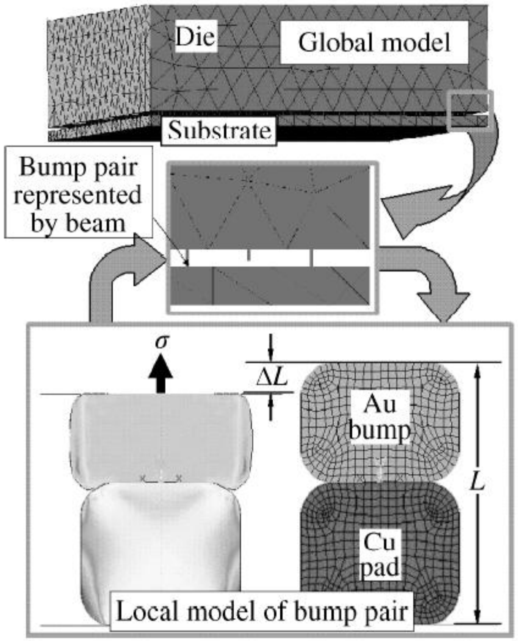


Image source: ECN

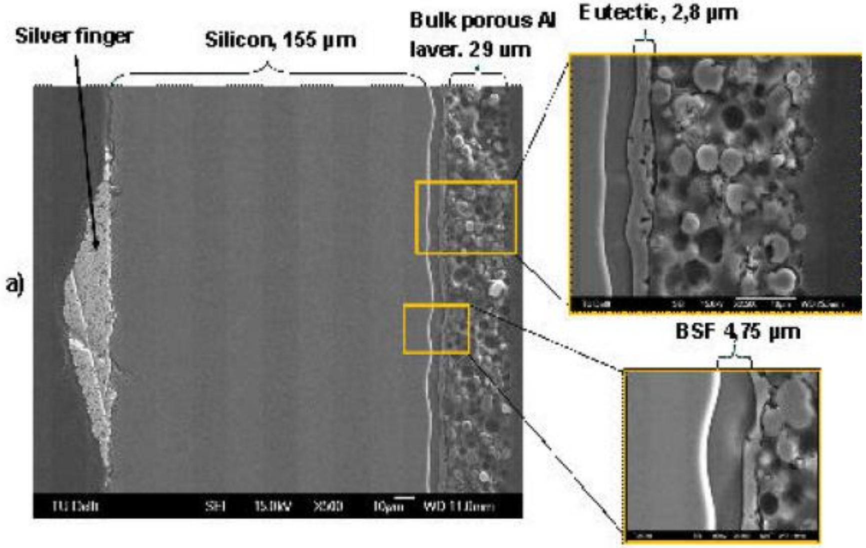


IC modeling, source: D. Farley et al. / J. Adh Sci

Advanced Issues

Some common mechanical modeling non-idealities:

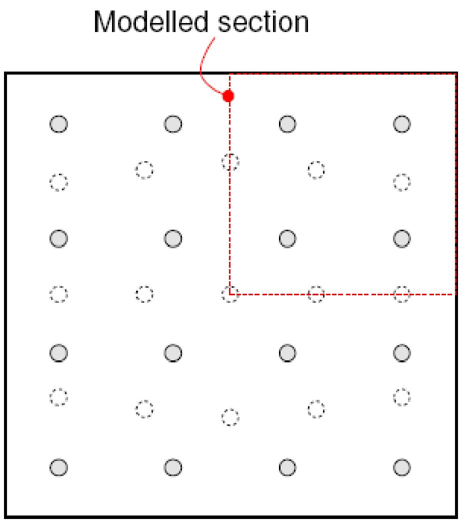
- Traditional furnace-fired cell metallization can have very different mechanical properties from the bulk properties of aluminum or silver.
  - See, for example 2.CV.2.13 from EUPVSEC 2009, suggesting a modulus only about 50% of ideal, for porous rear metallization.



