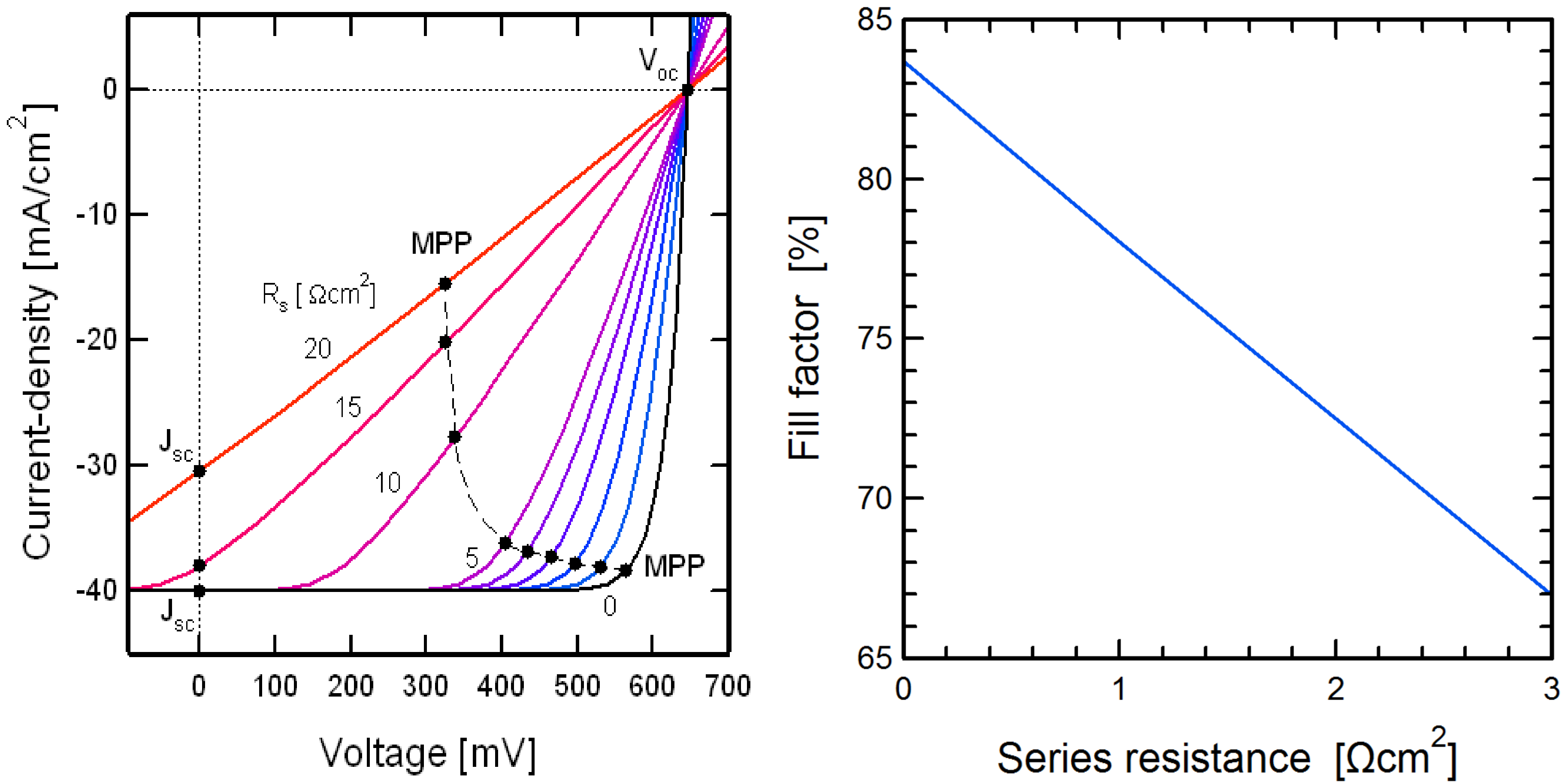
Understanding the fill factor by means of characterisation and simulation

Pietro P. Altermatt
Leinbiz University of Hannover, Germany

SPREE Seminar @ UNSW, 19th March 2015

Which parameters influence the fill factor?

…the lumped series resistance R_s

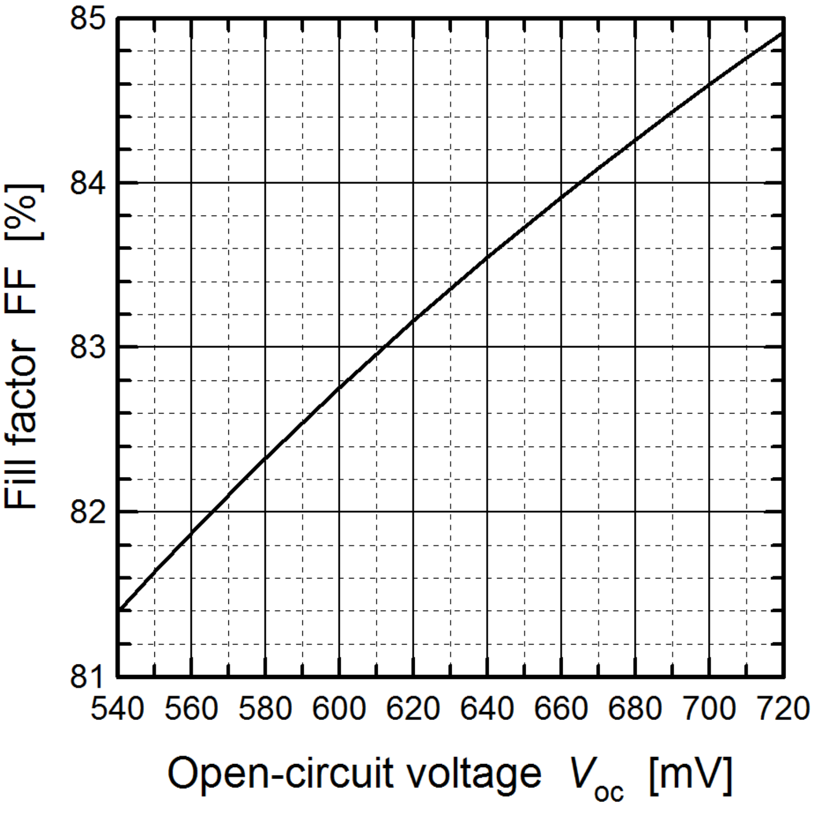


… the V_{oc}

$$FF = \frac{V_{oc}/V_{th} - \ln(V_{oc}/V_{th} + 0.72)}{V_{oc}/V_{th} + 1}$$

n = 1.0

$R_s = 0$

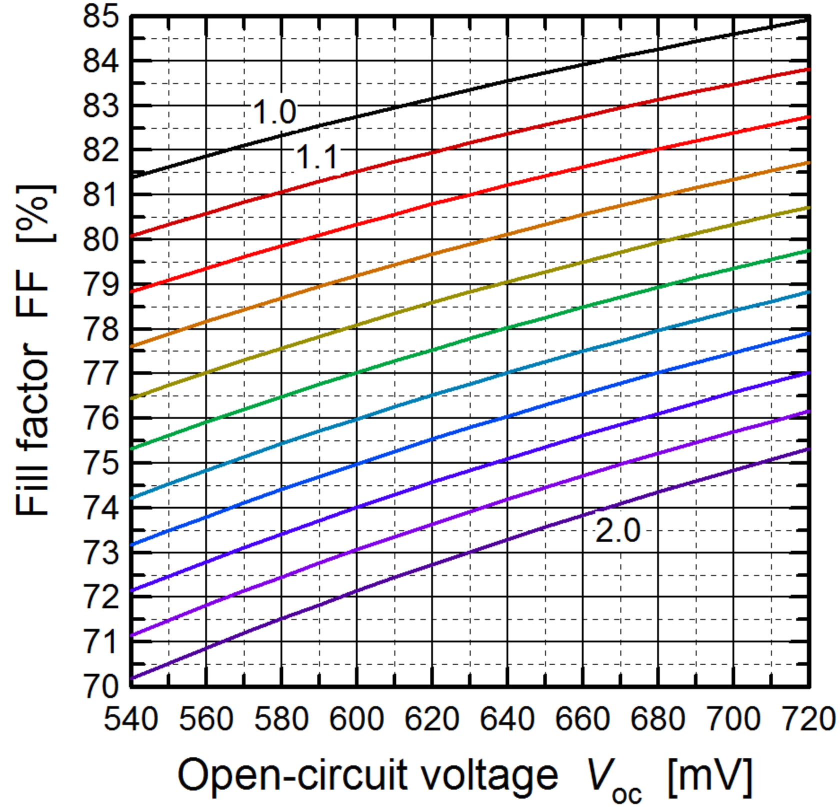


M.A. Green, Solar Cells, 1992, (ISBN 0 85823 580 3), p. 96

M.A. Green, Solar Cells 7, 337 (1982)

… der ideality factor *n*

$$FF_n = \frac{V_{oc}/nV_{th} - \ln(V_{oc}/nV_{th} + 0.72)}{V_{oc}/nV_{th} + 1}$$



$R_s = 0$

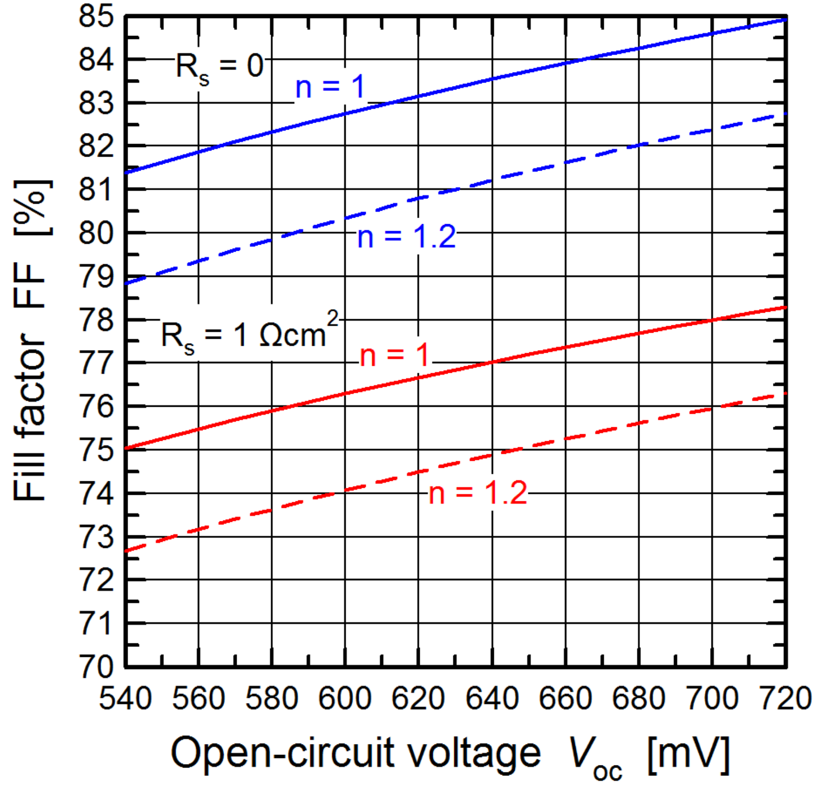
M.A. Green, Solar Cells, 1992, (ISBN 0 85823 580 3), p. 96
M.A. Green, Solar Cells 7, 337 (1982)

