Implementation of Advanced Solar-Cell Analysis at Cell Test

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A vision for end-to-end metrology for electronic quality (1999 NREL Silicon Workshop)

Table 1.

Process step	Electronic Process monitors		
	Sheet resistance	Lifetime	Voltage
Incoming wafers	X	X	
Etching		X	
Phosphorus Diffusion	X	X	X
Passivation & AR		X	X
Back metal/anneal	X	X*	X
Front Metal/anneal		X*	X

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A vision for end-to-end metrology for electronic quality (2016 NREL Silicon Workshop)

Step	Metric	Fundamental Analysis	Impact Analysis
Feedstock	τ vs. Δn	τ vs. Δn	Implied IV curve
Crystal	τ vs. Δn, Ω-cm, trapping	τ vs. Δn	Implied IV curve
Wafer	τ vs. Δn, Ω-cm, trapping	τ vs. Δn	Sorting
Dopant diffusion	τ vs. Δn, Ω-cm, trapping	τ vs. Δn	Implied IV curve
Passivation	τ vs. Δn, Ω-cm, trapping	τ vs. Δn	Implied IV curve
Cell	I, V, R_s, R_{sh}, τ vs. Δn, N_A	τ vs. Δn	Real/pseudo-IV curve
Module	I, V, R_s, R_{sh}, τ vs. Δn, N_A	τ vs. Δn	Real/pseudo-IV curve
System	I, V, R_s, R_{sh}, τ vs. Δn, N_A	τ vs. Δn	Real/pseudo-IV curve

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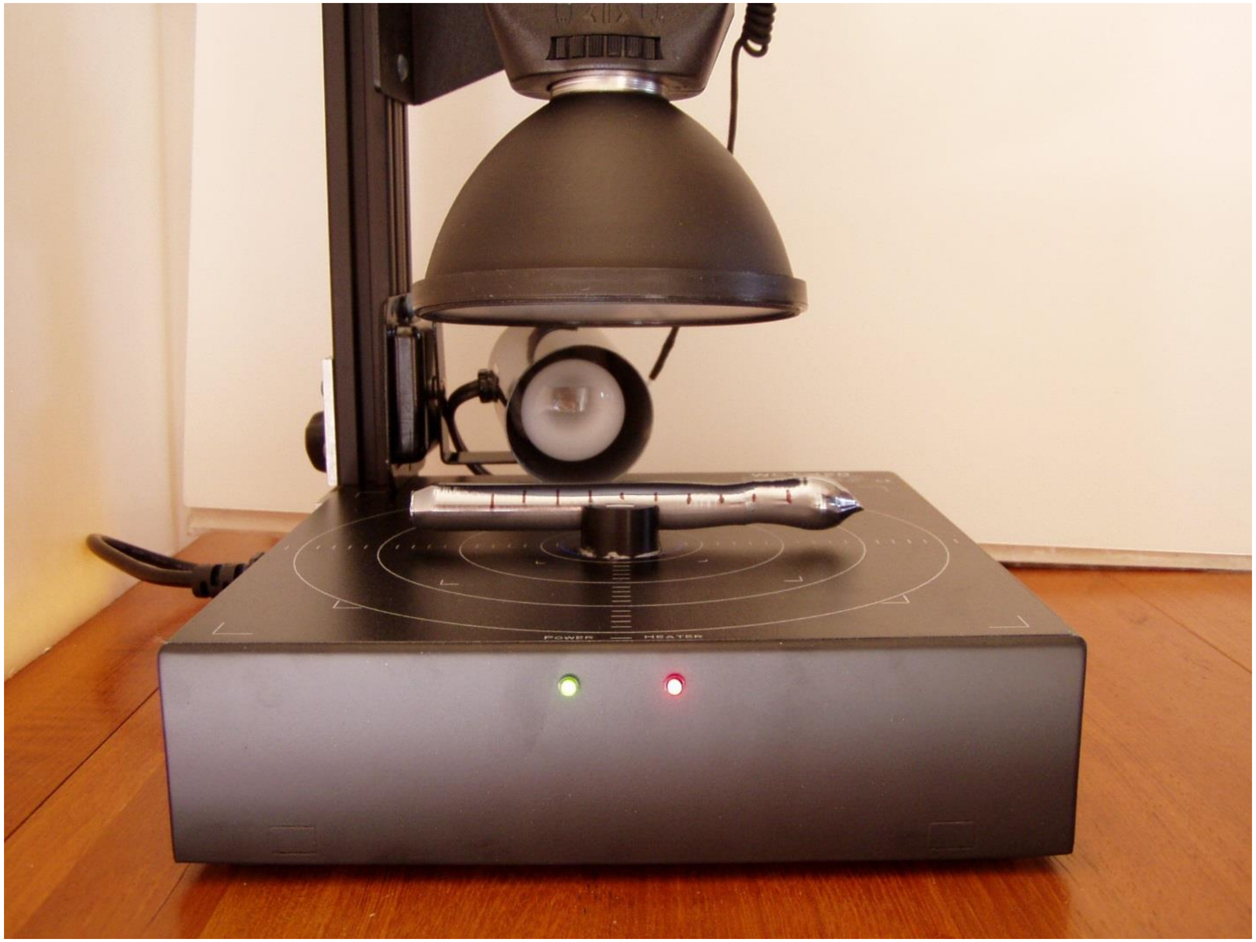
Feedstock Qualification (Lifetime Test)



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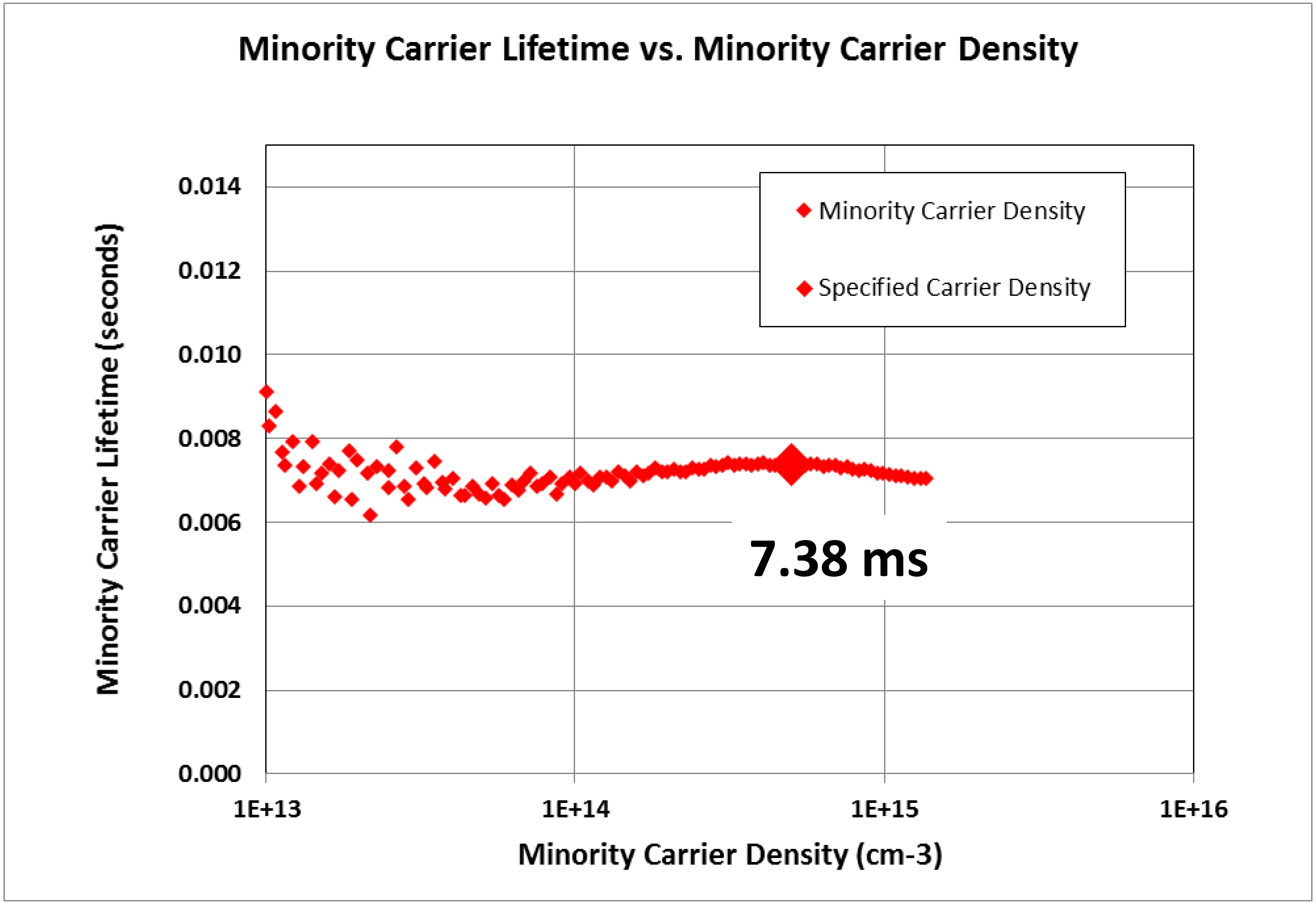
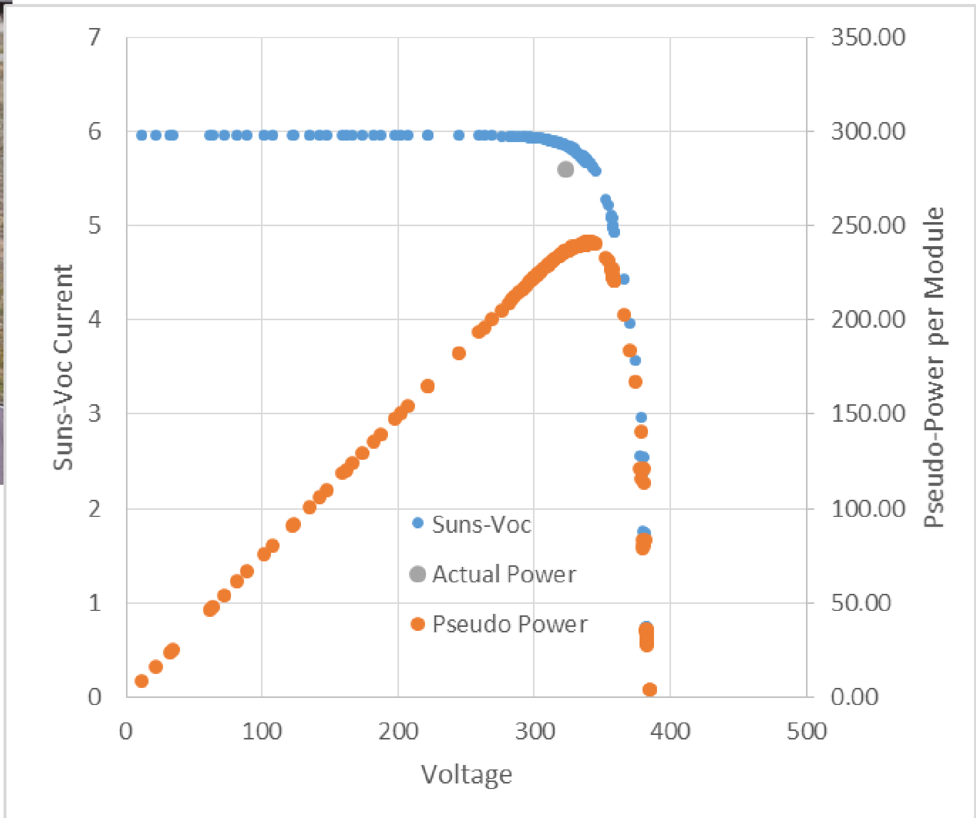
Feedstock Qualification (Lifetime Test)



Suns-V_{oc} Curves at the Array Level (3.6 KW)



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A vision for end-to-end metrology for electronic quality

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Cell Test is Unique: 100% Testing of Wafers

We need to take maximum advantage of this opportunity!

Device physics at cell test:

- Lifetime vs. injection level
  - bulk lifetime and emitter saturation current densities
- Relevant measurement of series resistance (Suns-V_{oc} curve)
- Time response of high-efficiency cells (Capacitance)
- Examples:
  - n-type high-efficiency solar cell
  - A study of p-type solar cells spanning low to high efficiency
  - Power loss analysis for record-efficiency cell

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R&D and Production Cell Testing

- Laboratory cell tester
  - MultiFlash technology
  - Measures full IV curve with conventional parameters (Eff, J_{sc}, V_{oc}, V_{mp}, J_{mp}, FF)
  - Measures Suns-V_{oc} (pseudo parameters, lifetime vs. injection level, J_0, BRR, lifetime at V_{mp}, dark R_{sh}, SUBSTRATE DOPING)

- Production cell tester
  - Production cell tester (250 MW installed in production to date)
  - All the same parameters
  - New SingleFlash technology enables high-speed testing
  - Potential for 4800 tests per hour
    - ~ 200ms cell test time of stationary cell

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Methodology: Outline

Parameter	Method
IV parameters	MultiFlash or SingleFlash technology; filtered Xenon light
Substrate doping	Time-dependent continuity equation
Lifetime vs. excess carrier density	Time-dependent Suns-V_{oc} data using doping result
R_s	Evaluation of IV and Suns-V_{oc} curves at J_{mp}
R_{sh}	Ohm-meter in dark at 0 Volts
Voltage (Strategic, 6 points)	8 Channel simultaneous data acquisition
Current	same
Intensity	same (using silicon reference cell)
Temperature	RTD
Capacitance effects	Constant charge method (EUPVSEC Dresden, 2006)