Paste type	Porosity, %	Bismuth glass, %	Bowing over 150mm, mm	Young's Modulus, GPa
A	10.9	1.8	1.4	41
B	14	3.9	2.6	44
C	16	4.2	1.8	46

Advanced Issues, FEA Tips

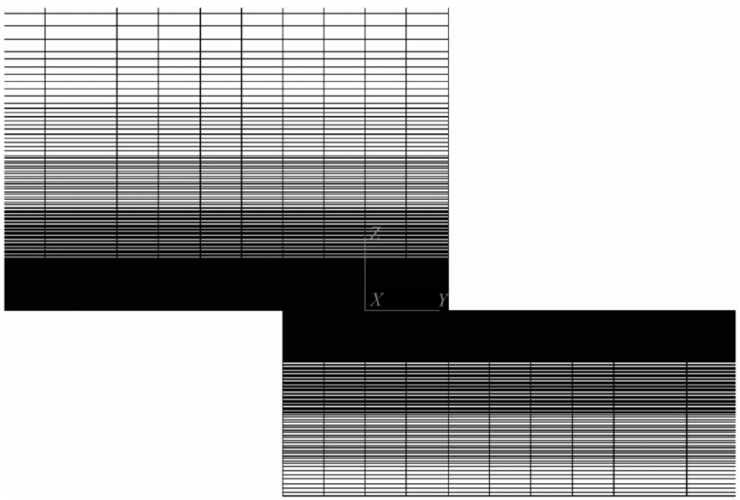
- Consider 2D simplifications, but understand differences in “plane stress” vs. “plane strain” assumptions.
- Use symmetry to reduce model size
  - Most 2D module models can be modeled as a half module, and 3D cell modules may be reducible to a quarter-cell model via symmetry in two planes.

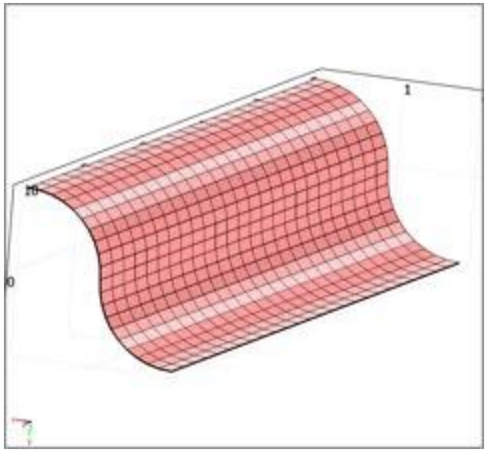


Source: ECN paper

Advanced Issues, FEA Tips

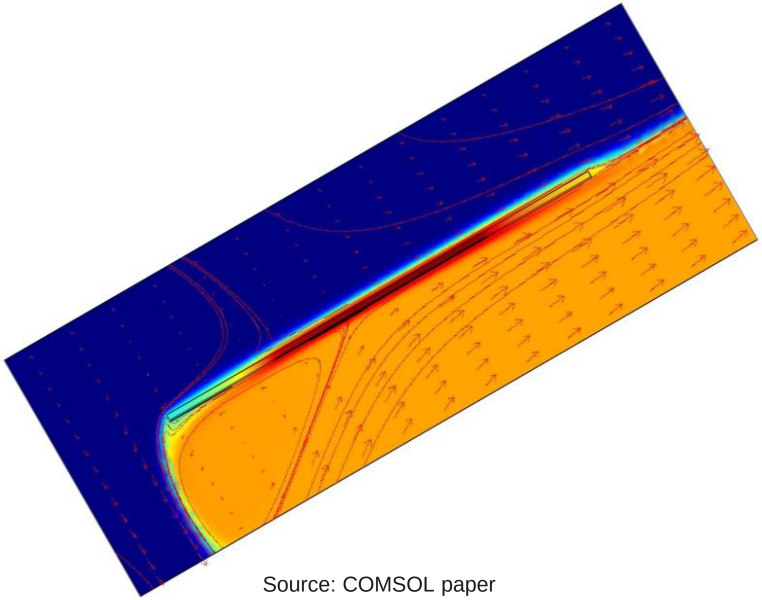
- Typically in FEA packages, meshing high-aspect-ratio models (like solar modules, which consist of many thin, stacked, large-area layers) can be a challenge.
  - Using triangular or tetrahedral elements leads to huge mesh density, or poor element quality.
  - Using rectangular or “brick” elements to mesh in 2D and then extruding or sweeping this mesh into 3D can give you much more control over mesh density in the areas you care about (interfaces and so on).