Analytical approximation using V_{oc}, n and R_s

$$FF_n = \frac{V_{oc}/nV_{th} - \ln(V_{oc}/nV_{th} + 0.72)}{V_{oc}/nV_{th} + 1}$$

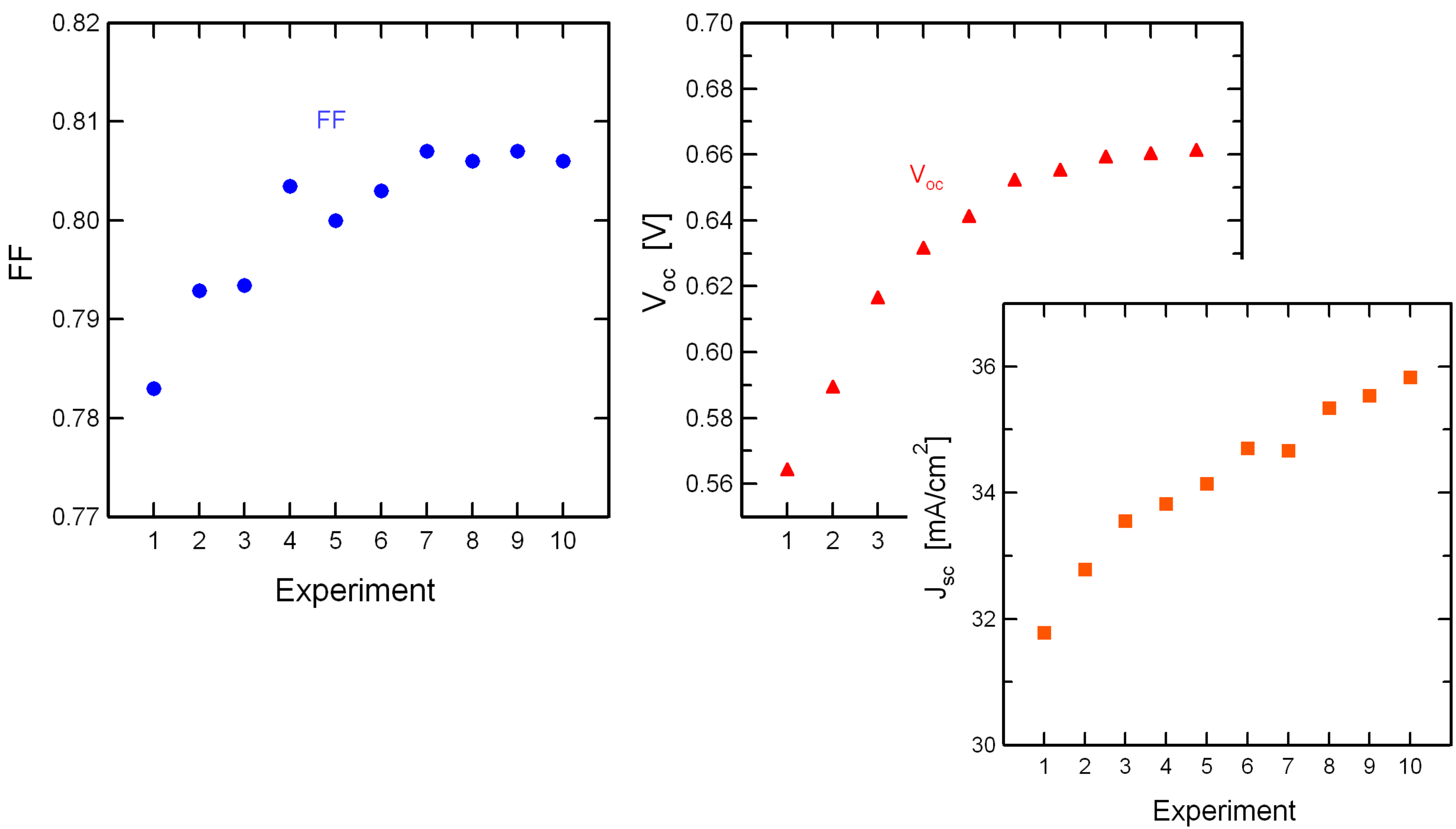
$$FF_{Rs} = FF_n \left(1 - \frac{R_s J_{sc}}{V_{oc}}\right)$$

J_{sc} = 39 mA/cm^2

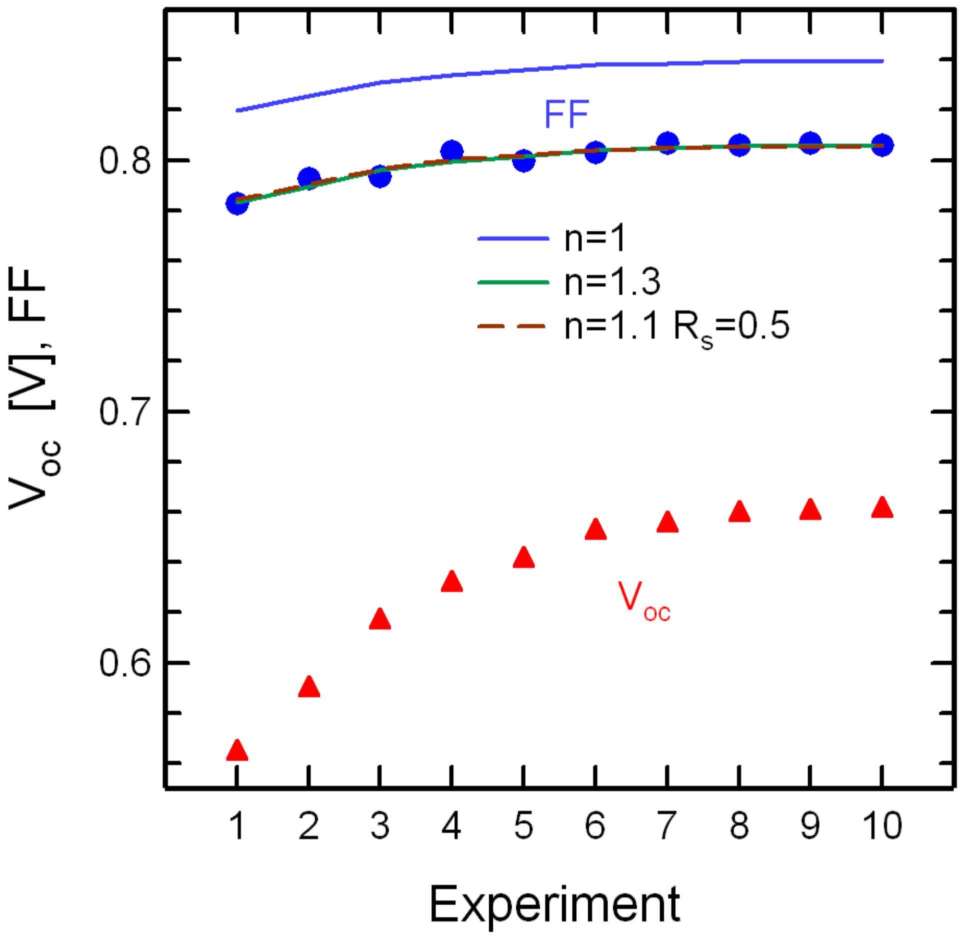


Detailed overview of analytical equations for FF:
E. Sanchez and G.L. Araujo, Solar Cells 20, 1 (1987)

Do we here have a „FF problem“ ?

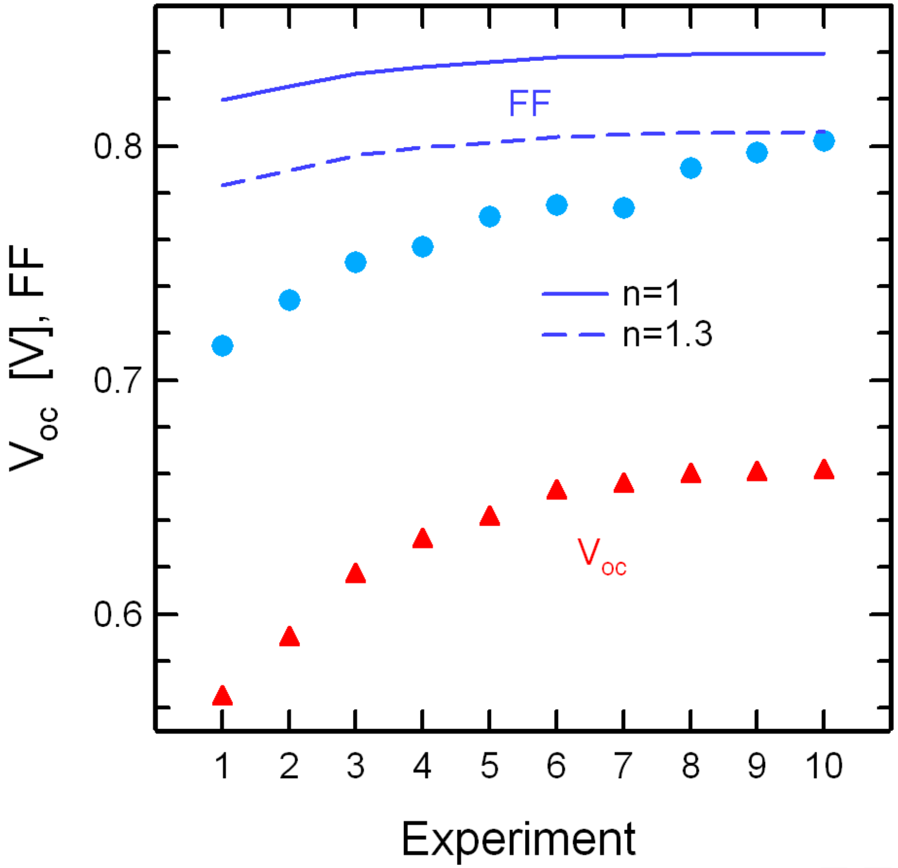


No



FF
n=1
n=1.3
n=1.1 R_s=0.5
V_oc
V_oc [V], FF
0.8
0.7
0.6
1
2
3
4
5
6
7
8
9
10
Experiment