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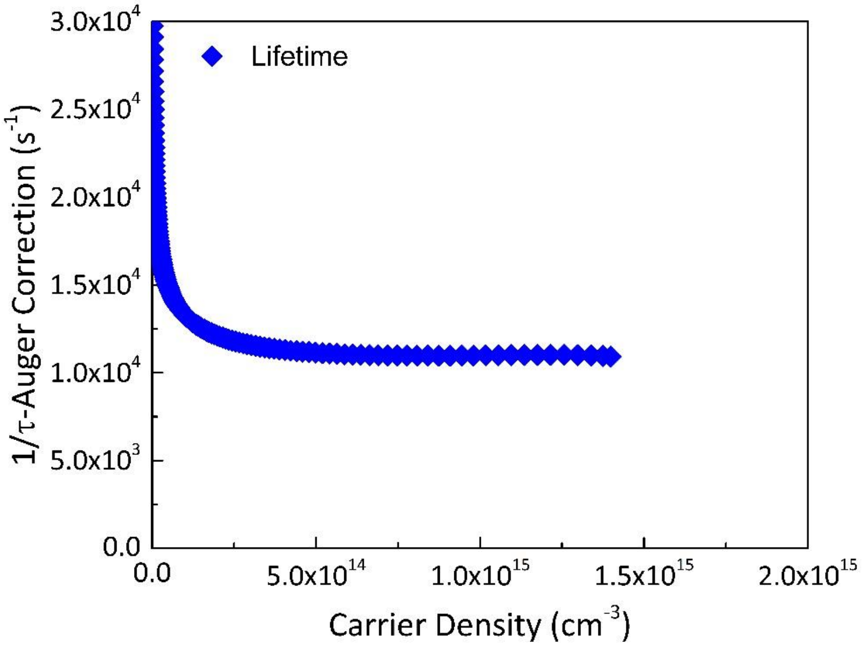
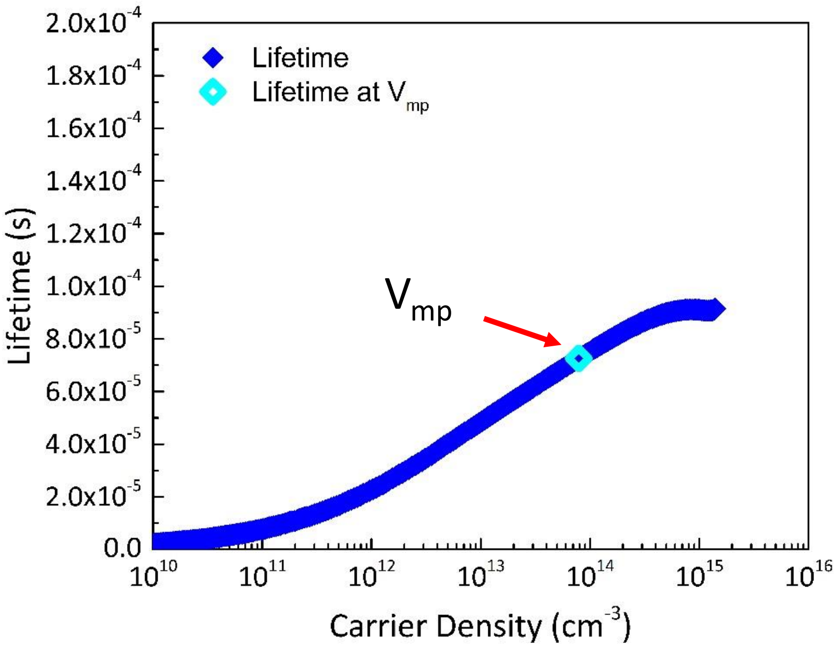
Lifetime data: Everyone does this with test wafers and a lifetime tester





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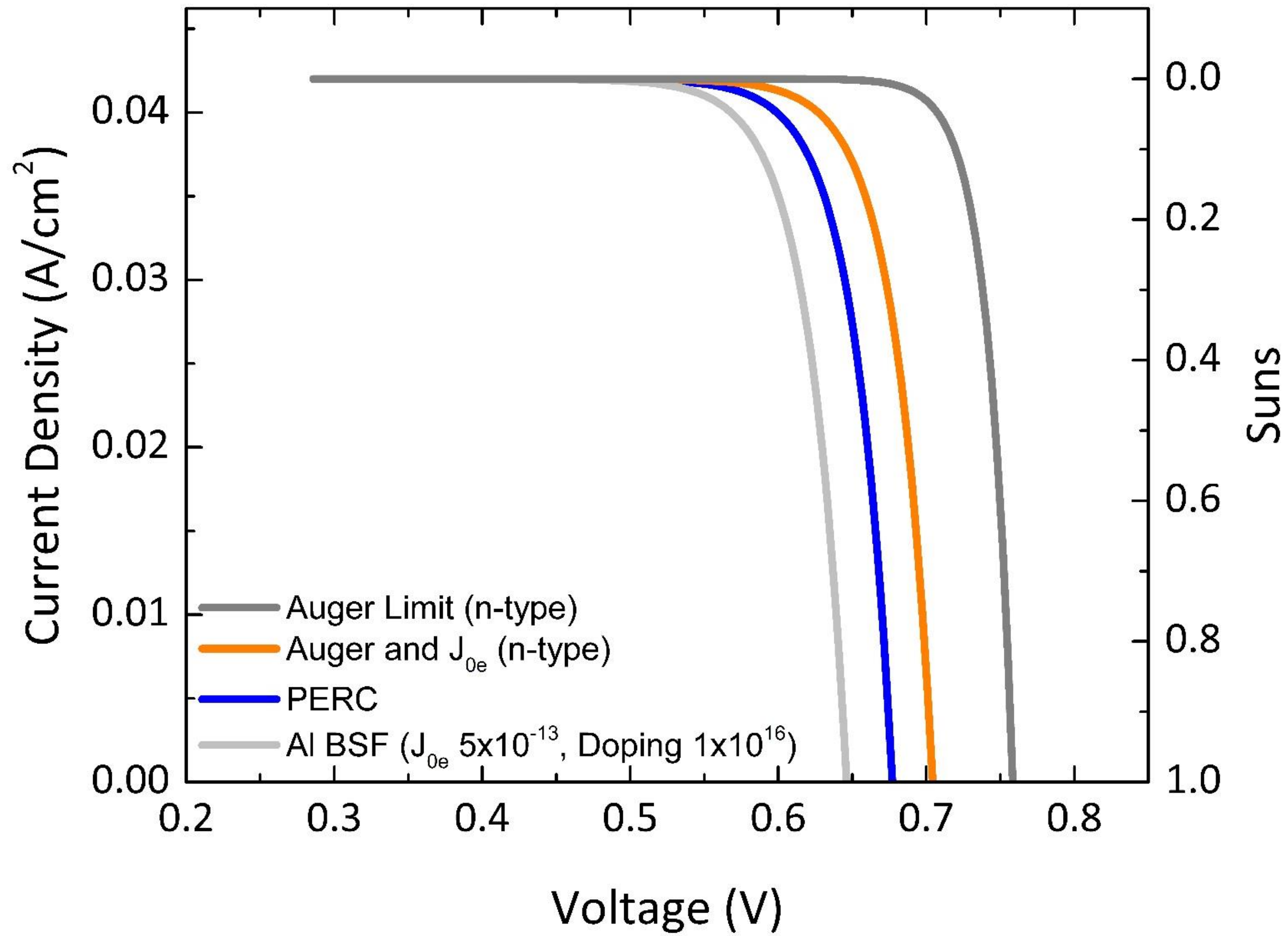
IV curves: BSF, PERC, n-type, Auger limit



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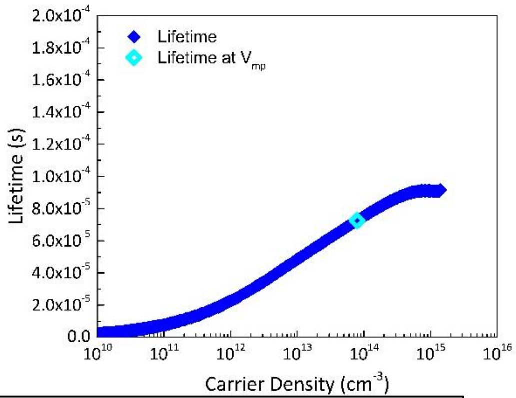
But it is the same thing! Lifetime data and IV data



$$\Delta n_k\,,\Delta n_{k+1},\Delta n_{k+2}\ \ldots$$

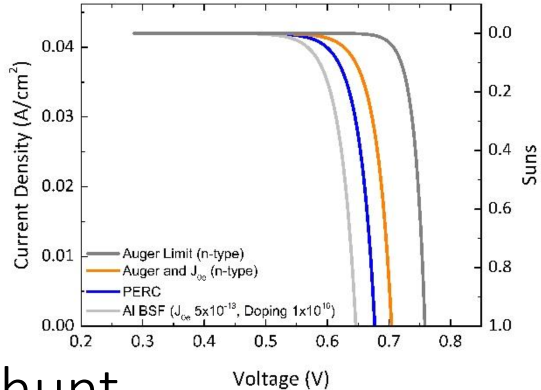
Calculate Recombination:

$$J = Photogeneration - Recombination - \frac{V}{R_{sh}}$$

Calculate Voltage:

$$V + JR_s = \frac{kT}{q}\ln\left(\frac{[(N_A + \Delta p)(\Delta n)]}{{n_i}^2}\right)$$

$$(J_k, V_k), (J_{k+1}, V_{k+1}), \ldots$$



Including series resistance and shunt

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IV in Terms of Emitters and Bulk Lifetime

$$V = \frac{kT}{q} \ln\left[\frac{(N_A + \Delta p)(\Delta n)}{{n_i}^2}\right] - JR_s$$

$$Current = Photogeneration - \left[\frac{\Delta n q W}{\tau_{bulk}} + \left[J_{0front} + J_{0back}\right] \frac{(N_A + \Delta p)(\Delta n)}{{n_i}^2}\right] - \frac{V}{R_{sh}}$$

[Recombination]

“Thin-base limit”

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IV in Terms of Emitters and Bulk Lifetime

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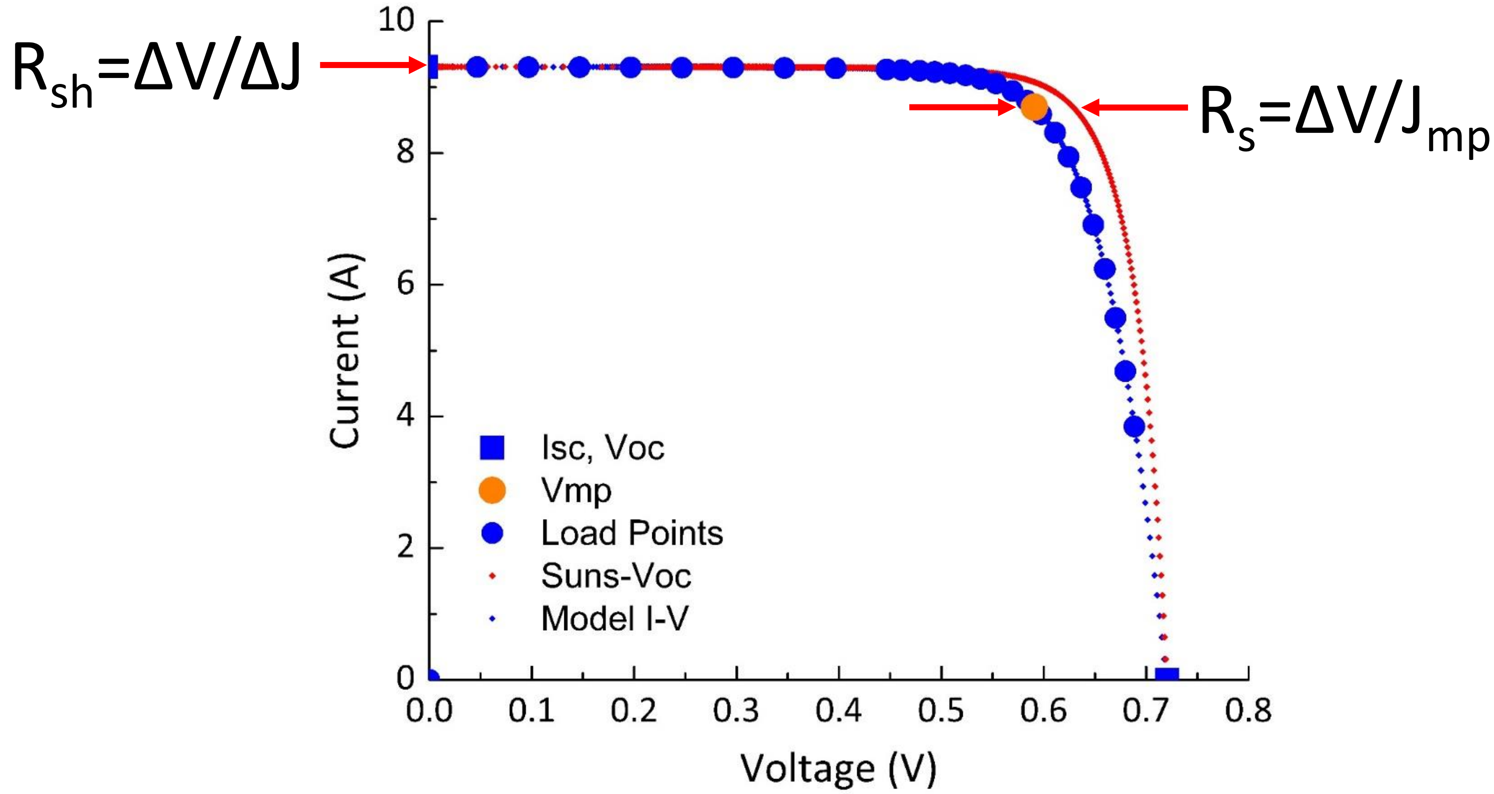
R_s Measurement Using Suns-V_{oc} Curve



R_s from Suns-V_{oc} does NOT depend on quality of fit to a model (no 1- or 2-diode equations or such nonsense)

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Biggest Challenge with High-Efficiency n-type

Time response of high-efficiency cells (capacitance)