Thermal Modeling

- In addition to thermal-stress modeling, pure thermal modeling can examine areas such as:
  - Module temperature due to material stack-up, convection, stagnation, mounting structures
  - Temperature distribution in CPV and heat sinks



Source: COMSOL paper

Conclusions

Conclusions

- Useful and feasible electrical models include:
  - Series resistance losses in cells, metallization, interconnects
  - Losses due to shading, bypass, string layout, and cell variation
  - Performance of cells under concentration
- Useful and feasible mechanical models include:
  - Stresses due to thermal expansion, wind, weight
  - Fatigue of adhesives, bonds, and interconnects
  - Creep and viscoelasticity of encapsulants
- Material testing can help determine model parameters and benchmark and validate models.
- Complex models can be time-consuming: rules of thumb, hand calculations, engineering intuition, and testing can help prequalify designs before detailed modeling.

Bibliography & Acknowledgments

This presentation was based on a number of modeling projects done at GreenMountain Engineering, as well as excellent publications by a number of authors at research institutes and companies.

I'm in the process of assembling a detailed bibliography related to modeling of PV modules: contact me if you want a copy when it is ready.

Thanks to John Lawler and Tyler Williams for feedback and certain images, and to Sarah Kurtz and NREL for the invitation to speak.

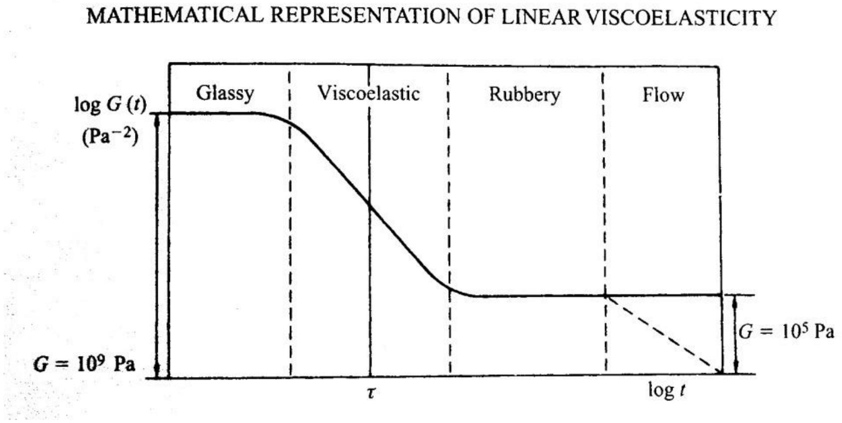
Appendix A: Viscoelasticity

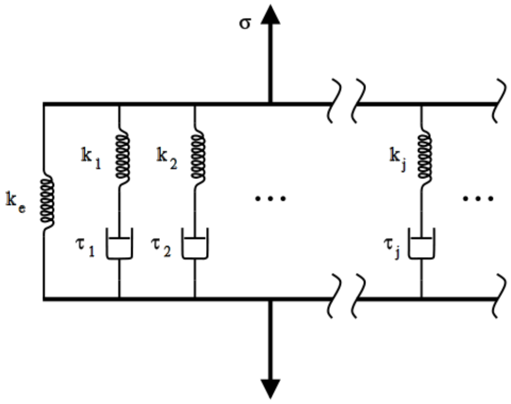
Viscoelasticity

Some materials (notably encapsulants, but to some extent solders and copper) exhibit viscoelasticity or creep.

This can be a strain that gradually increases over time under a certain load, or a stress that relaxes over time.