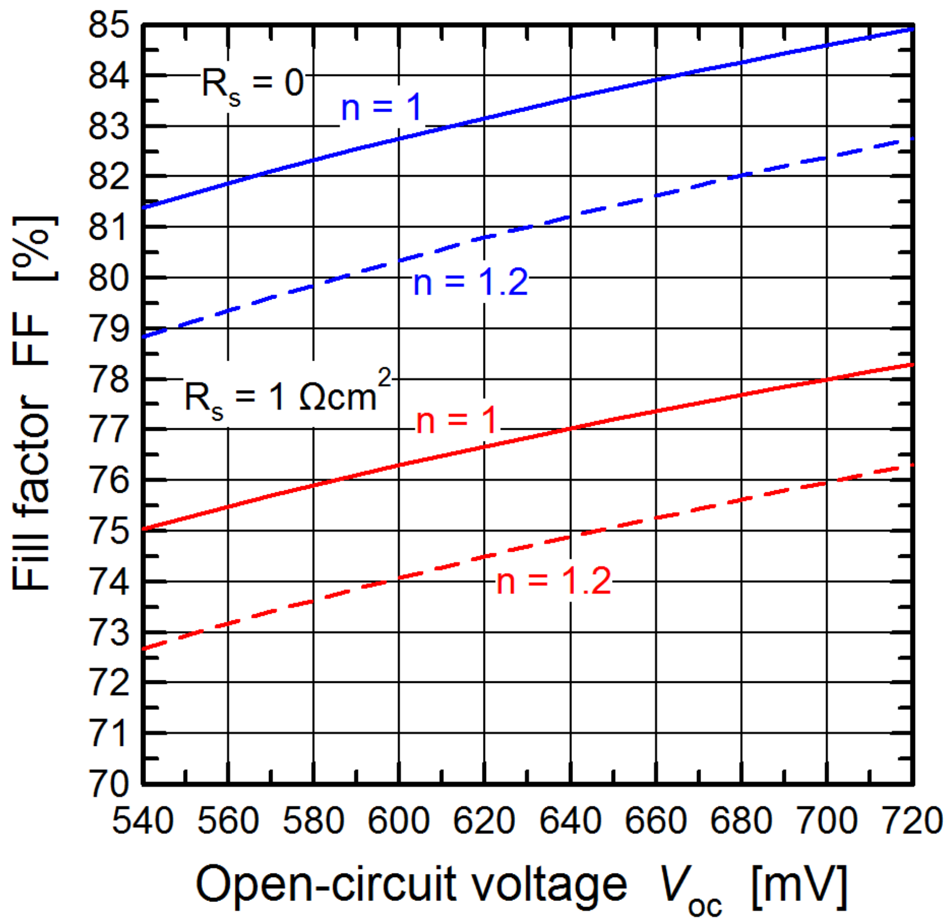
FF in relation to V_{oc}



It is advantageous to consider *FF* in relation to V_{oc}

$$FF = \frac{V_{oc}/V_{th} - \ln(V_{oc}/V_{th} + 0.72)}{V_{oc}/V_{th} + 1}$$

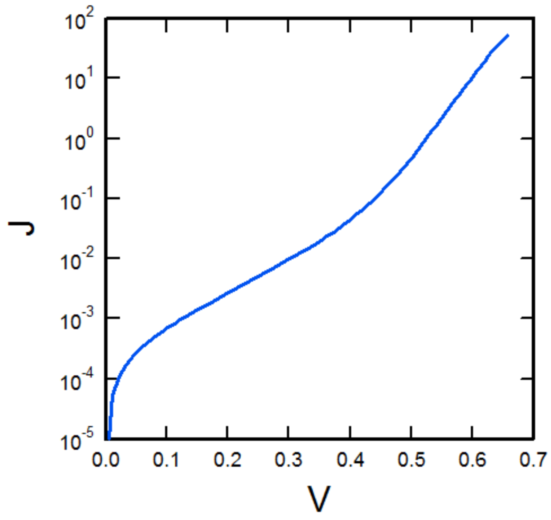
FF depends on *n*



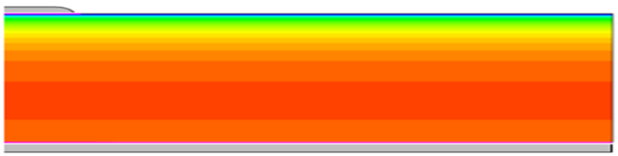
The idality factor may influence FF as strongly as R_s.

Contents

1 Characterization
using I-V measurements

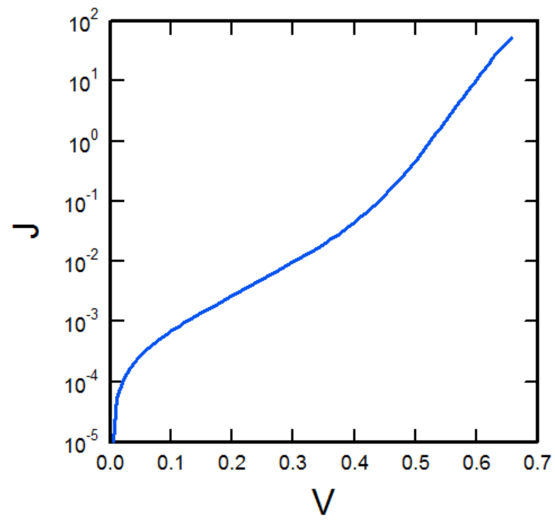


2 (Loss)-analysis
using simulations



Contents

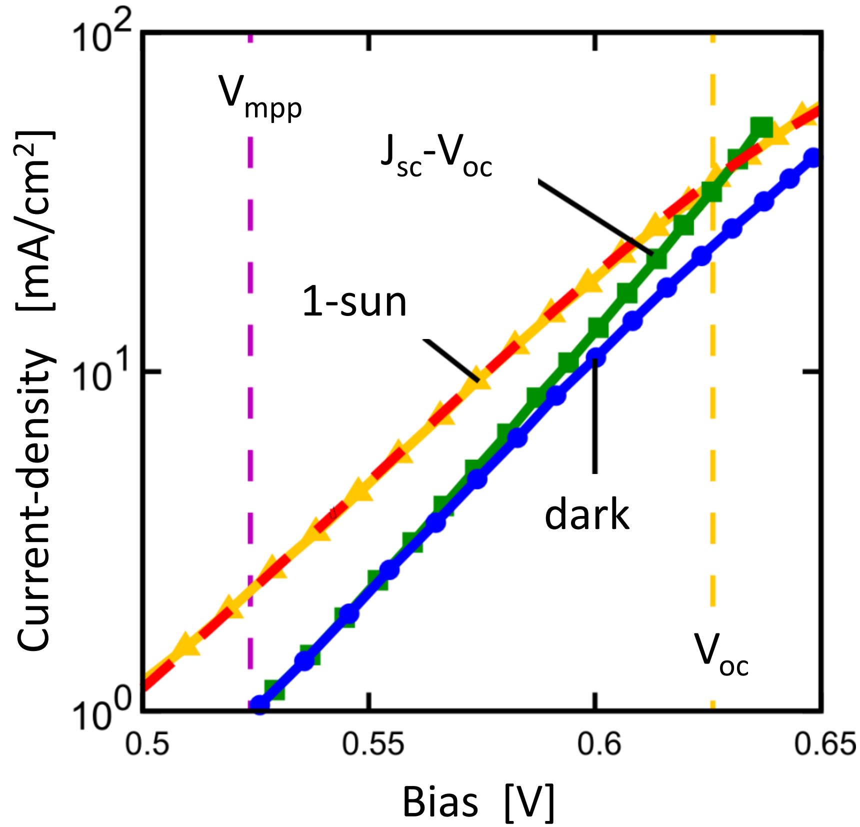
1 Characterization using I-V measurements



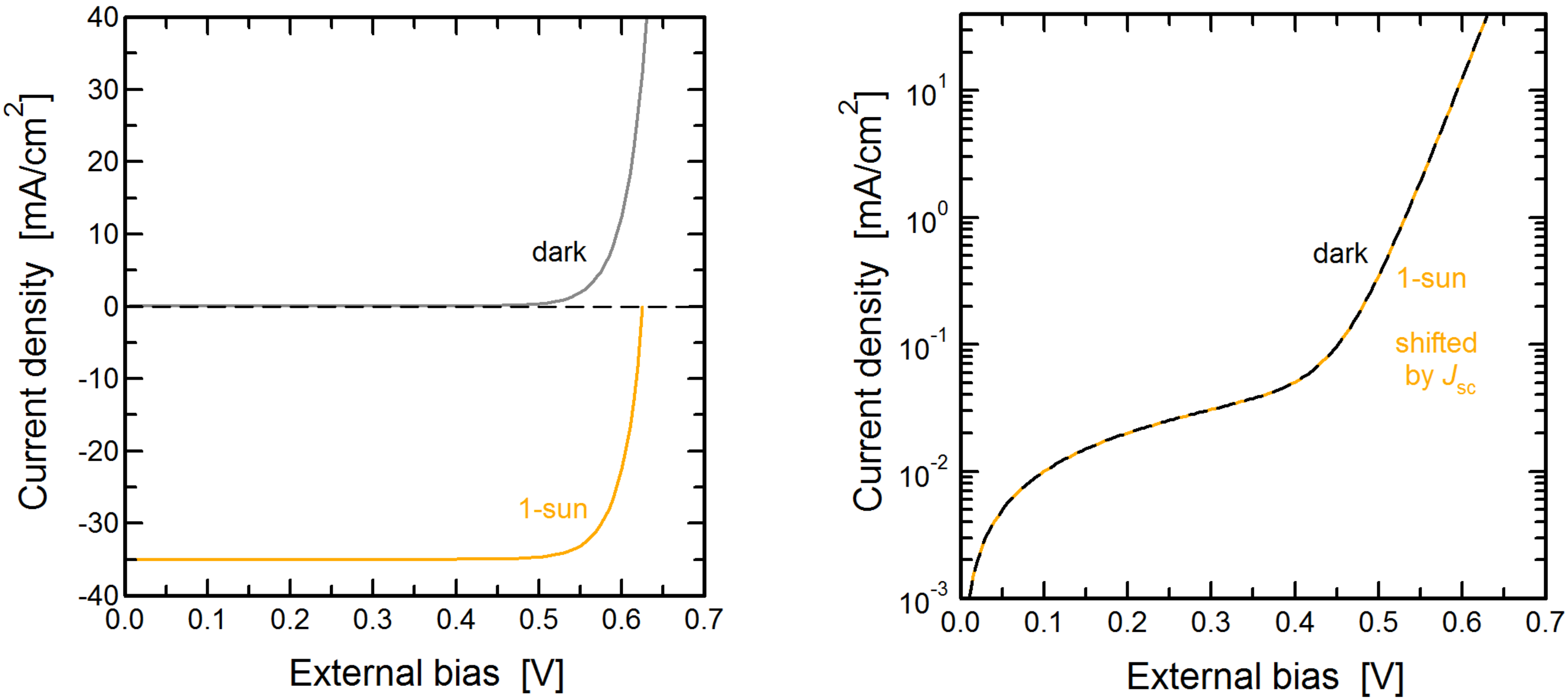
Measurement of I-V curves

Measurement

Dark
1-sun
≈1.1-sun
≈ 0.9 sun
(J_{sc}-V_{oc})