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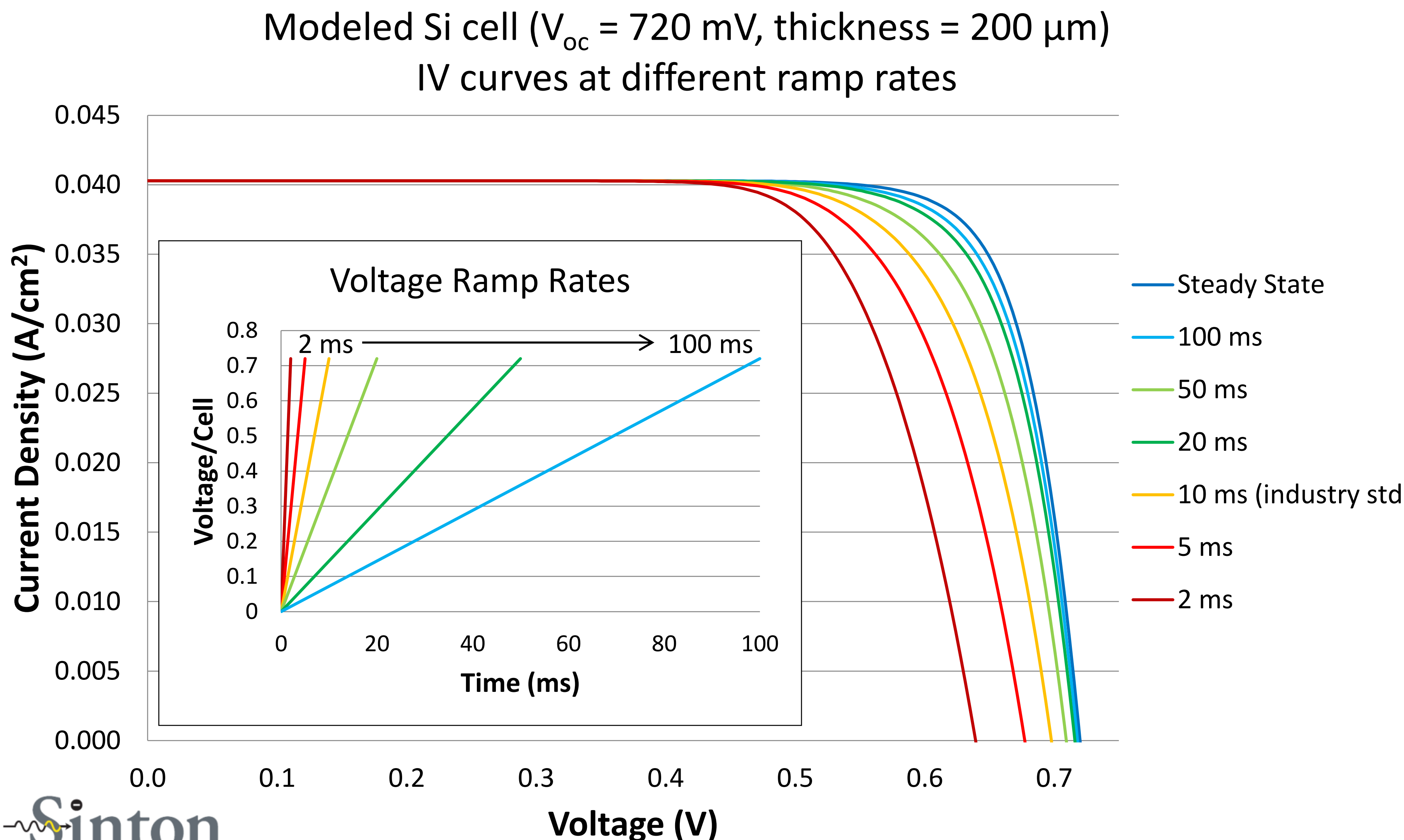
Ramp-rate Artifacts (PC1D simulations)



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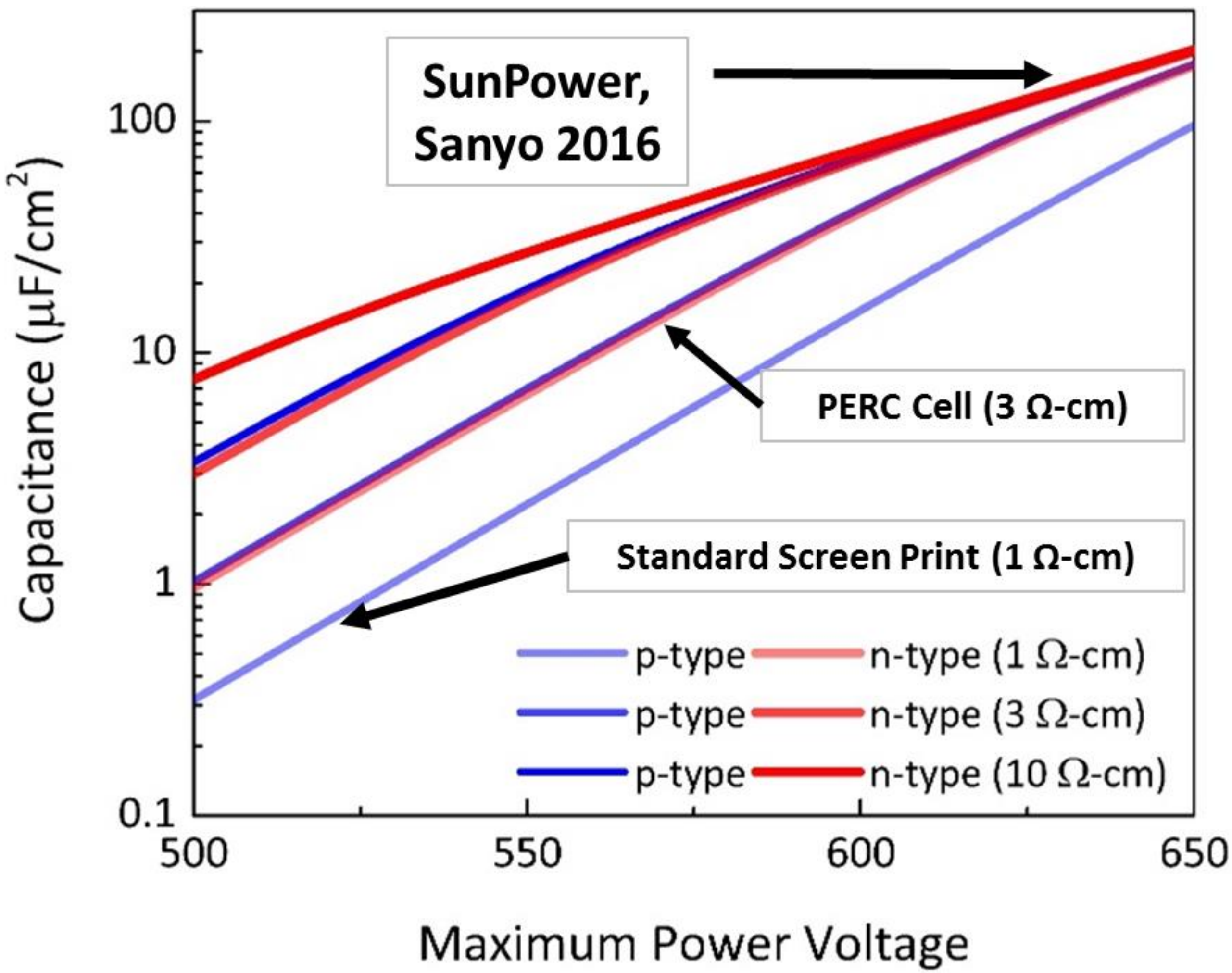
High-Efficiency n-type Cells: 200X Higher Capacitance!



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Eliminating errors due to slow time response during flash testing

$$\Delta n_k, \Delta n_{k+1}, \Delta n_{k+2} \ldots$$

Calculate Recombination:

$$J = Photogeneration - Recombination - \frac{V}{R_{sh}}$$

Calculate Voltage:

$$V + JR_s = \frac{kT}{q} \ln\left(\frac{[(N_A + \Delta p)(\Delta n)]}{{n_i}^2}\right)$$

$$(J_k, V_k), (J_{k+1}, V_{k+1}), \ldots$$

Solution: Test under constant charge conditions:

Measure V and J, while holding ($V + J \times R_s$) constant using a feedback circuit. 10 years of industrial production and R&D experience with this technique.

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R. A. Sinton, 21st EU PVSEC, (2006); pp. 634-638;
US patents 7696461 B2 2010, 7309850B2 2007

Eliminating errors due to slow time response during flash testing

- SintonDresden2006.pdf

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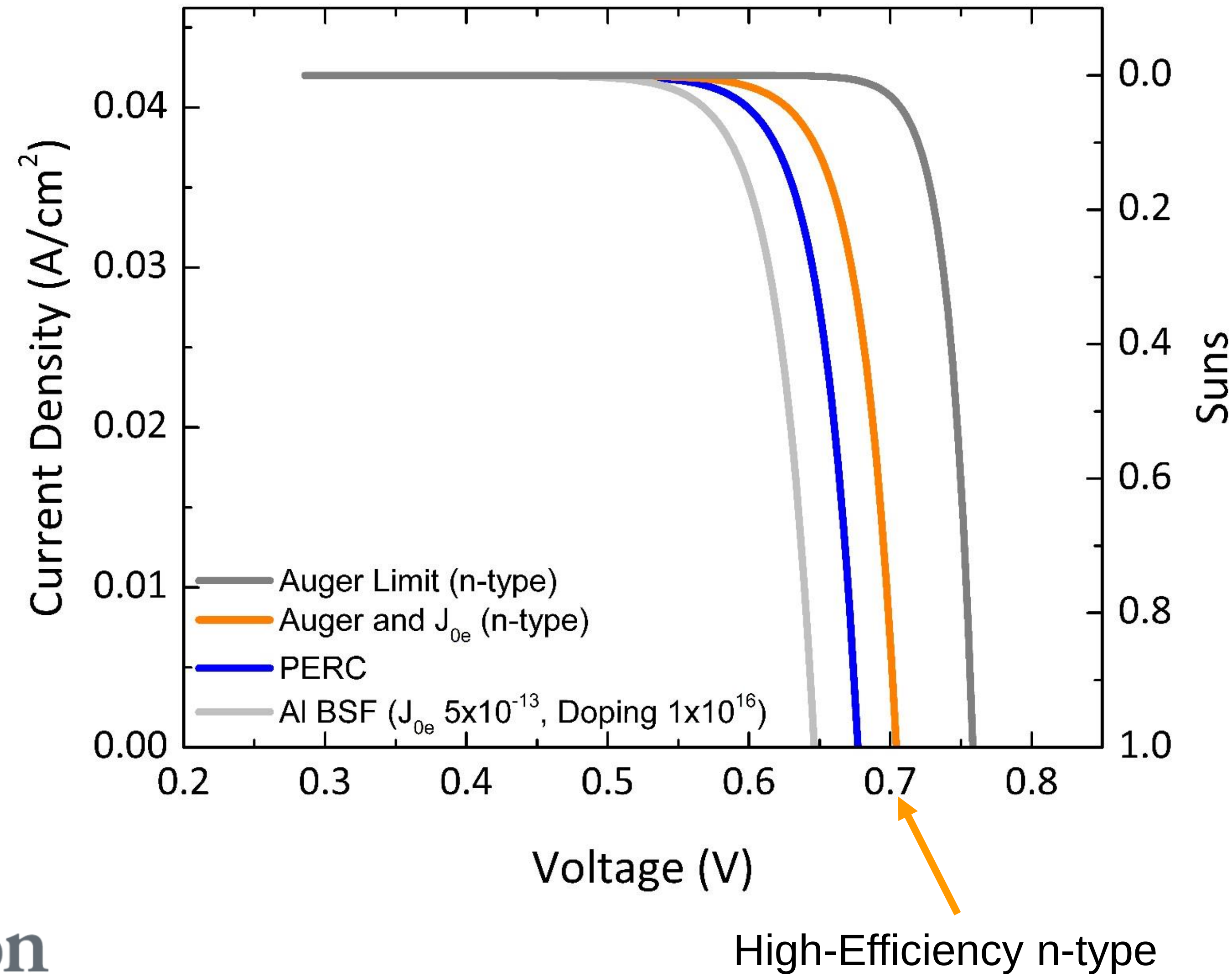
Example: IV test of a high-efficiency n-type cell



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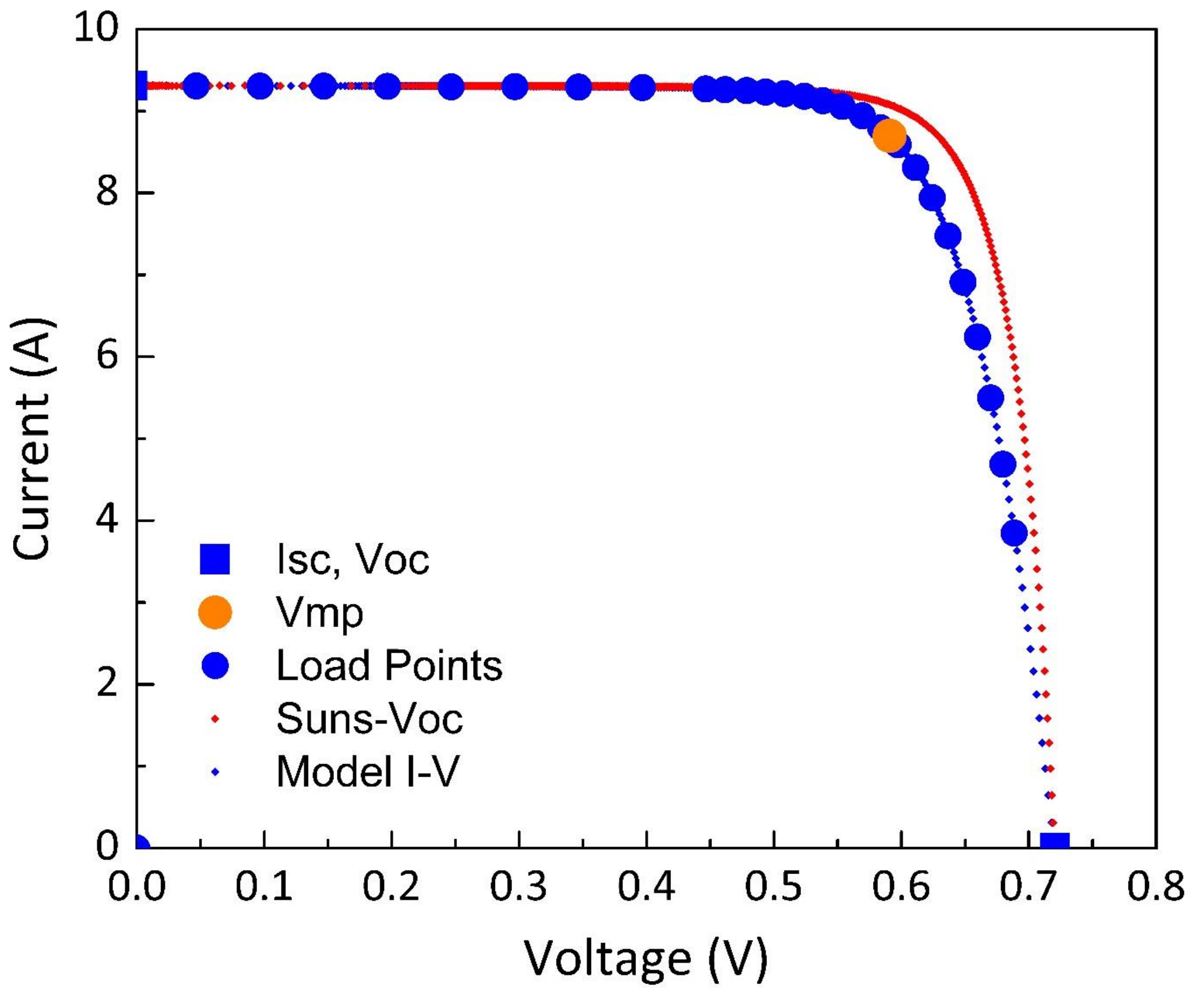
IV-test example: N-type high efficiency