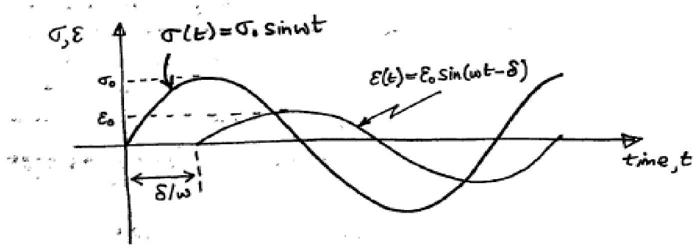
One typical way to model this is the “Generalized Maxwell Model”, representing the material as a parallel combination of springs and dampers (each branch models behavior on a certain time constant)





Viscoelasticity: Storage & Loss Moduli

- For a sinusoidal stress profile, the strain in a viscoelastic material will be out of phase by some angle *δ.*



- Qualitatively, a high value of the *loss tangent*, tan*δ,* suggests greater material stiffness at high-frequency loading.
- This behavior is specifically described by decomposing the elastic modulus into real and imaginary components:

$$E^*(i\omega) = E_S + iE_L$$

Storage & Loss Moduli

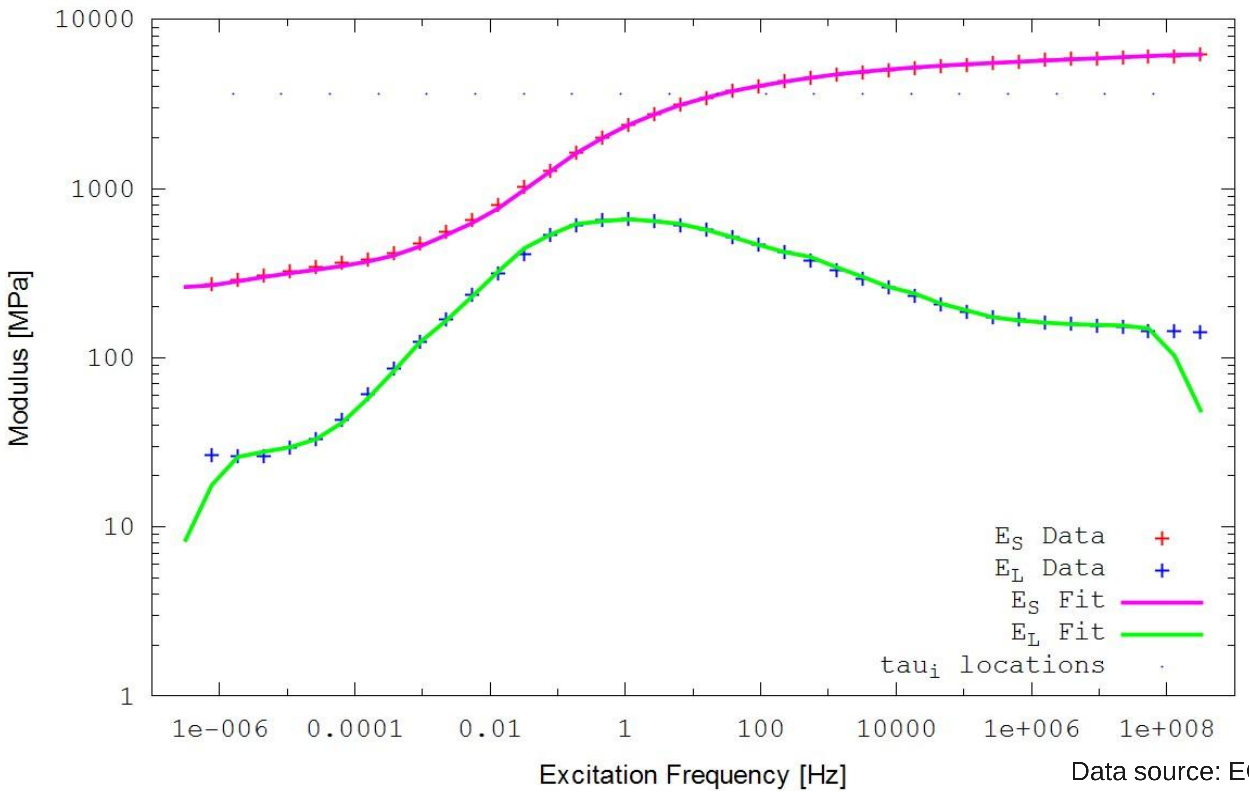
- E_S (also called E'), the *storage modulus,* and E_L (also called E''), the *loss modulus,* can also be expressed as