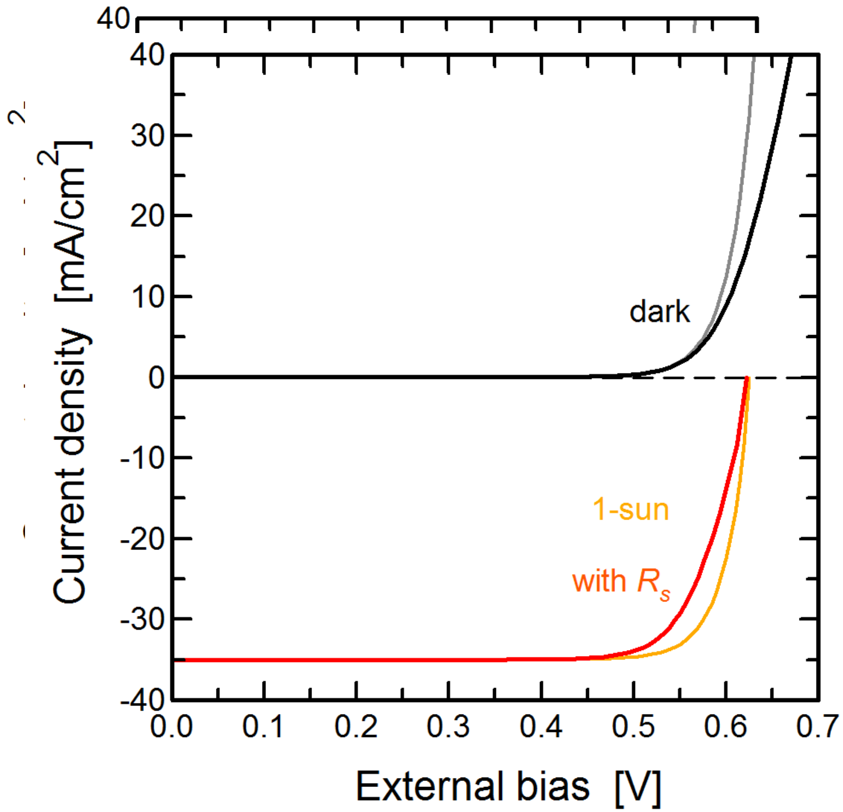


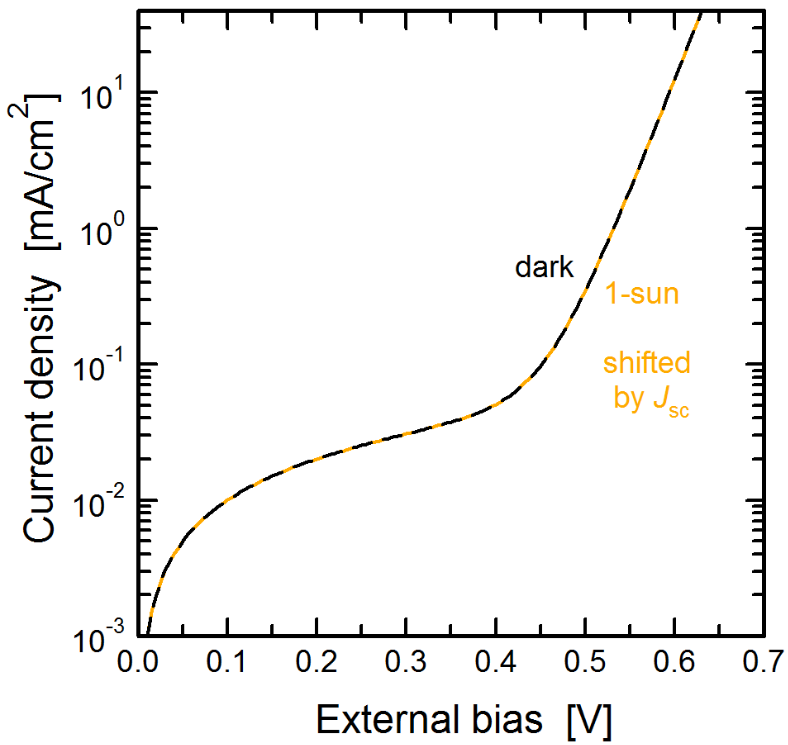
I-V curves – logarithmic



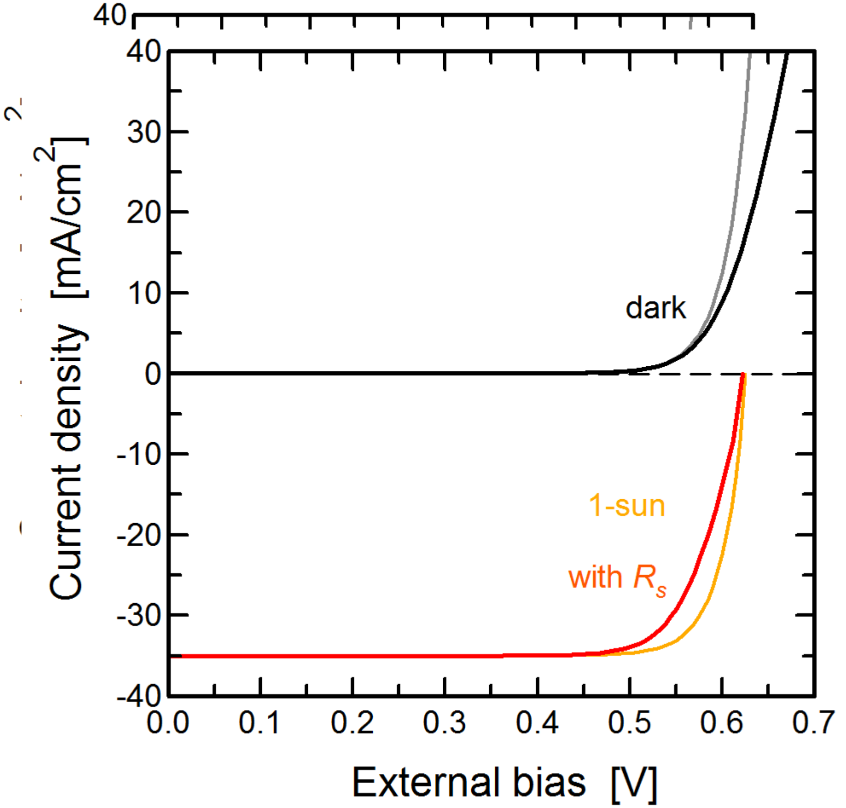
LUH

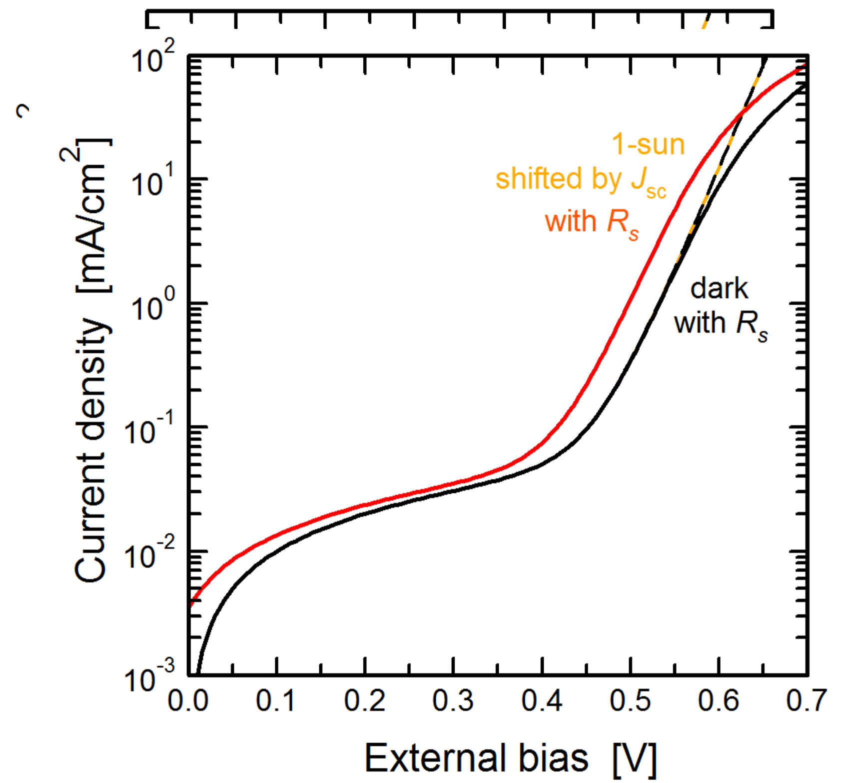
I-V curves – logarithmic





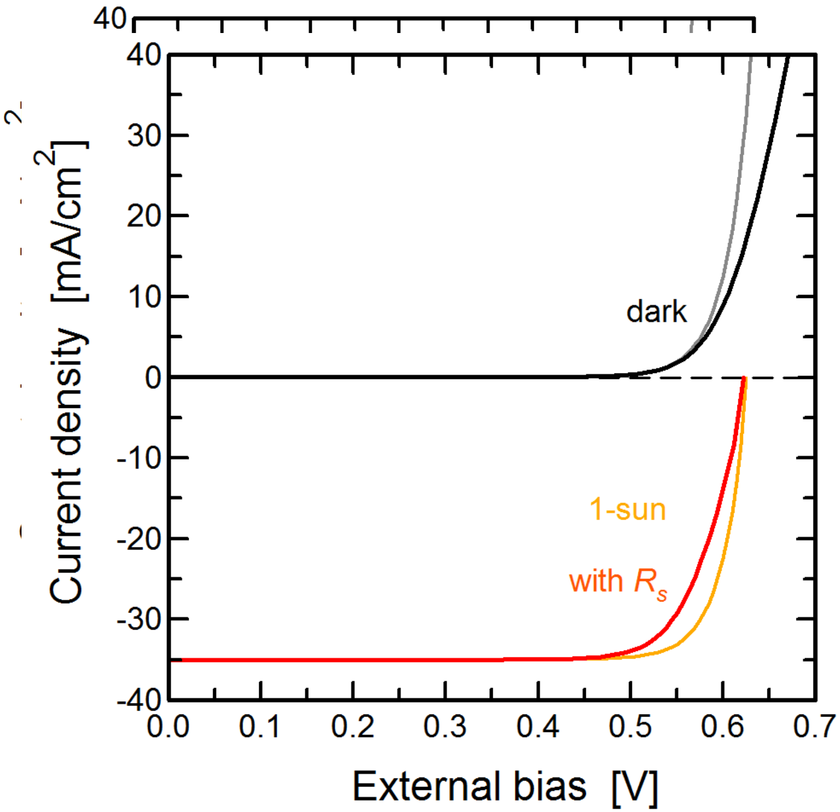
I-V curves – logarithmic

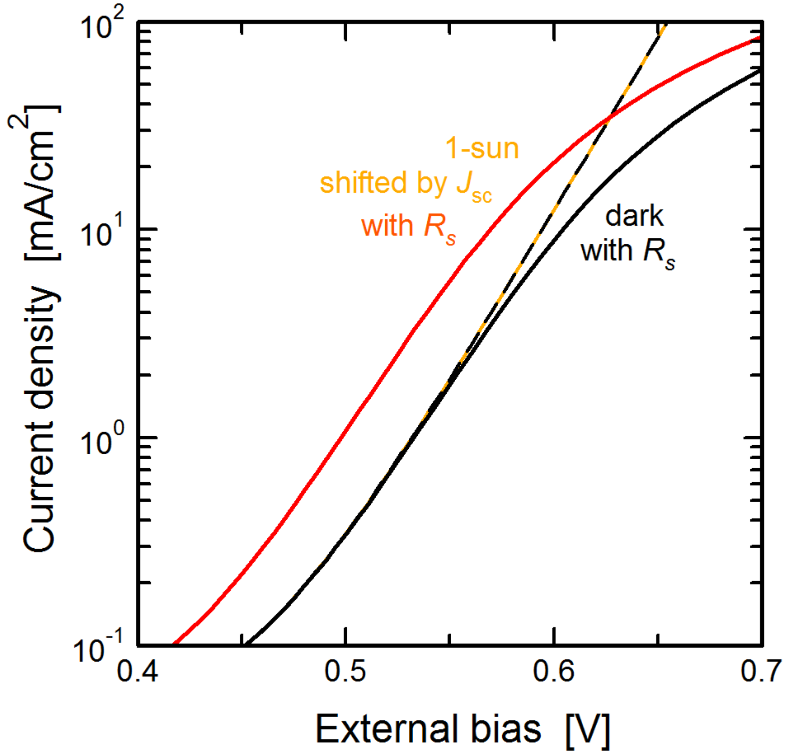