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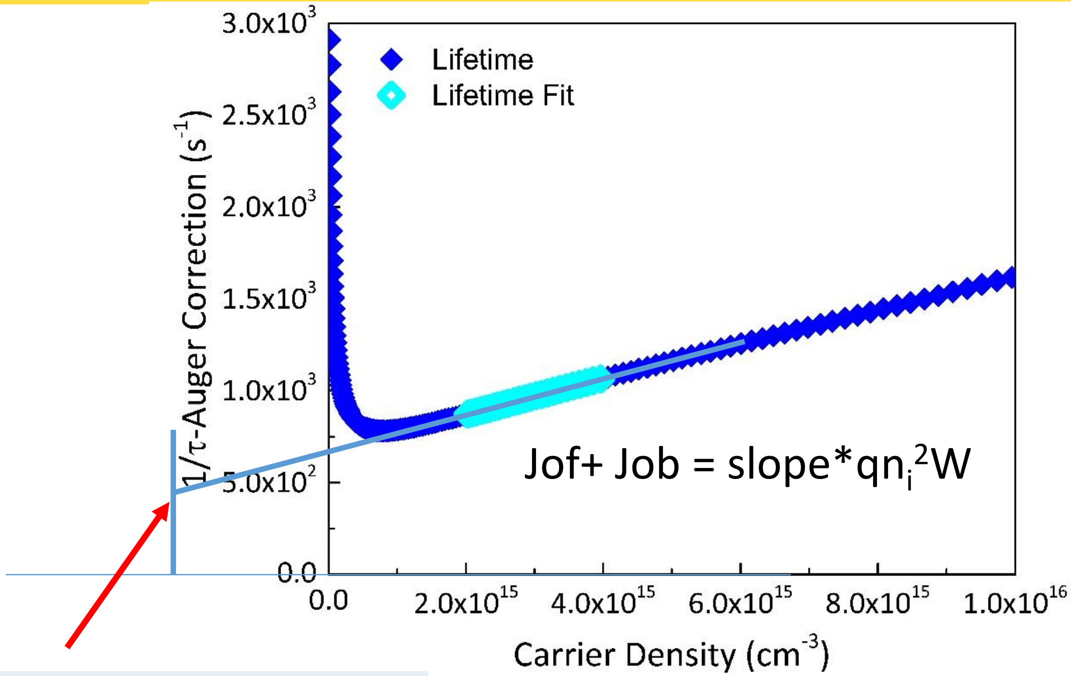
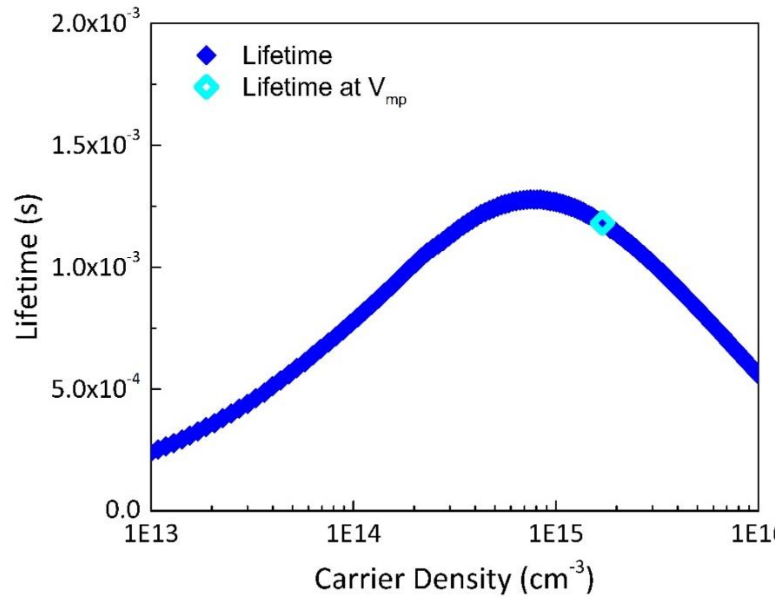


Bulk lifetime @ $-N_D$



IV-test Example: n-type High Efficiency

Normalized Results	
Parameter	Result
J_{sc} (A/cm^2)	0.03786
V_{oc} (V/cell)	0.7201
J_{mp} (A/cm^2)	0.03535
V_{mp} (V/cell)	0.5912
P_{mp} (W/cm^2)	0.209
R_{sh} (Ω-cm^2)	140151
R_s (Ω-cm^2)	1.058
Cell Efficiency (%)	20.9

Suns-Voc Outputs	
Parameter	Result
pJ_{mp} (A/cm^2)	0.03786
pV_{mp} (V/cell)	0.7201
pP_{mp} (W/cm^2)	0.209
pFF (%)	81.6
pEfficiency (%)	22.25
n @ 1 sun	1.141
n @ 0.1 suns	1.413
J_{01} (A/cm^2)	2.478×10^{-14}
J_{02} (A/cm^2)	7.956×10^{-9}
J_{0e} (fA/cm^2)	15.08
Est. Bulk Lifetime (µs)	1632
BRR (Hz)	612.9
Lifetime @ V_{mp} (µs)	1186
Doping (cm^{-3})	7.27×10^{14}
Measured Resistivity (Ω-cm)	6.307
Lifetime Fit R^2	1

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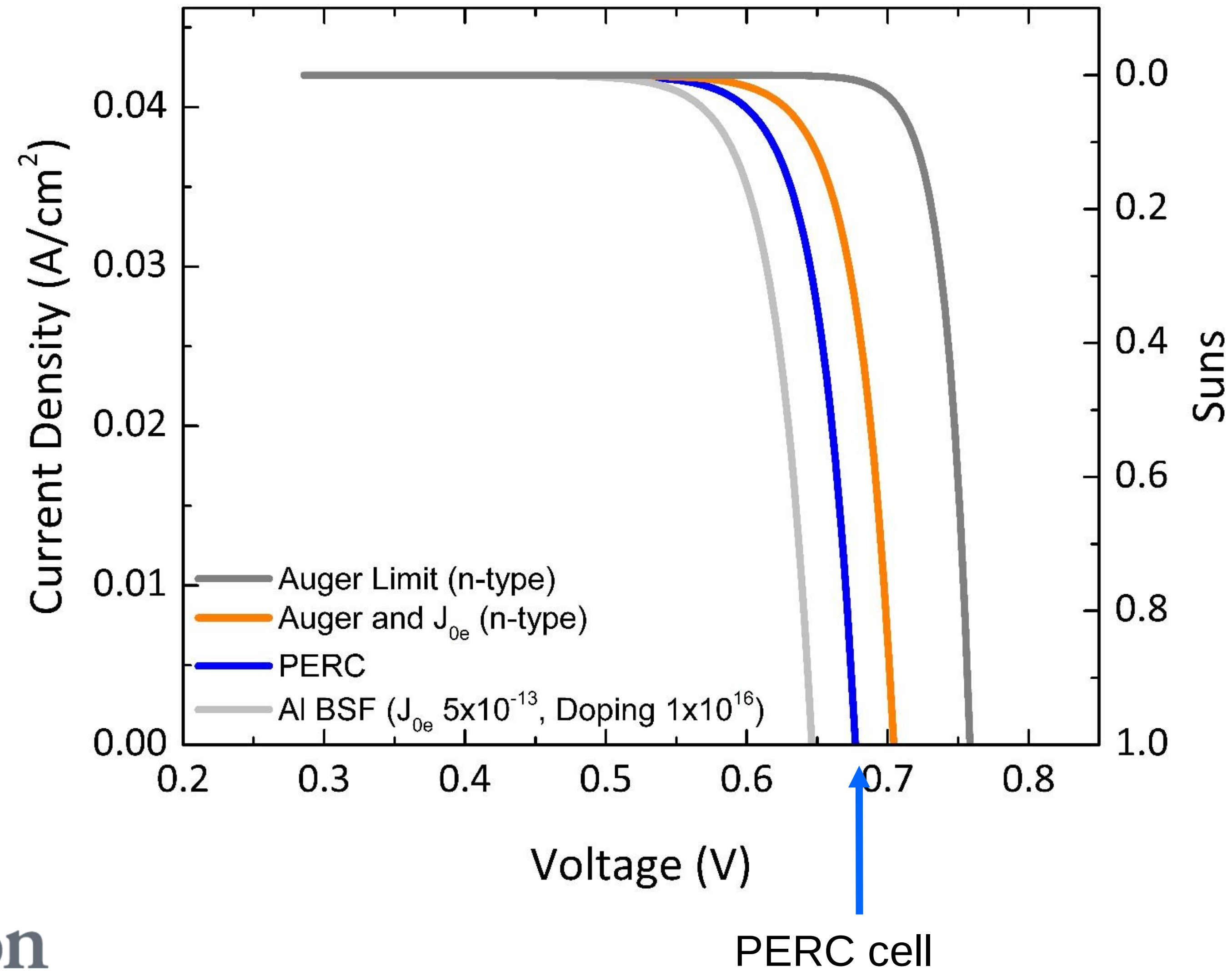
Example: IV test of a PERC cell



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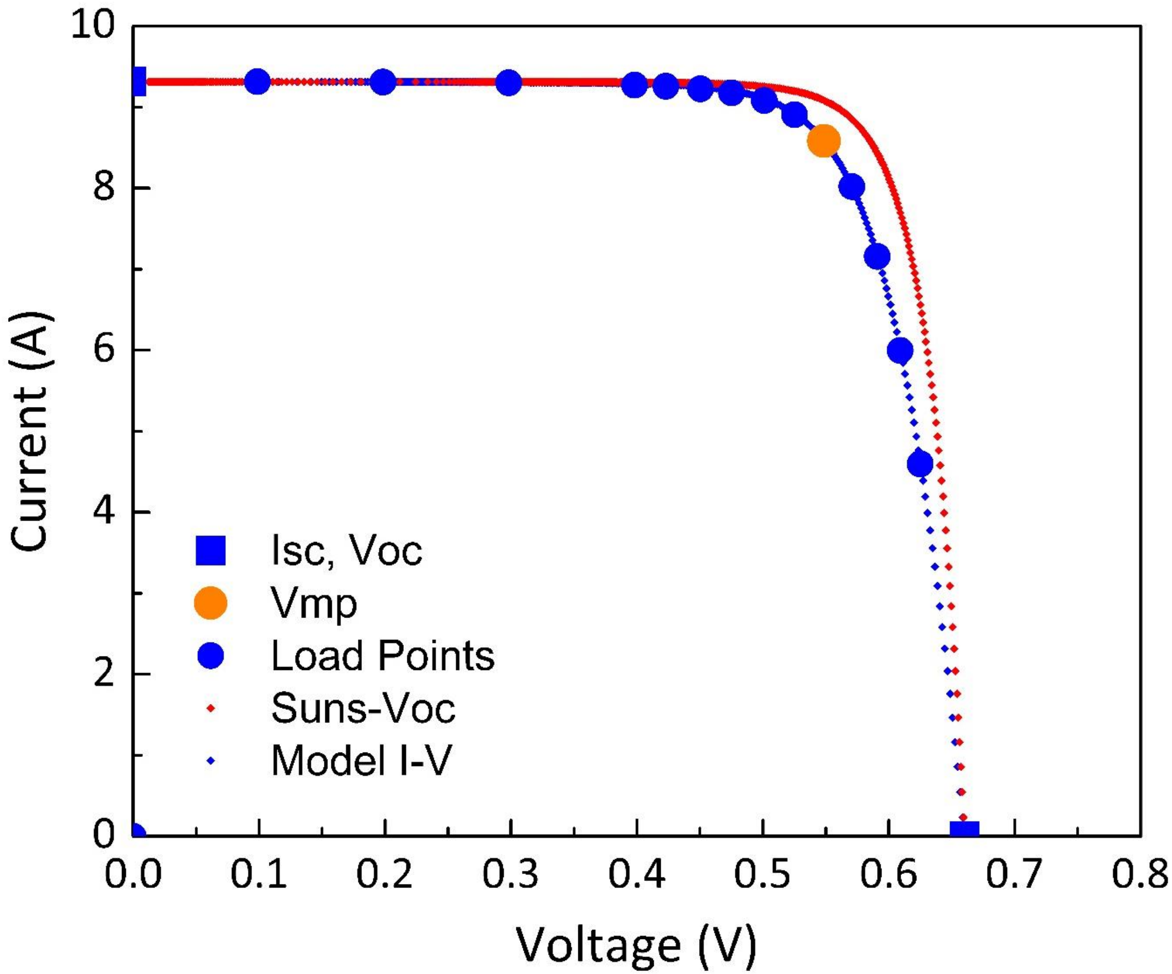
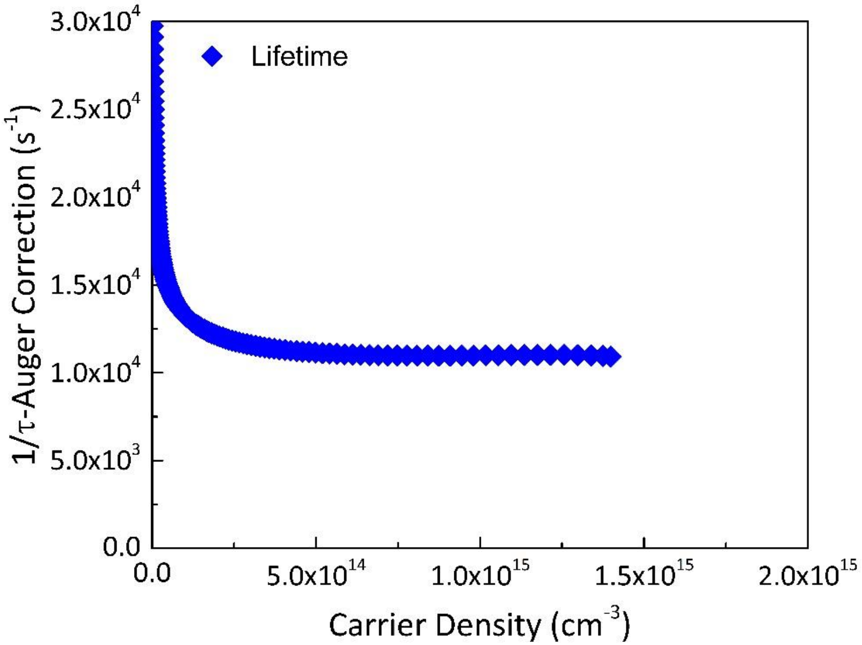
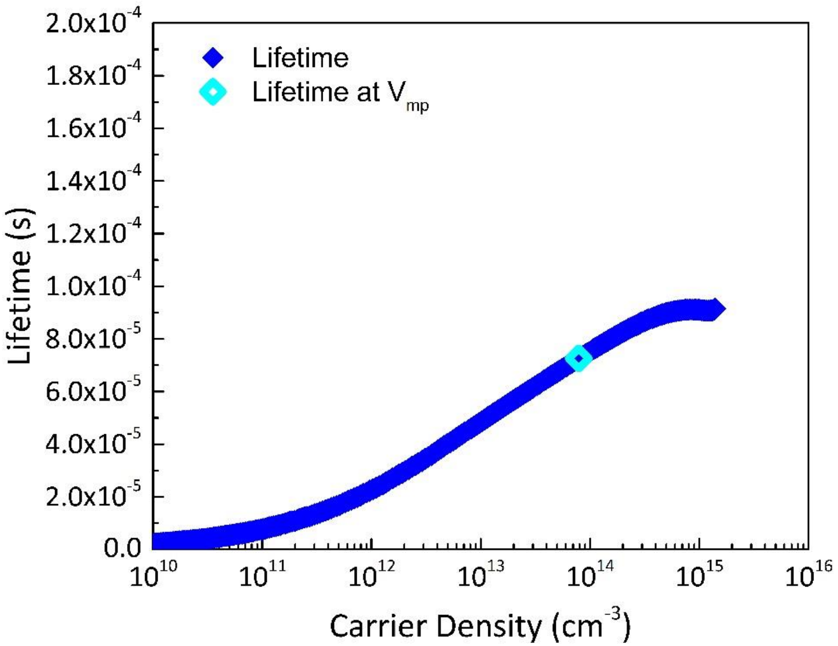