$$E_S = \frac{\sigma_0 \cos\delta}{\varepsilon_0} \qquad E_L = \frac{\sigma_0 \sin\delta}{\varepsilon_0}$$

- Qualitatively, a high loss modulus suggests that viscous effects are having an effect on material behavior.

Data Reduction

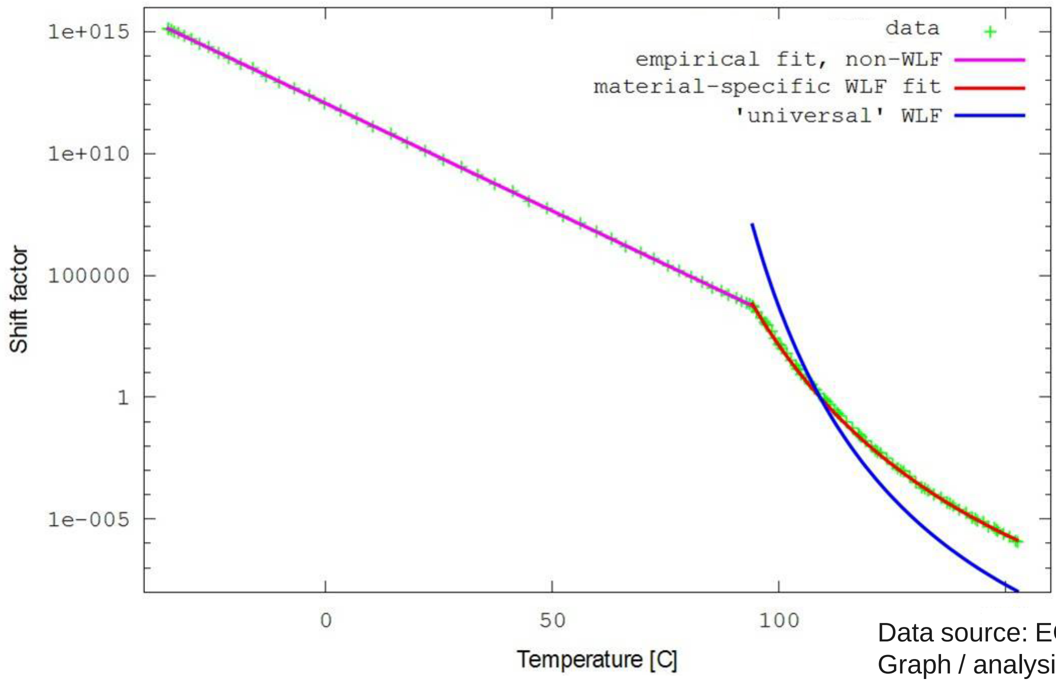
Once material data under a number of different conditions has been measured, algorithms can fit a frequency-dependent viscoelastic model to the data.



Data source: ECN publication
Graph / analysis: GreenMountain Engineering

Viscoelasticity and Temperature

The viscoelasticity of polymers can change by many orders of magnitude over a temperature range. While a challenge to model, “time-temperature curves” and “WLF shifts” can use this phenomenon to help predict long-time viscoelastic behavior from shorter tests done at higher temperatures.



Data source: ECN publication
Graph / analysis: GreenMountain Engineering

Creep in Copper

As an example of slower creep, room-temperature strain data for C11000 copper is shown here.

On a time scale of hours, the strain is below 0.05%. Over several years, this increases to 0.2% or more.