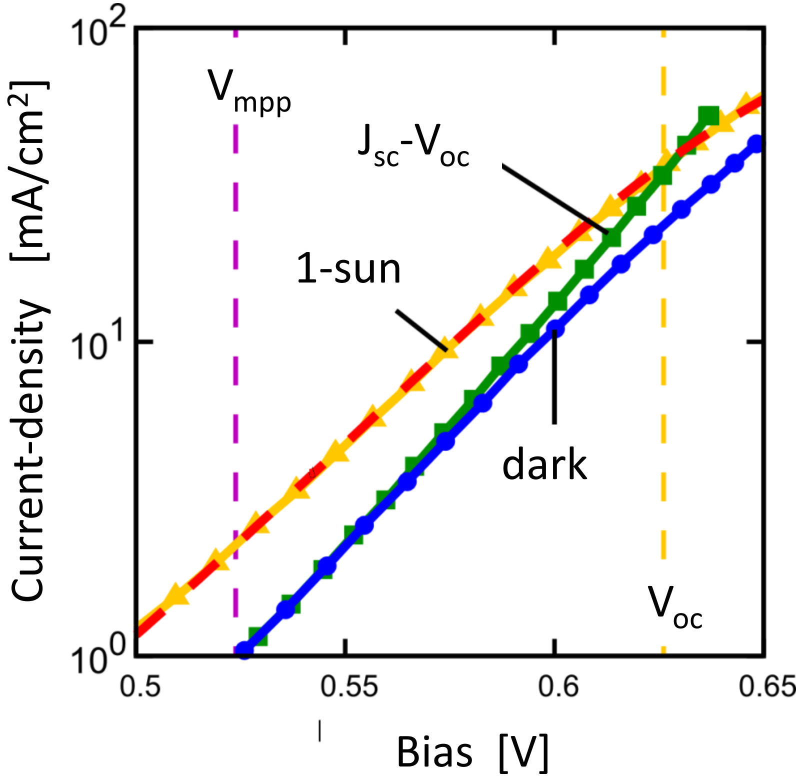
LUH

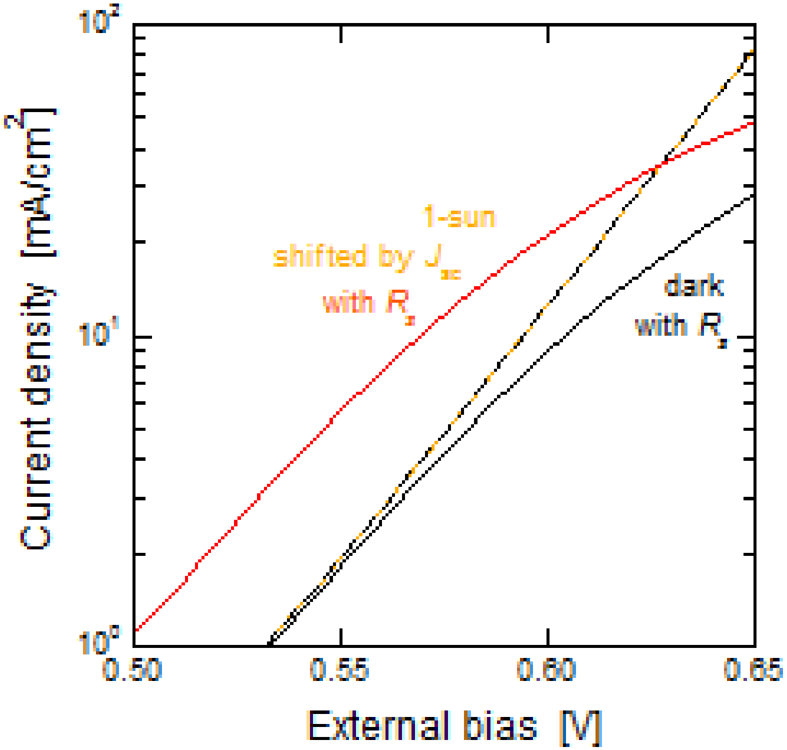
I-V curves – logarithmic



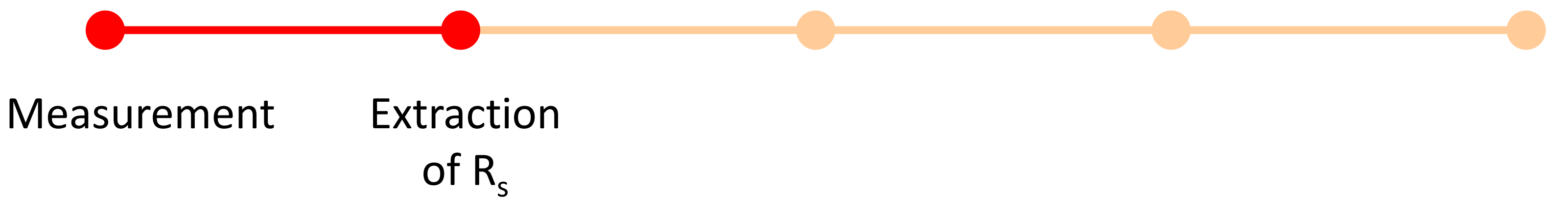


I-V curves – logarithmic

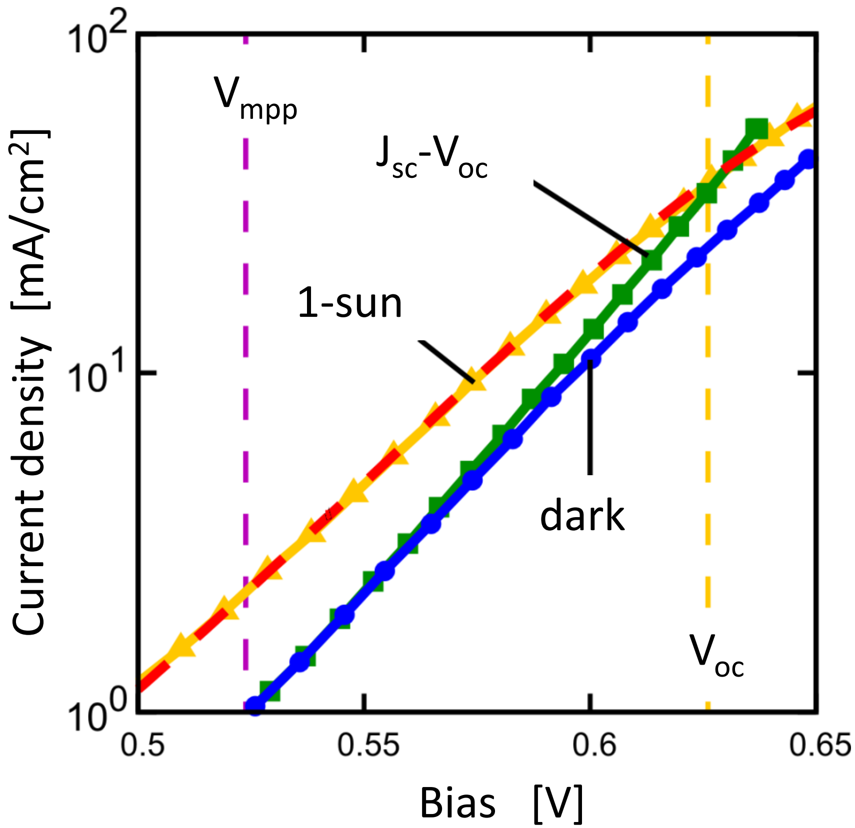


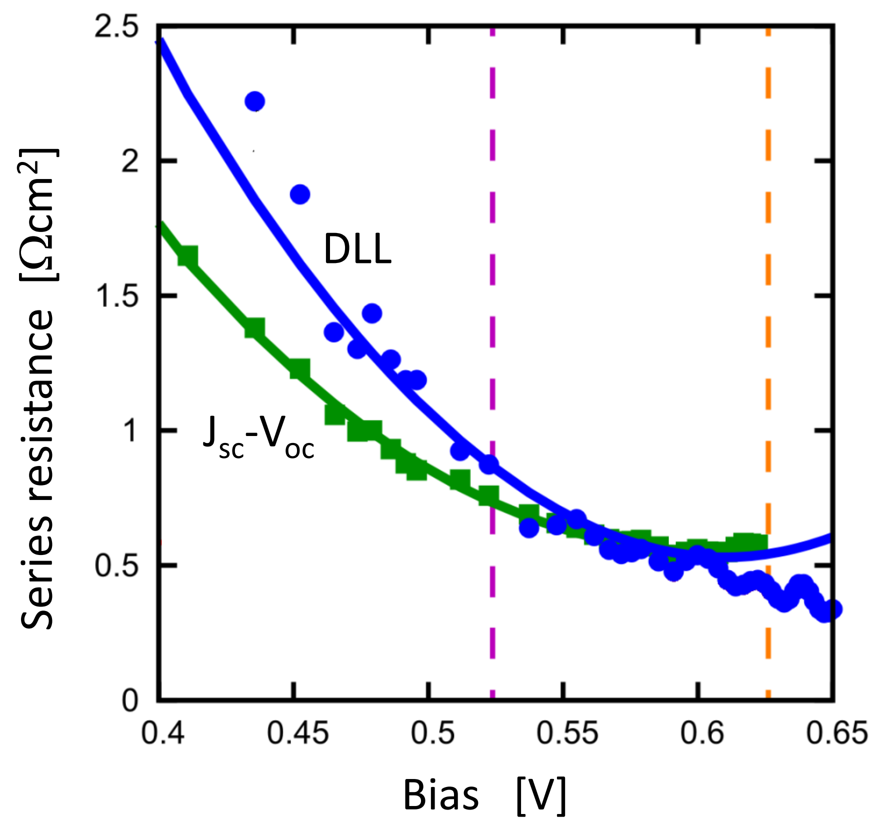


Extraction of R_s



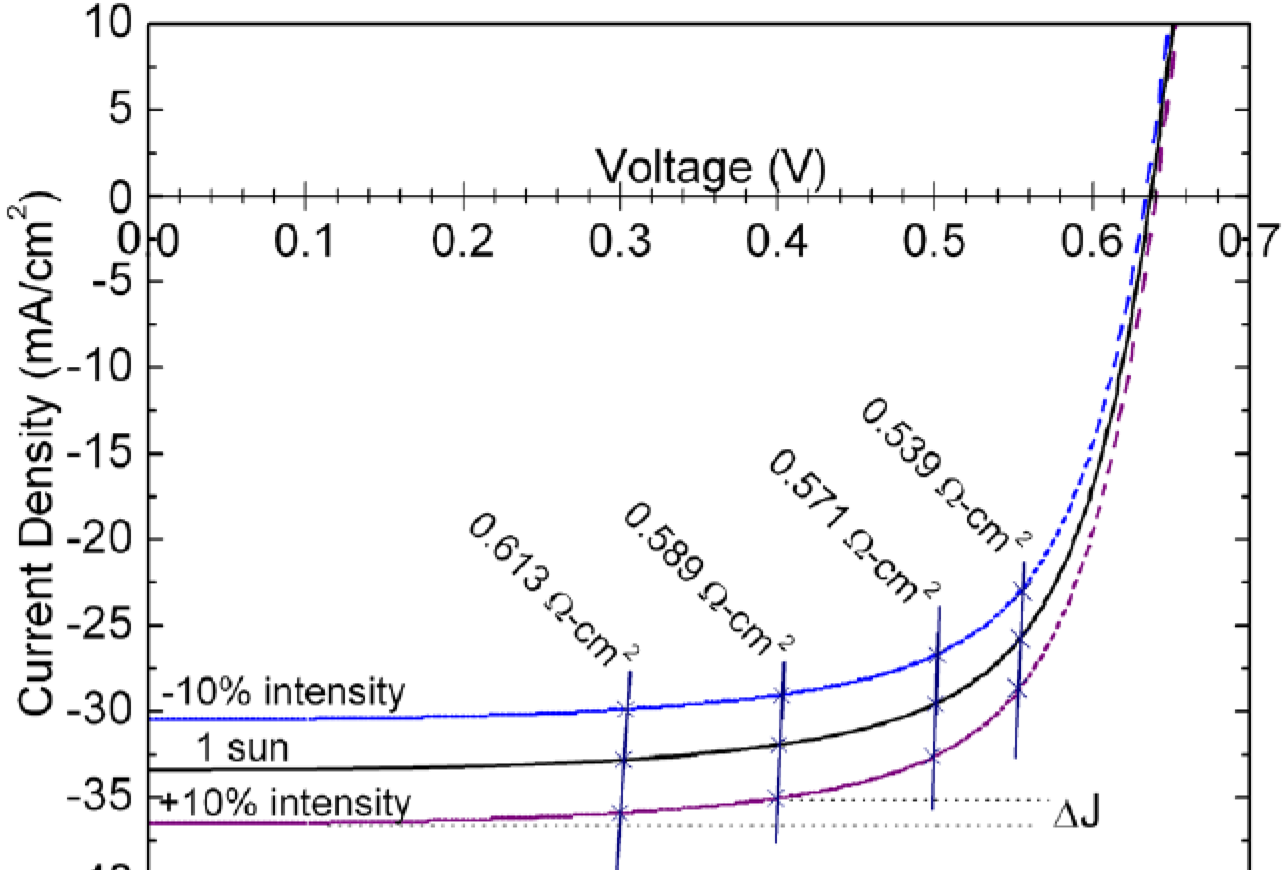
R_s extraction from I-V curves