IV-test example: PERC cells





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Lifetime and Substrate Doping Measurements of Solar Cells and Application to In-Line Process Control

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IEEE PVSC, Portland, Oregon, 2016

Measurement Samples: P-type Study

- P-type cells processed with varying techniques:
  - Multi-crystalline Al BSF cells
  - High Performance Multi-crystalline Al BSF cells
  - Multi crystalline PERC cells
  - Monocrystalline PERC cells
  - Monocrystalline PERC cells

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Doping Measurement: An Opportunity

- Substrate doping and τ vs. Δn at the cell level
  - Substrate doping
    - Wafer position in ingot or brick → prediction of [O]/other impurities → potential prediction of LID behavior
    - Information relevant to lateral series resistance in PERC cells
    - Gives final substrate doping, including changes from high temp steps
  - Effective lifetime
    - Surface passivation quality
    - Substrate quality
    - Contamination during high-temperature processing

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Measurement Parameters

- Analyze pV_{mp} and efficiency dependence on substrate doping (N_A) and effective lifetime (τ_{eff})
  - pV_{mp} is used because the five groups of cells come from different processing techniques, allows for a comparison independent of R_s

- pV_{mp}: 515-584mV
- Efficiency: 15.8-21%
- τ_{eff}: 5-100µs
- N_A: 5×10^{15}-3×10^{16}cm^{-3}

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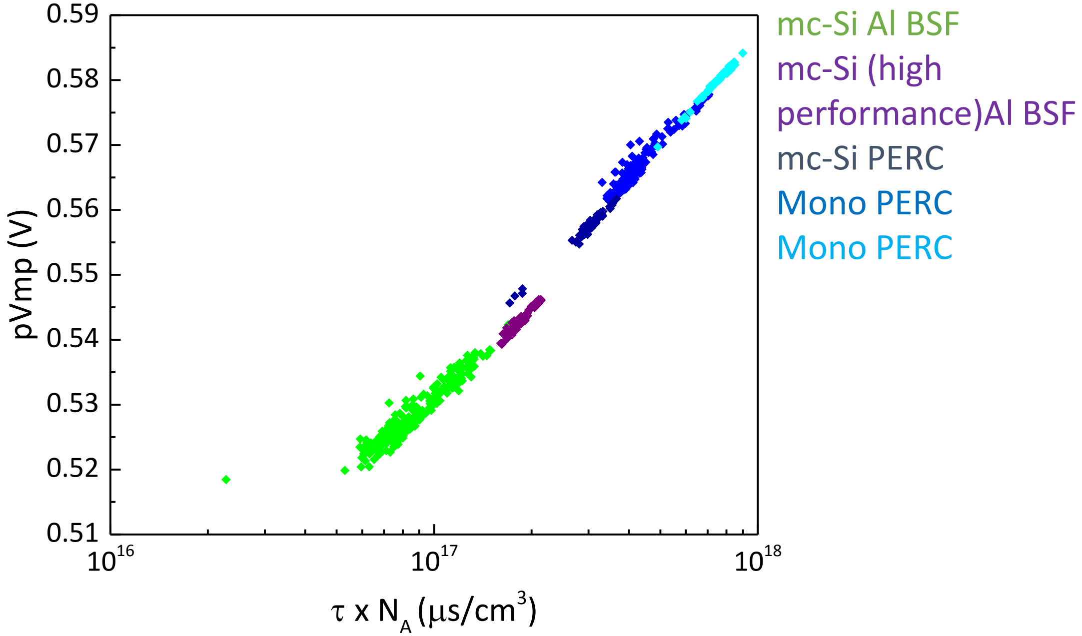
pV_{mp} and Efficiency Correlate to $\tau \times N_A$

- Five different cell processing techniques all follow the same trend



$$V + R_s J = \frac{kT}{q} ln\left[\frac{(J_{sc} - J)\left(N_A + \Delta n\right)\tau_{eff}}{qWn_i{}^2}\right]$$

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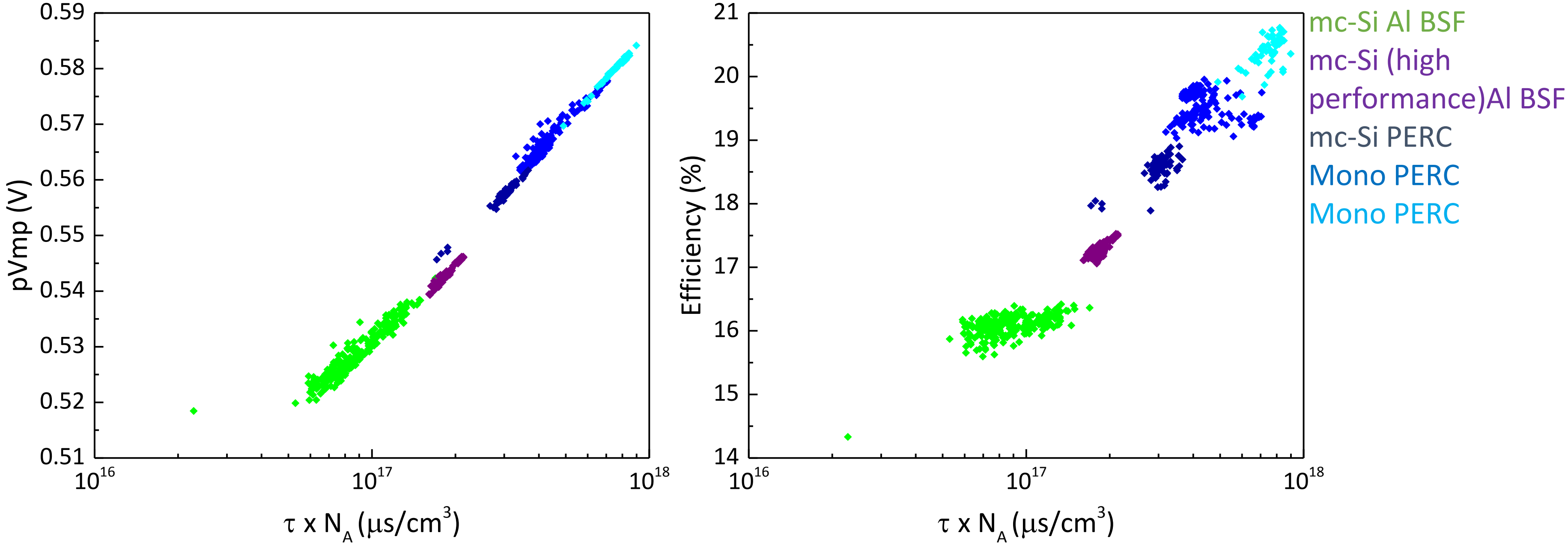

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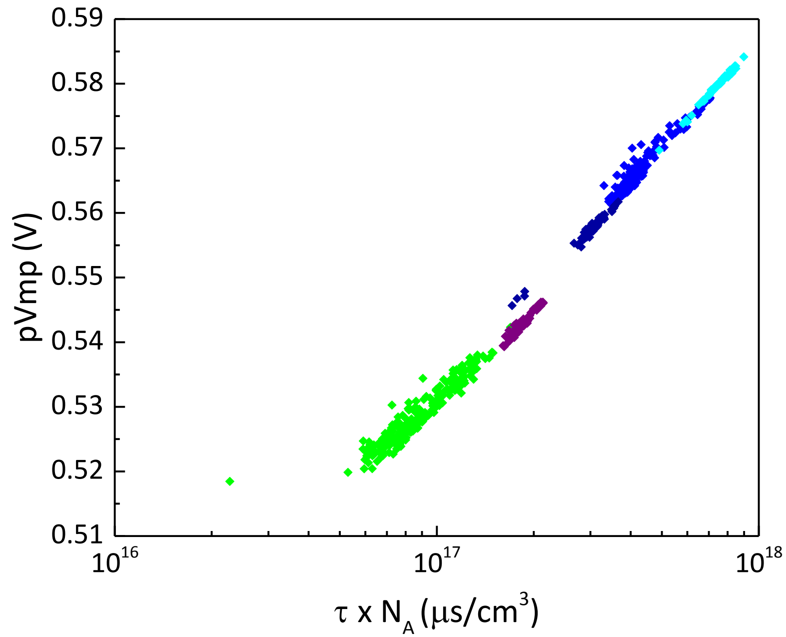
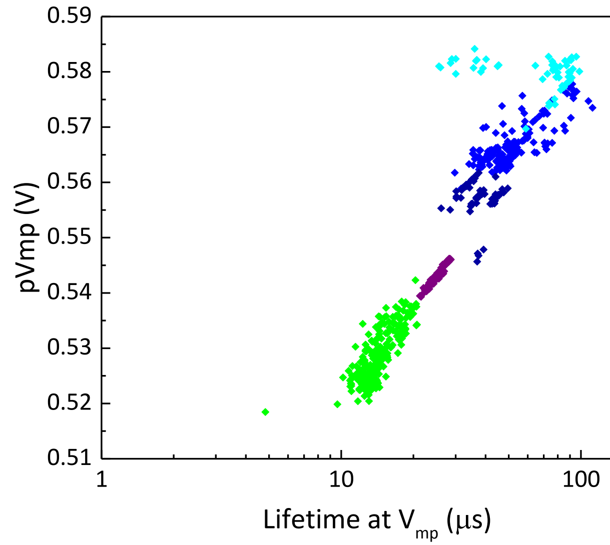
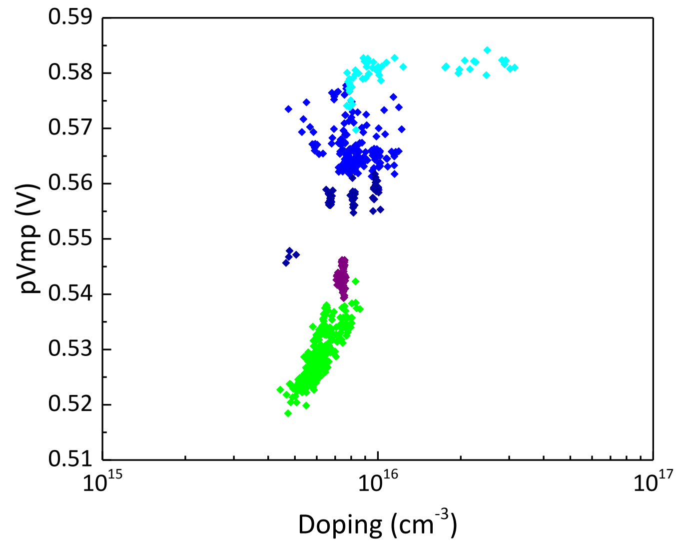
Substrate Doping Doesn't Tell the Whole Story