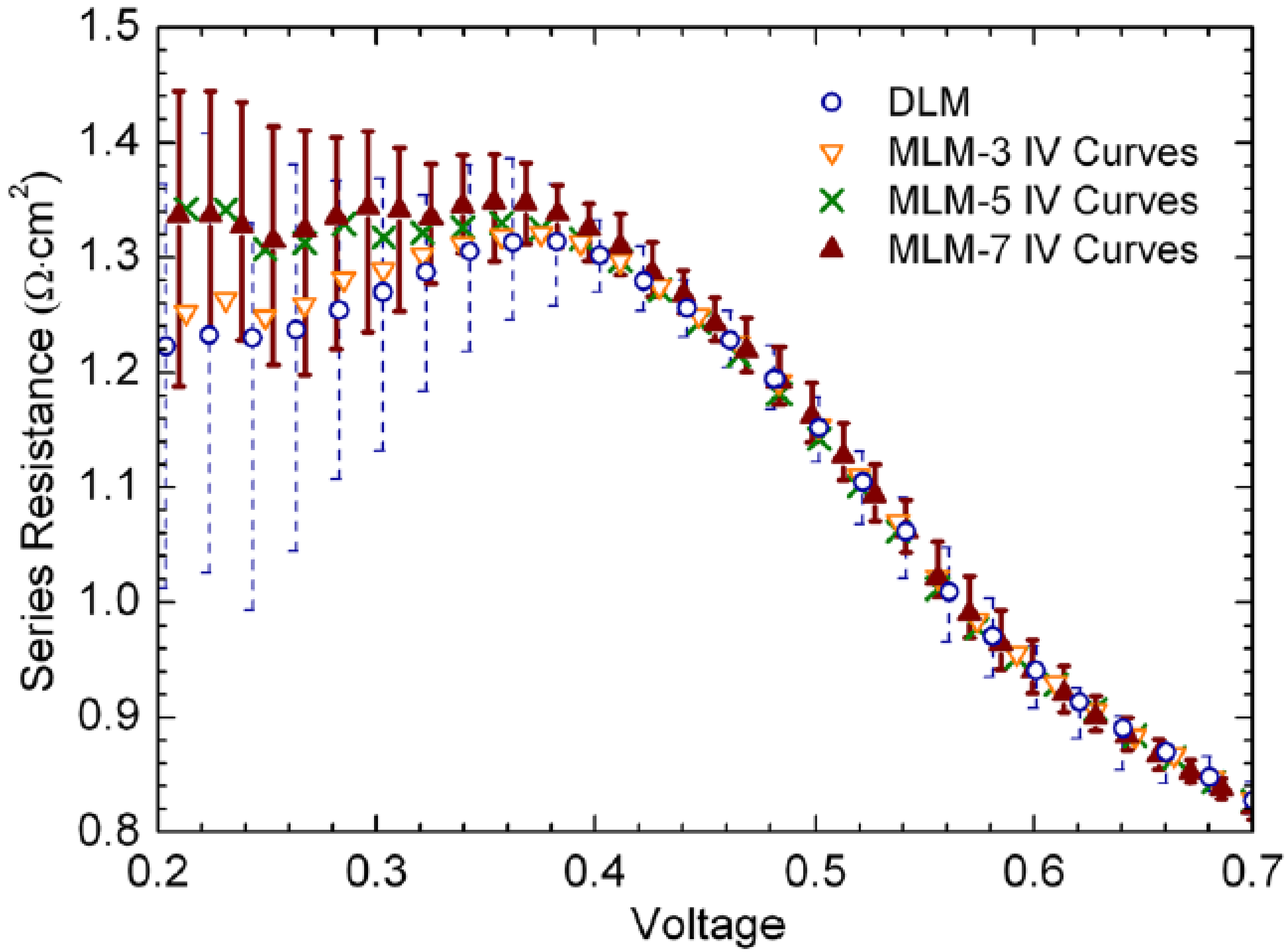
Overview: P.P. Altermatt et al, Prog. PV 4, 399 (1996)

Tripple light-level (TLL) method



K. F. Fong, K. R. McIntosh, A. W. Blakers, Prog. PV 21, 490 (2013)

Tripple light-level (TLL) method



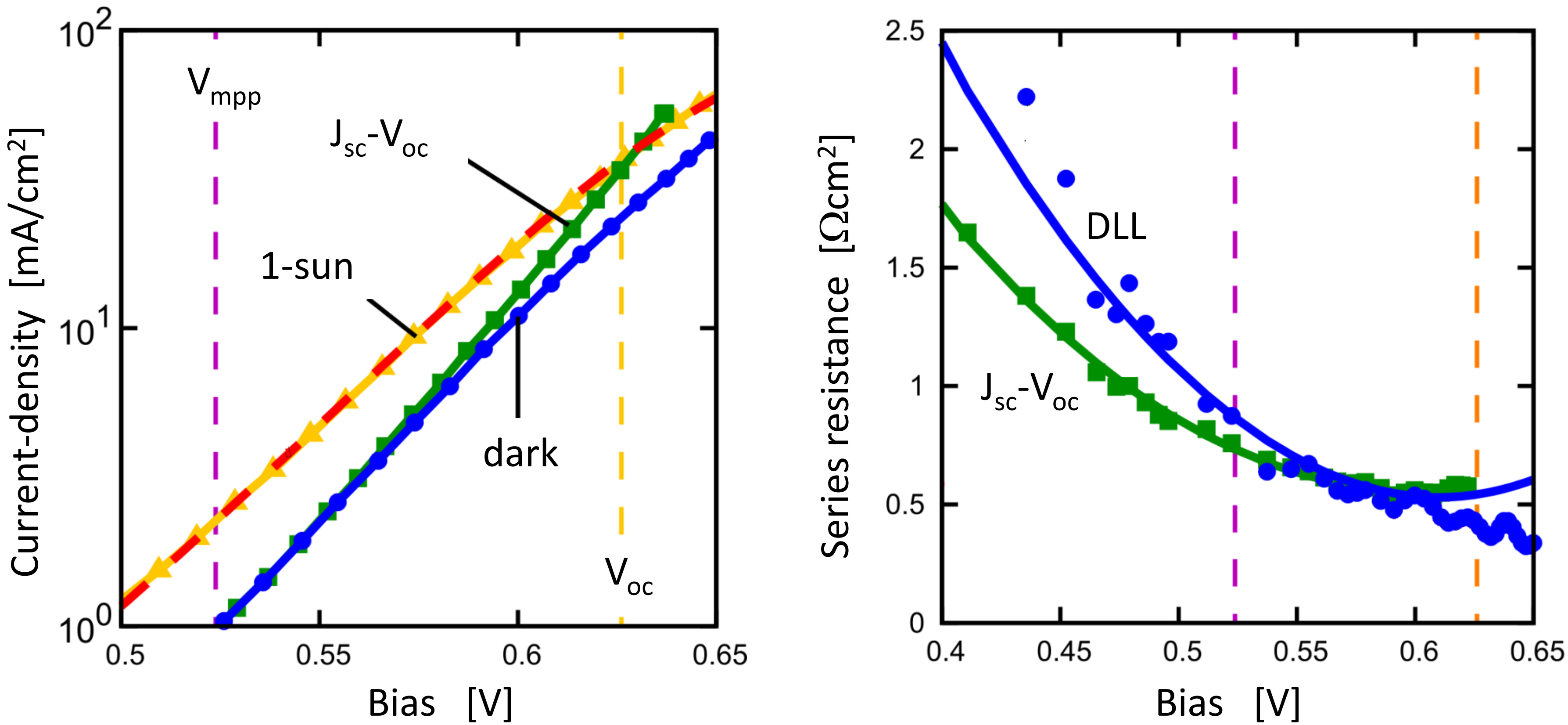
K. F. Fong, K. R. McIntosh, A. W. Blakers, Prog. PV 21, 490 (2013)

Large J_0 → I-V curve is higher

LUH

Large J_0 → I-V curve is higher

R_s extraction from I-V curves



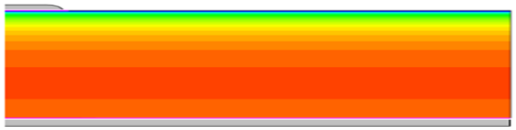
If possible, use the tripple light-level method to measure R_s

K. F. Fong, K. R. McIntosh, A. W. Blakers, Prog. PV 21, 490 (2013)

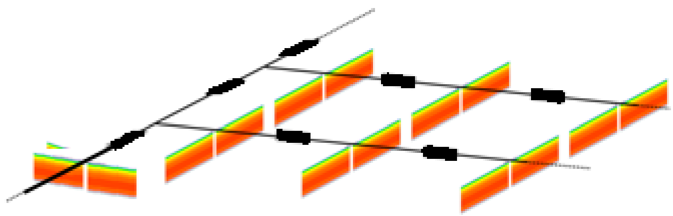
LUH

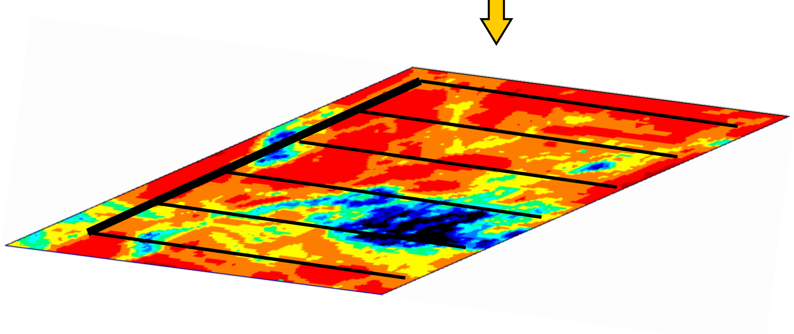
Simulation of the metallised parts

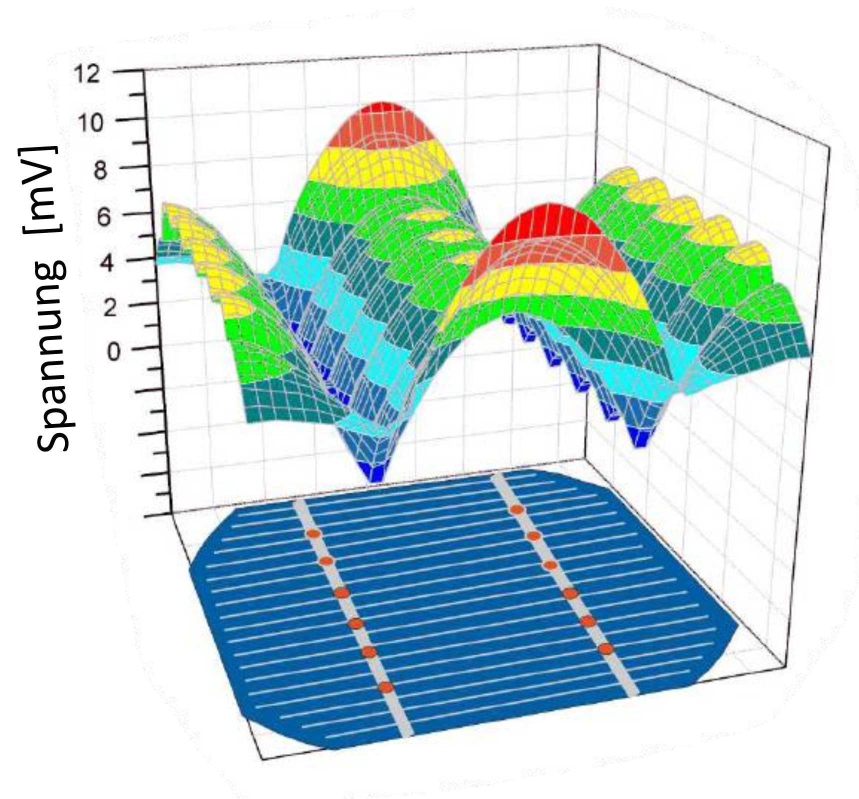
Device simulation



Circuit simulation





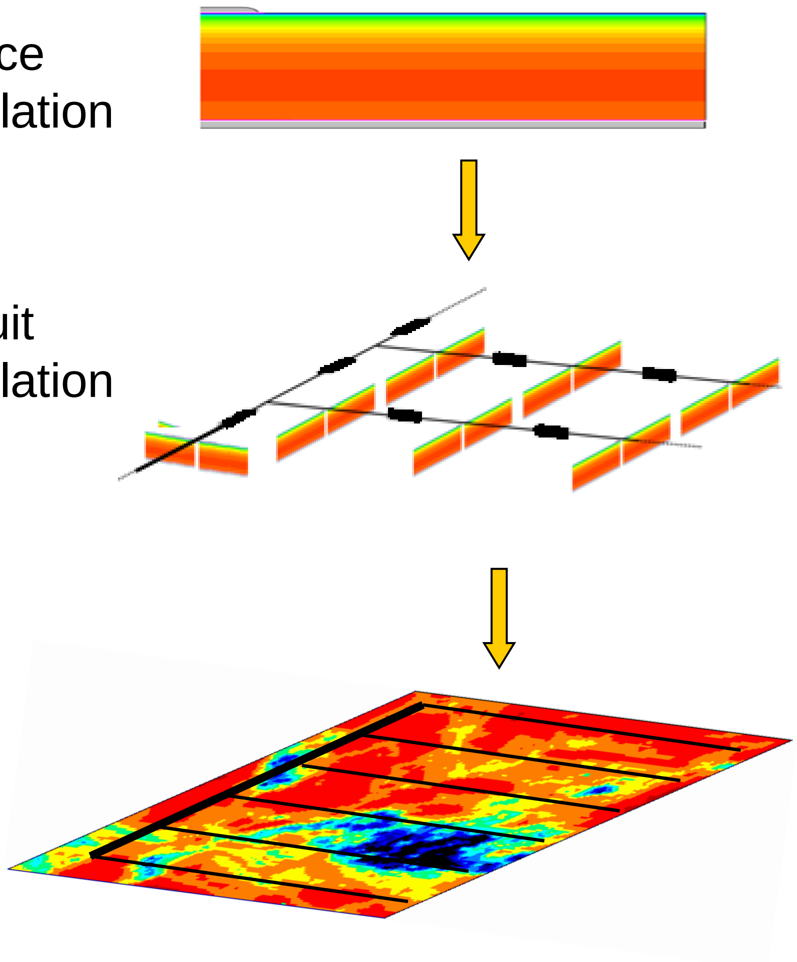


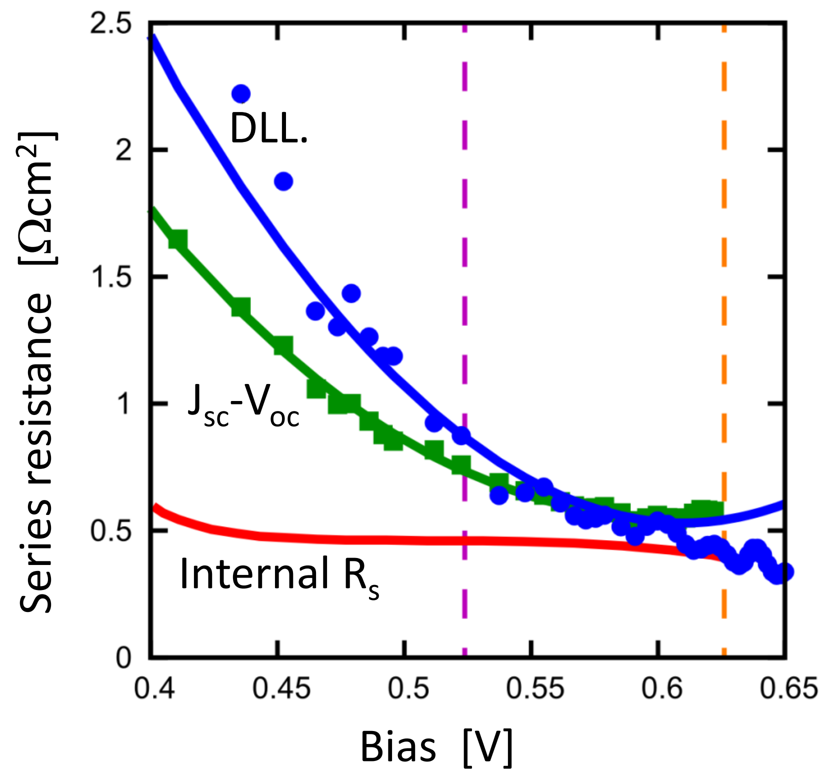
Y. Yang et al, Prog. PV 20, 490 (2012)