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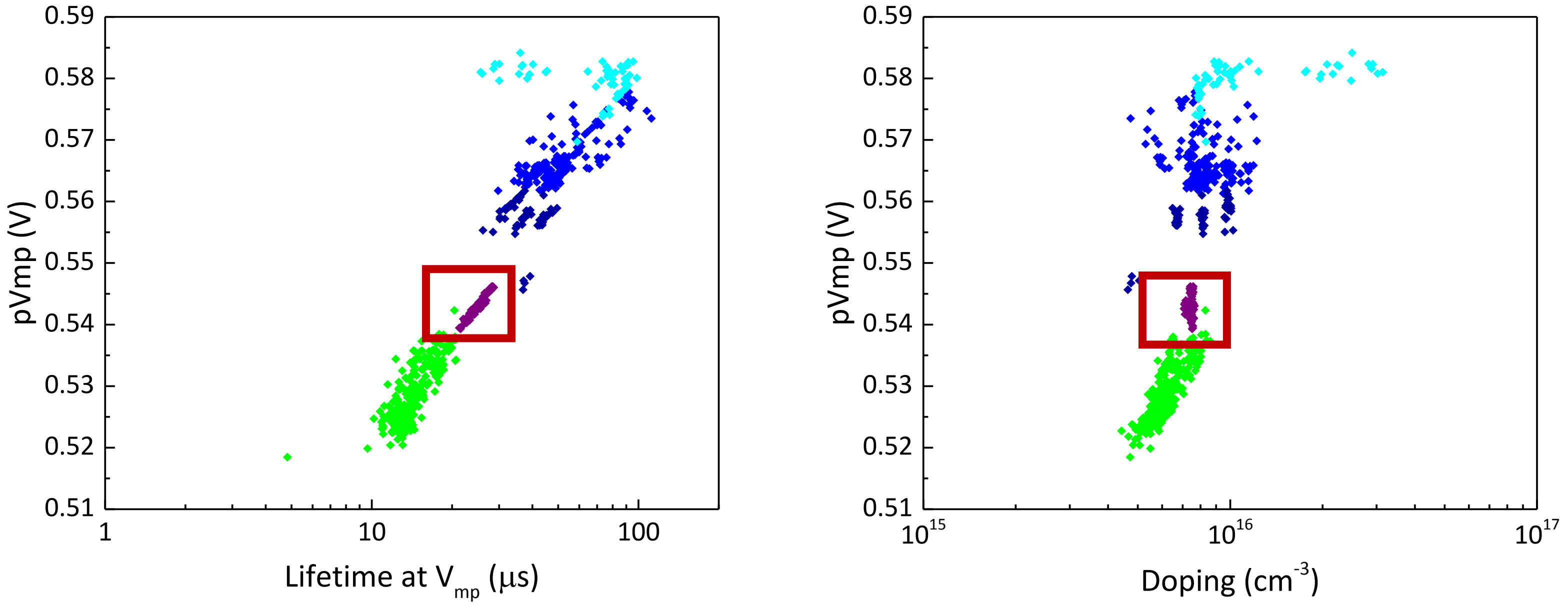
High Performance Multi Al BSF

- pV_{mp} ranging from 518.5 to 542.3 mV
- Similar substrate doping ~$7.5x10^{15}$ cm^{-3}
  - No pV_{mp} trend due to doping
- Clear trend due to lifetime



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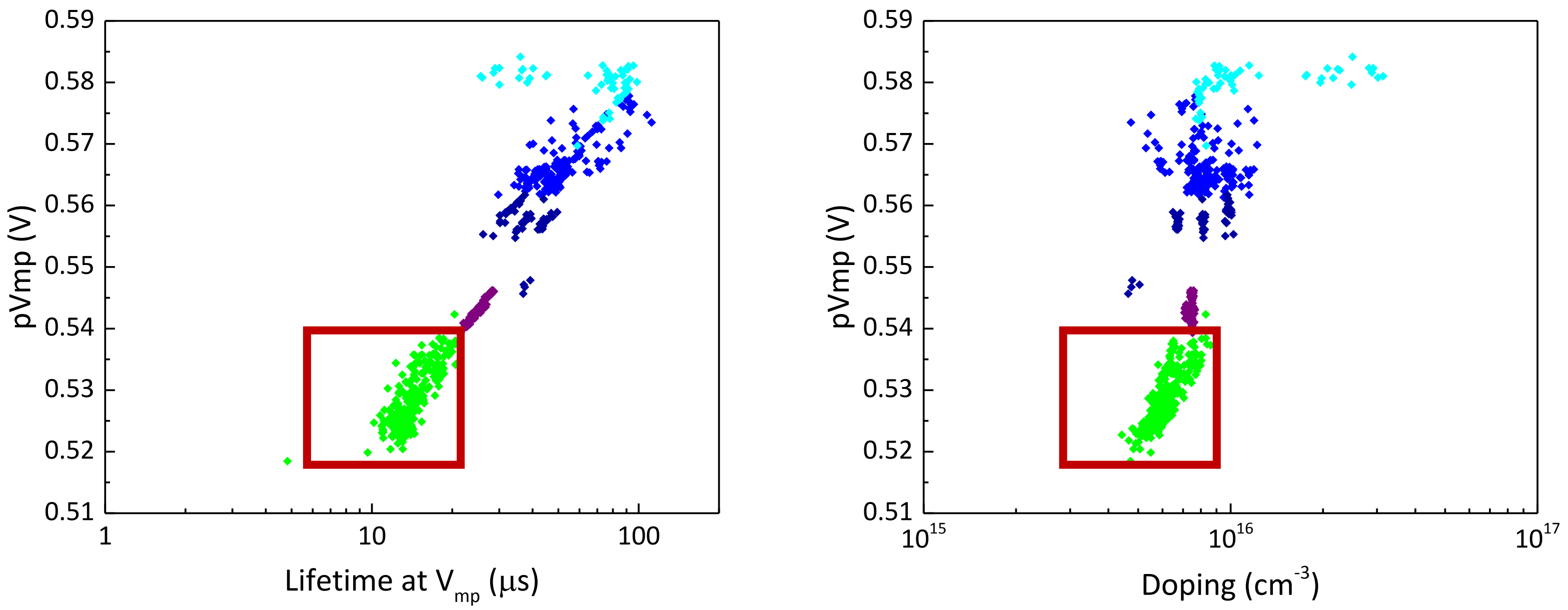
Multi-crystalline Al BSF

- pV_{mp} correlation to both doping and lifetime
- Indicating independent effects of these parameters
  - Expected for variations in wafers from multi-crystalline bricks



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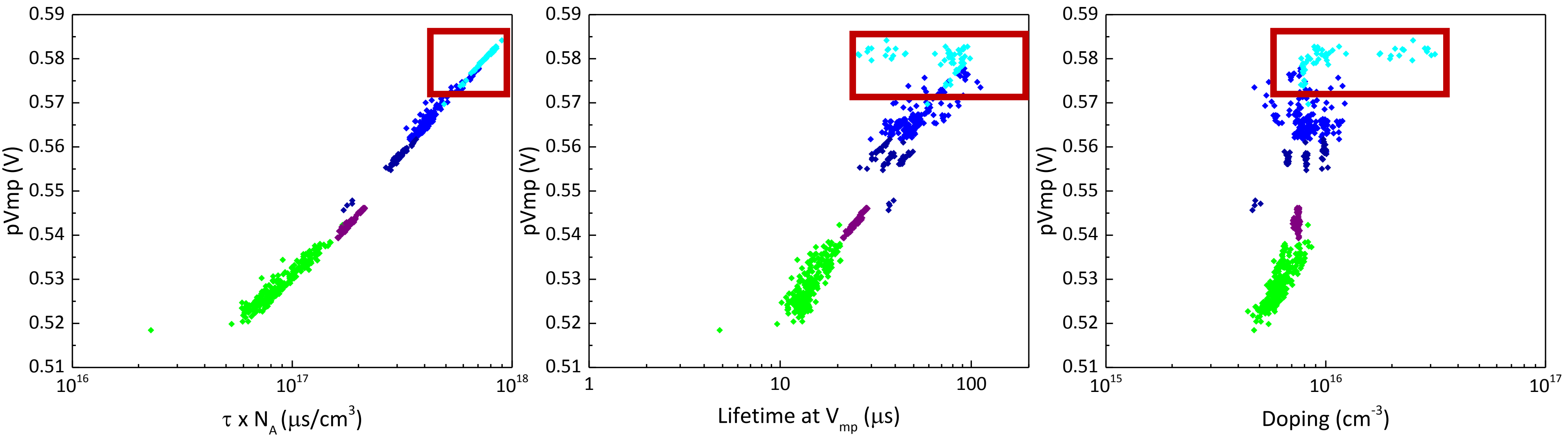
Mono-crystalline PERC

- Strong dependence on lifetime-doping product
- No distinct correlation to lifetime or doping independently
- Cause of high quality substrate
  - Bulk lifetime is very good
  - Lifetime-doping product is determined by the front and back J_{0e}



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$$(N_A + \Delta n)\tau_{eff} = \frac{1}{\frac{1}{\tau_{bulk}(N_A + \Delta n)} + \frac{J_{o\,front} + J_{o\,back}}{qn_i^2 W}}$$

Big Data: Simple Example

- Measure 200,000 multi-crystalline cells (2 days of data)
  - Resistivity varies from 1-3 Ω-cm
- If you want to isolate the dependence on doping, then:
  - Compare a histogram of cells with 10,000 1 Ω-cm resistivity with a histogram of 10,000, 2 Ω-cm cells
  - The resulting distributions (for each) are independent of the effects of doping, effectively isolating the experiment to look at other variables
  - Differences between the histograms indicate doping dependence

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Last Example: Energy-loss analysis at IV-test

Based on results published by SunPower at PVSC

David D. Smith et al. “Silicon Solar Cells with Total Area Efficiency over 25%” IEEE PVSC June 2016.

Example of use of lifetime data at cell test: 25.2% n-type cell (SunPower)

TABLE I
SUMMARY OF ELECTRICAL DATA

Area (cm2)	Voc (mV)	Jsc (mA/cm^2)	FF (%)	Vmp (mV)	Eff (%)
153.49	737	41.33	82.7	643.8	25.2 %

Cells used to demonstrate 24.1% module efficiency

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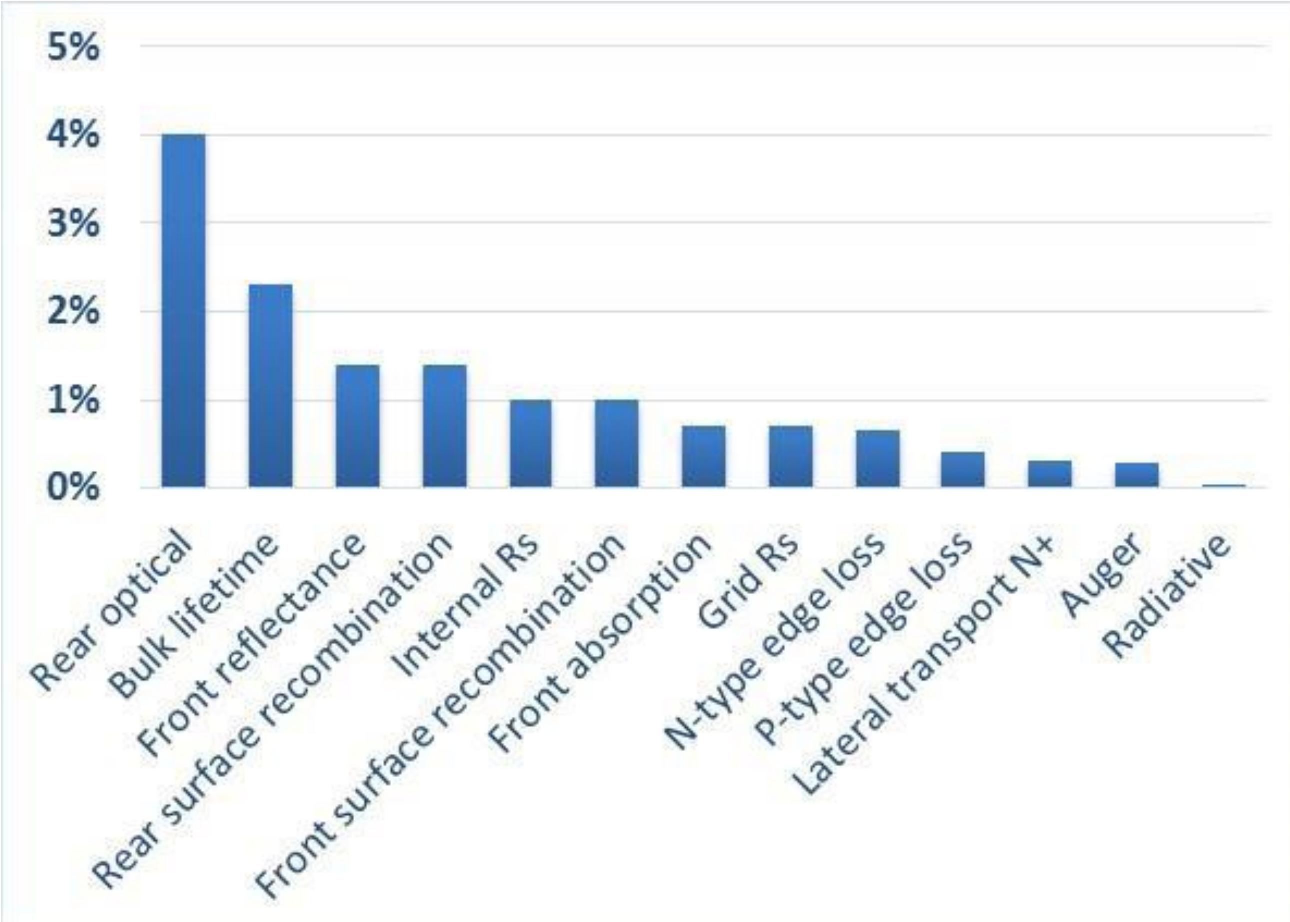
David D. Smith et al. "Silicon Solar Cells with Total Area Efficiency over 25%" IEEE PVSC June 2016.

Loss analysis presented by SunPower at PVSC



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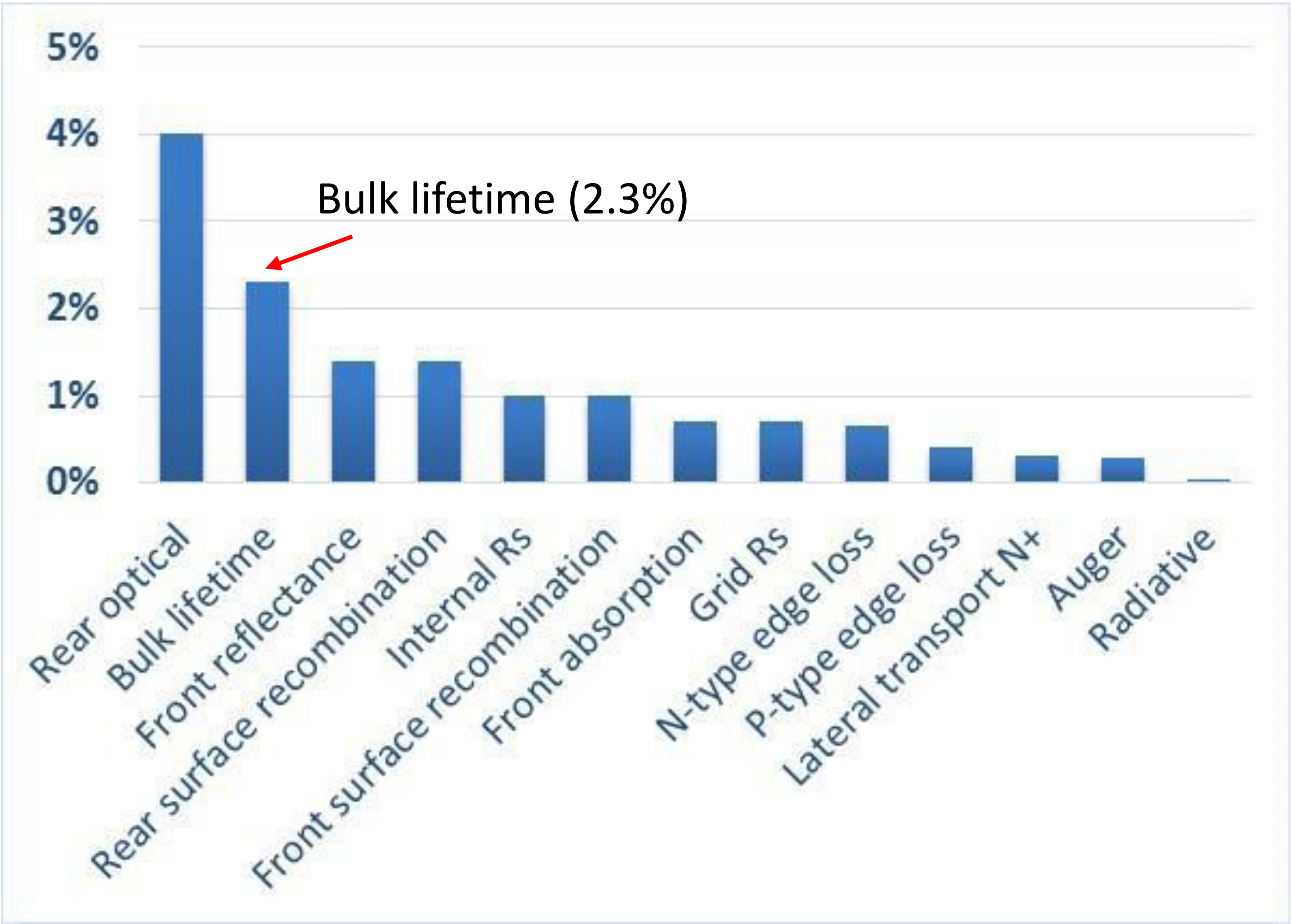
Loss analysis: Bulk Lifetime



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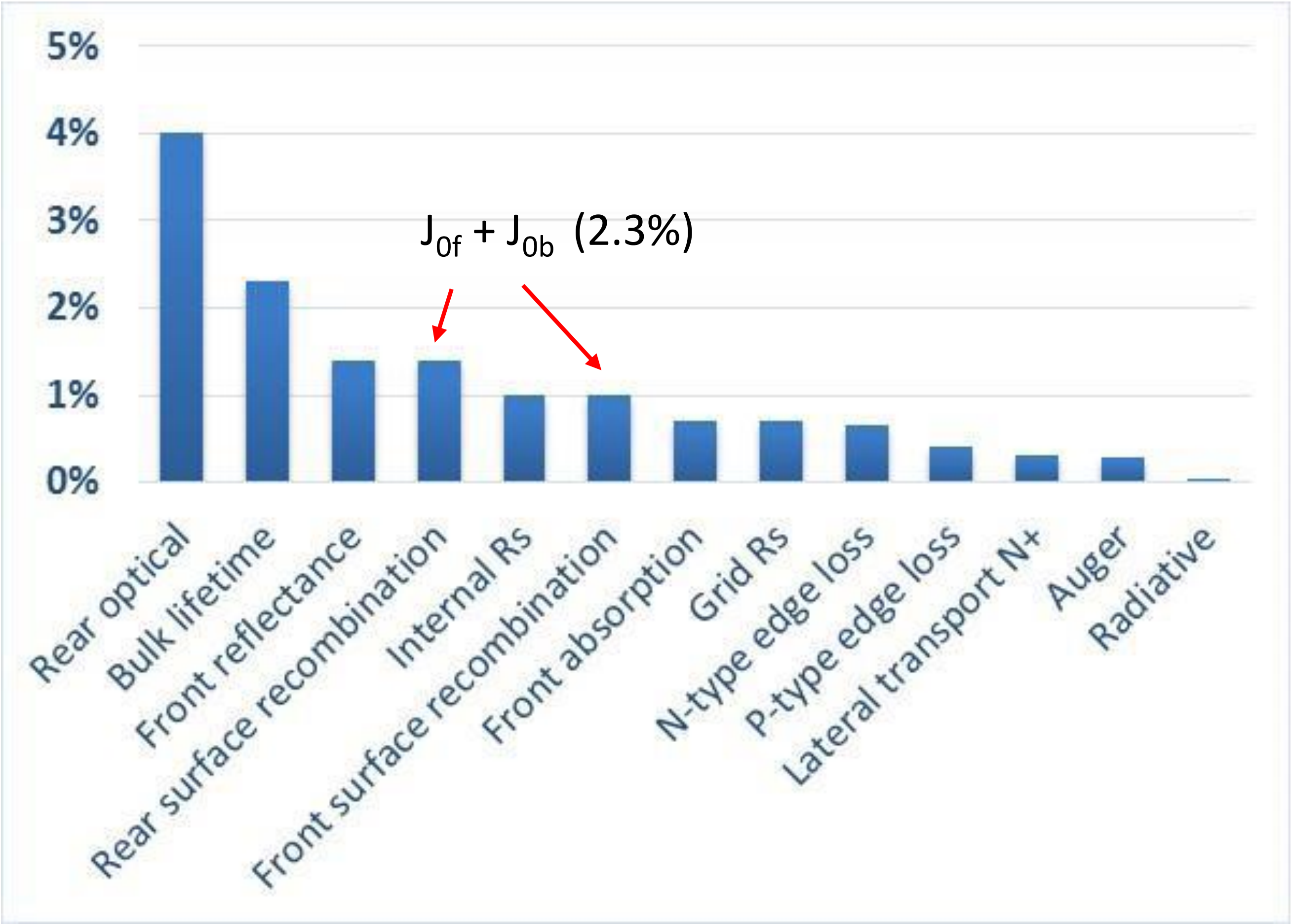
Loss analysis: J_0 (front and back)



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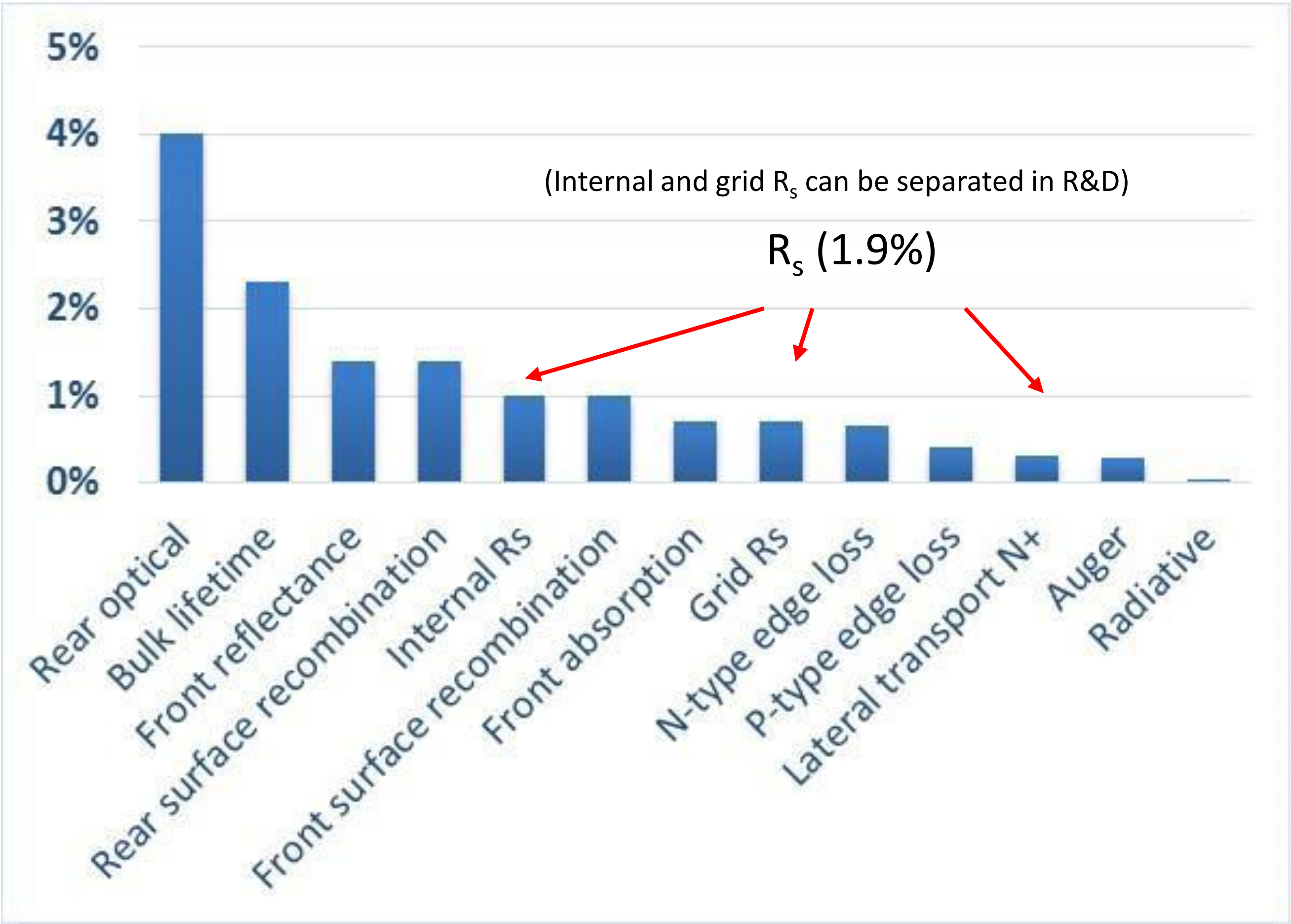
Loss analysis: Sum of R_s components



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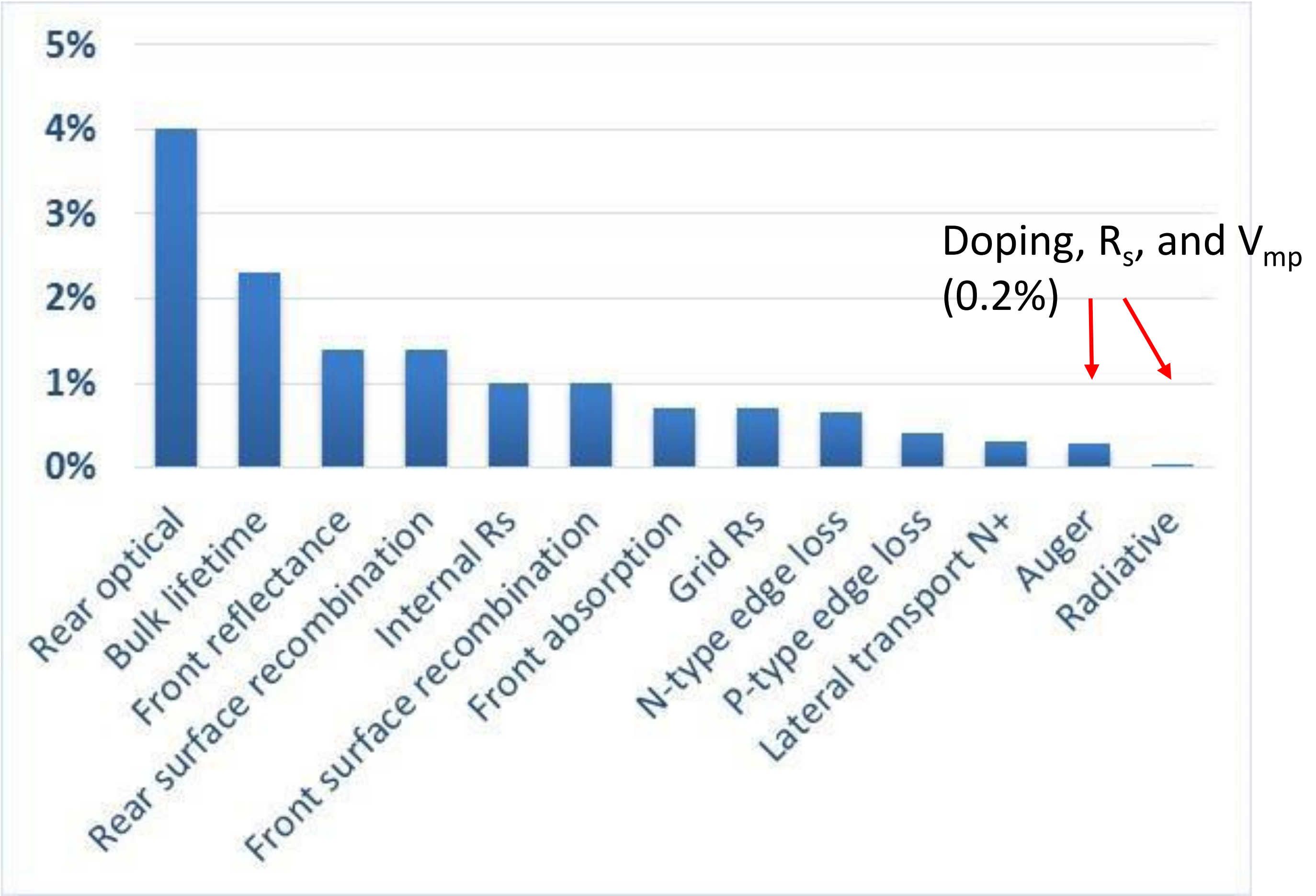
Loss analysis: Fundamentatal recombination



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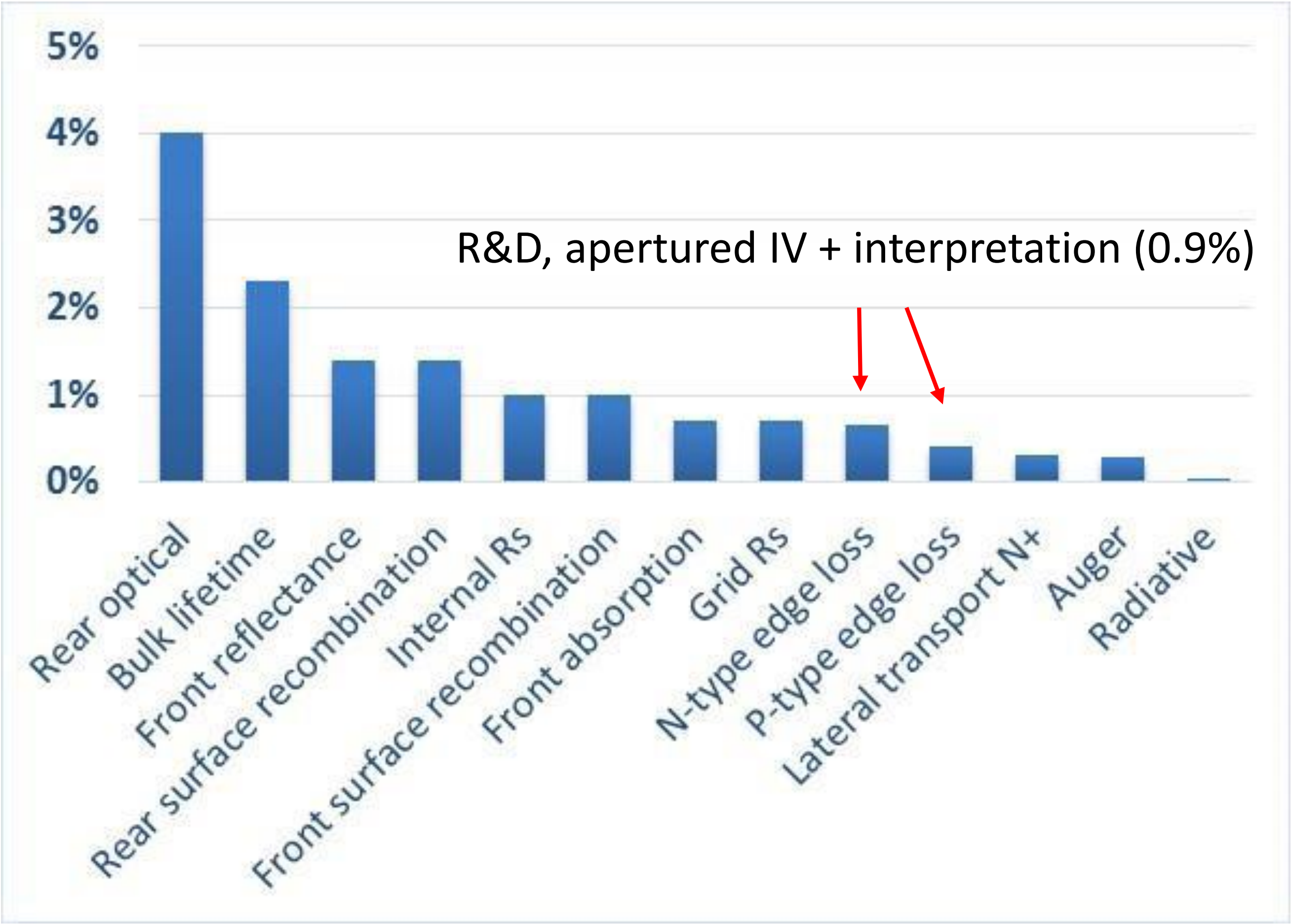
Loss analysis: Inactive area/edge effects



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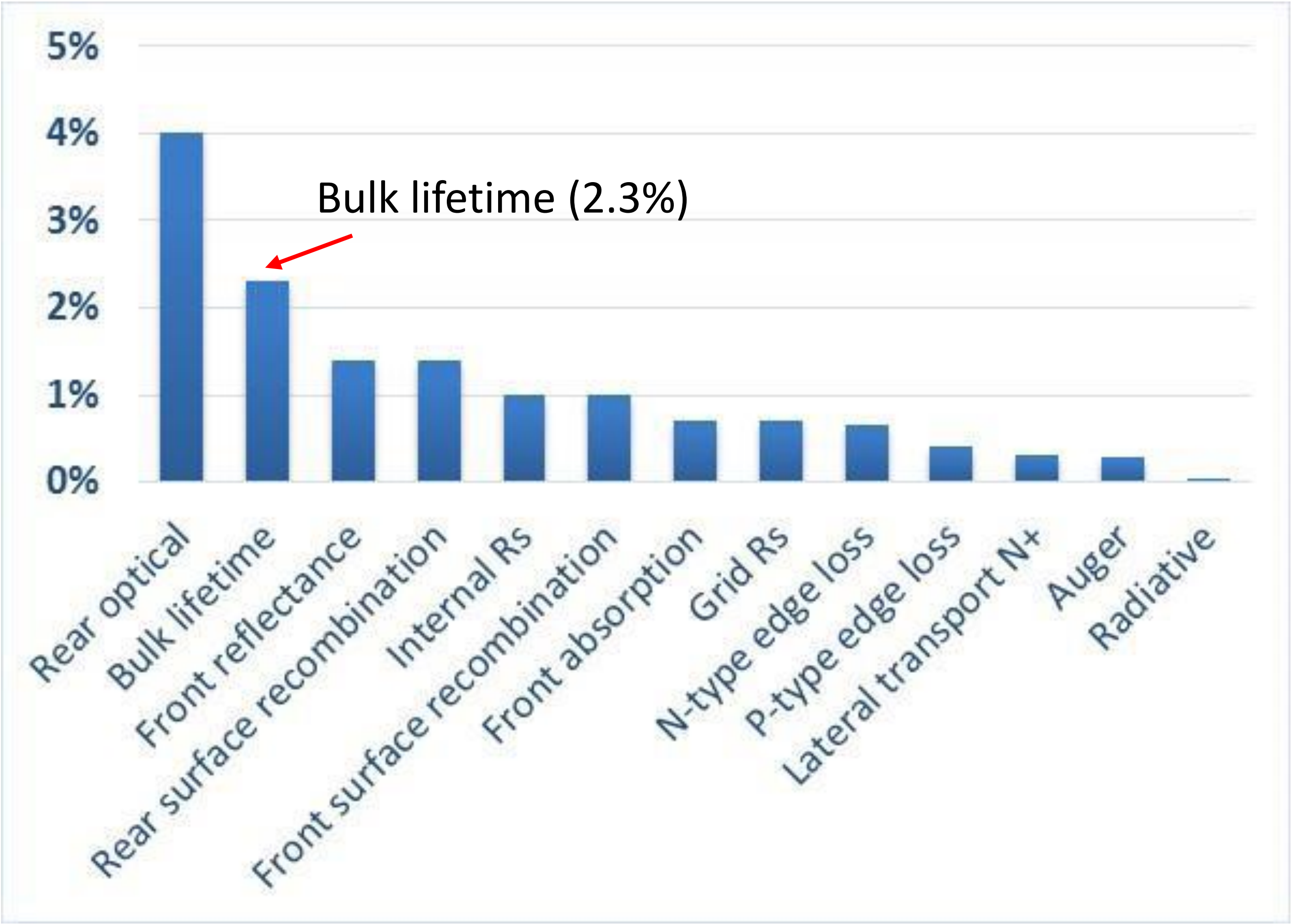
Loss analysis: Bulk Lifetime



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SunPower analysis from PVSC paper
Test wafers prior to IV test (statistically significant)

TABLE II

INVERSE BULK LIFETIME FOR EMITTER TEST WAFERS.

Region	Front	Back 1	Back 2	Back 3	Area weighted average
Inverse bulk lifetime (1/sec)	17	16	64	44	50

=20 ms

But the bulk lifetime extracted at cell test was **6.7** ms, not 20 ms!

(use of lifetime vs. injection level data at cell test to determine bulk lifetime)

David D. Smith et al. "Silicon Solar Cells with Total Area Efficiency over 25%" IEEE PVSC June 2016.

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SunPower analysis from PVSC paper
Test wafers including "patterning"

INVERSE BULK LIFETIME FOR MAGNIFIED UNIT CELL TEST WAFERS

Region	Region 1	Region 2	Region 3	Area weighted average
Inverse bulk lifetime (1/sec)	66	161	173	143

=7 ms

Going back and including "patterning" steps in the lifetime tests for the regions of interest on test wafers matches the bulk lifetime of the cell at cell test.

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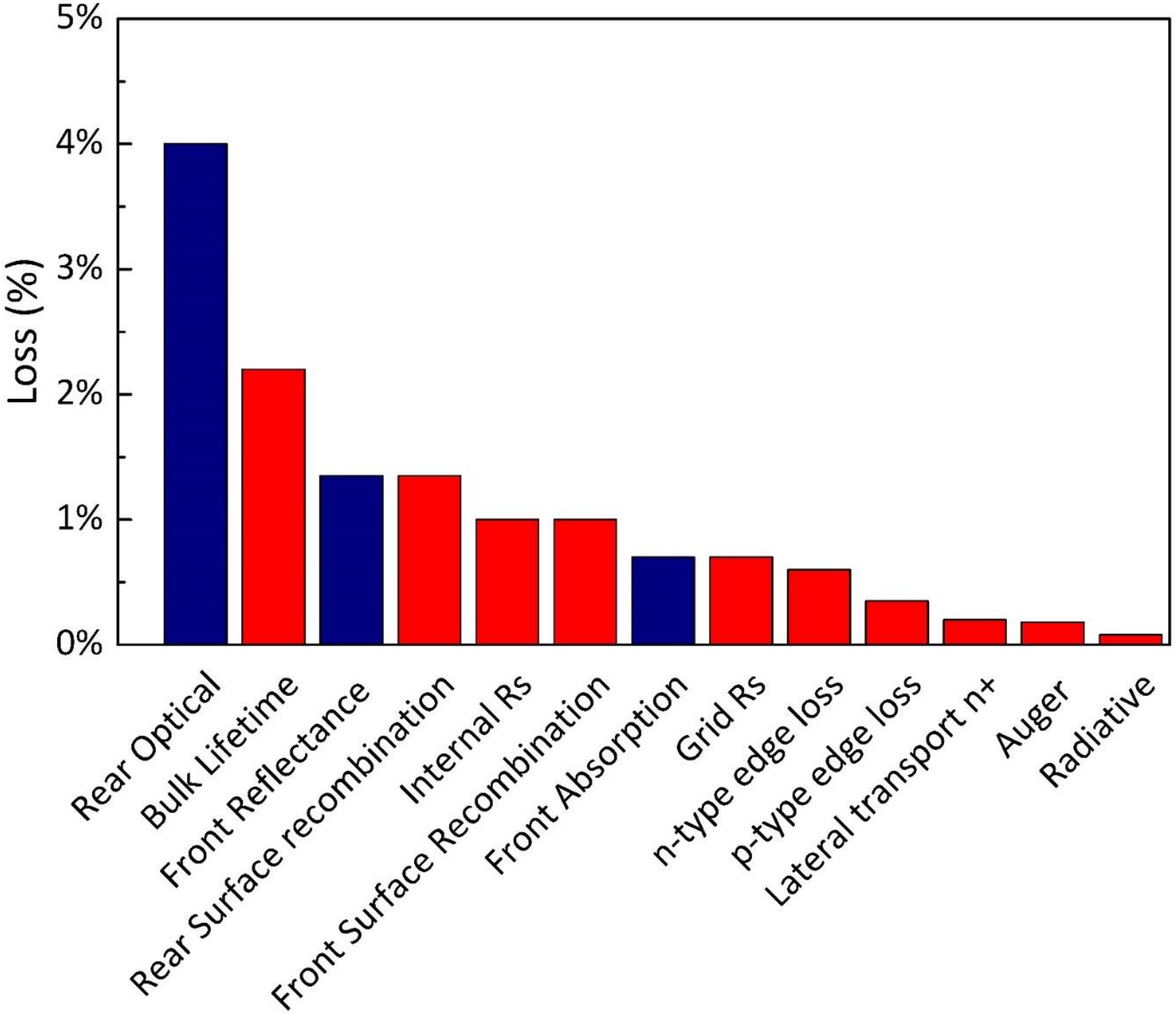
David D. Smith et al. "Silicon Solar Cells with Total Area Efficiency over 25%" IEEE PVSC June 2016.

Loss analysis: Requires ext. spectral response + model



David D. Smith et al. “Silicon Solar Cells with Total Area Efficiency over 25%” IEEE PVSC June 2016.

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Conclusions

- Advanced device physics can be performed at cell test
- Normal IV parameters + Suns-V_{oc}, τ vs. Δn, R_s, R_{sh}, substrate doping
- Enables sophisticated loss analysis, wafer by wafer, at cell test
- Fully implemented in line-speed production tools
  - Max speed 4800/hr (measurement time = 200ms). Limited by wafer transport to 2400/hr at present
  - Big data enables resolution for discriminating efficiency dependence on process control, substrate doping, surface passivation
- Extends well-known device-physics tools to cells and modules
  - Reliability studies (τ vs. Δn) on cells as well as test wafers

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Acknowledgements

- The authors would like to acknowledge Trina Solar and the Photovoltaics Manufacturing Consortium (PVMC) from providing solar cells for this work

- The information, data, or work presented herein was funded in part by the United States Department of Energy Phase II SBIR, under award number DE-SC0010156

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