Simulation of the metallized parts

Device simulation

Circuit simulation





Parametrization of R_s

Measurement

Extraction of R_s

Parametrization of $R_s(V)$

↓

Proper distinction between R_s- and recombination losses

↓

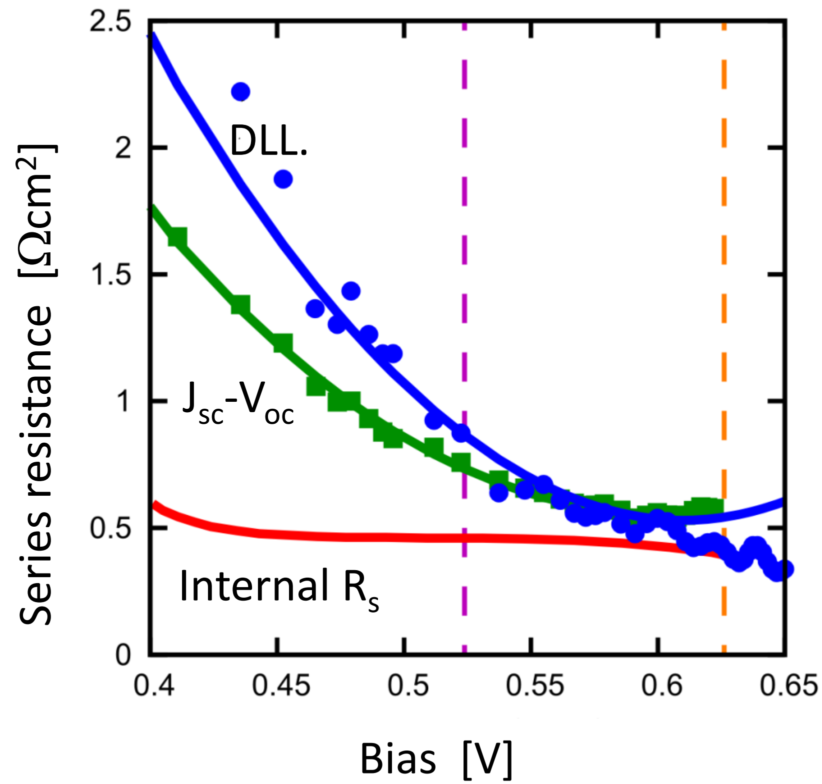
If simulation: internal R_s

$R_s(V)$ as polynome 2nd degree

$$R_s = a_0 + a_1(V - V_0) + a_2(V - V_0)^2$$

where V_0 is offen $\approx V_{oc}$

$$a_0 = 0.6$$
$$a_1 = 0$$
$$a_2 = 42$$
$$V_0 = 0.61$$



R_s-corrected I-V curves

Measurement

Extraction of R_s

Parametrization of $R_s(V)$

$R_s(V)$-free I-V curves

Proper distinction between R_s- and recombination losses

If simulation: internal R_s

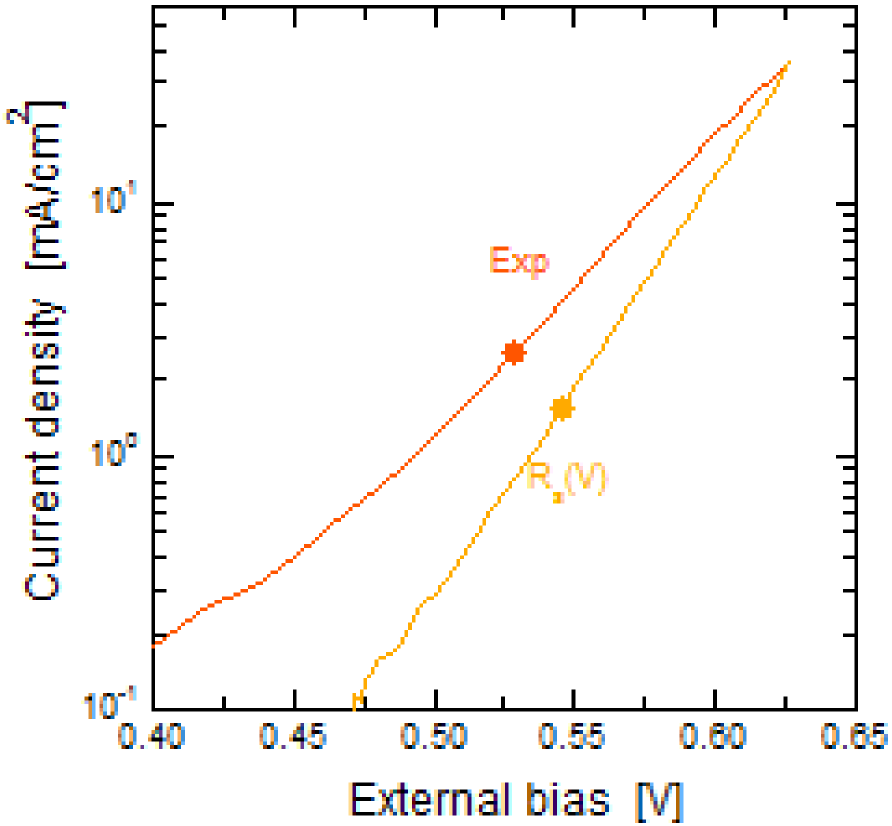
$R_s(V)$ polynome

R_s-corrected I-V curves

$$V_{corr} = V + R_s(V)J$$

FF Exp = 78.52

FF R_s(V) = 83.18



R_s-corrected I-V curves show recombination losses

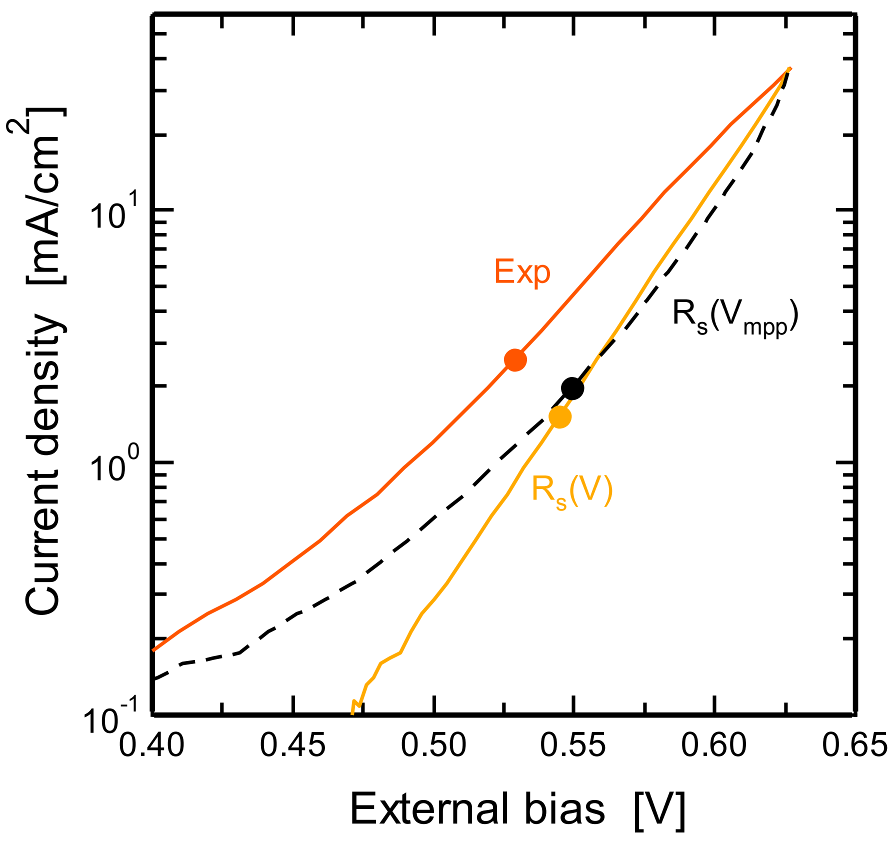
$$V_{corr} = V + R_s(V)J$$

$$V_{corr} = V + R_s(V_{mpp})J$$

FF Exp = 78.52

FF $R_s(V)$ = 83.18

FF $R_s(V_{mpp})$ = 83.09



LUH

Comparison of pseudo-FF with 1FF

$$FF = \frac{V_{oc}/V_{th} - \ln(V_{oc}/V_{th} + 0.72)}{V_{oc}/V_{th} + 1}$$

FF Exp = 78.52

FF $R_s(V)$ = 83.18

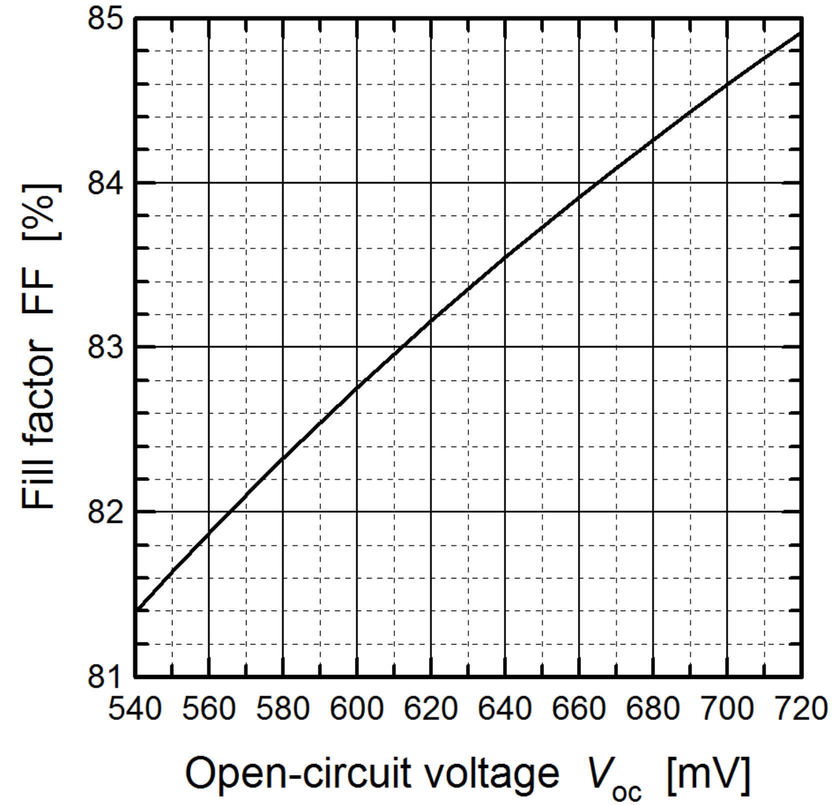
FF $R_s(V_{mpp})$ = 83.09

FF n=1 = 83.28

pFF
is often smaller
than 1FF

n = 1.0

$R_s = 0$



M.A. Green, Solar Cells, 1992, (ISBN 0 85823 580 3), p. 96

M.A. Green, Solar Cells 7, 337 (1982)

Loss analysis

Measurement → Extraction of R_s → Parametrization of $R_s(V)$ → $R_s(V)$-free I-V curves → **Loss analysis** Predictions

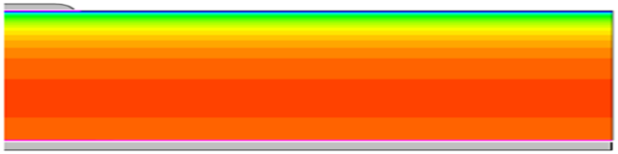
Extraction of R_s
↓
Proper distinction between R_s- and recombination losses
↓
If simulation: internal R_s

Parametrization of $R_s(V)$
↓
$R_s(V)$ polynome

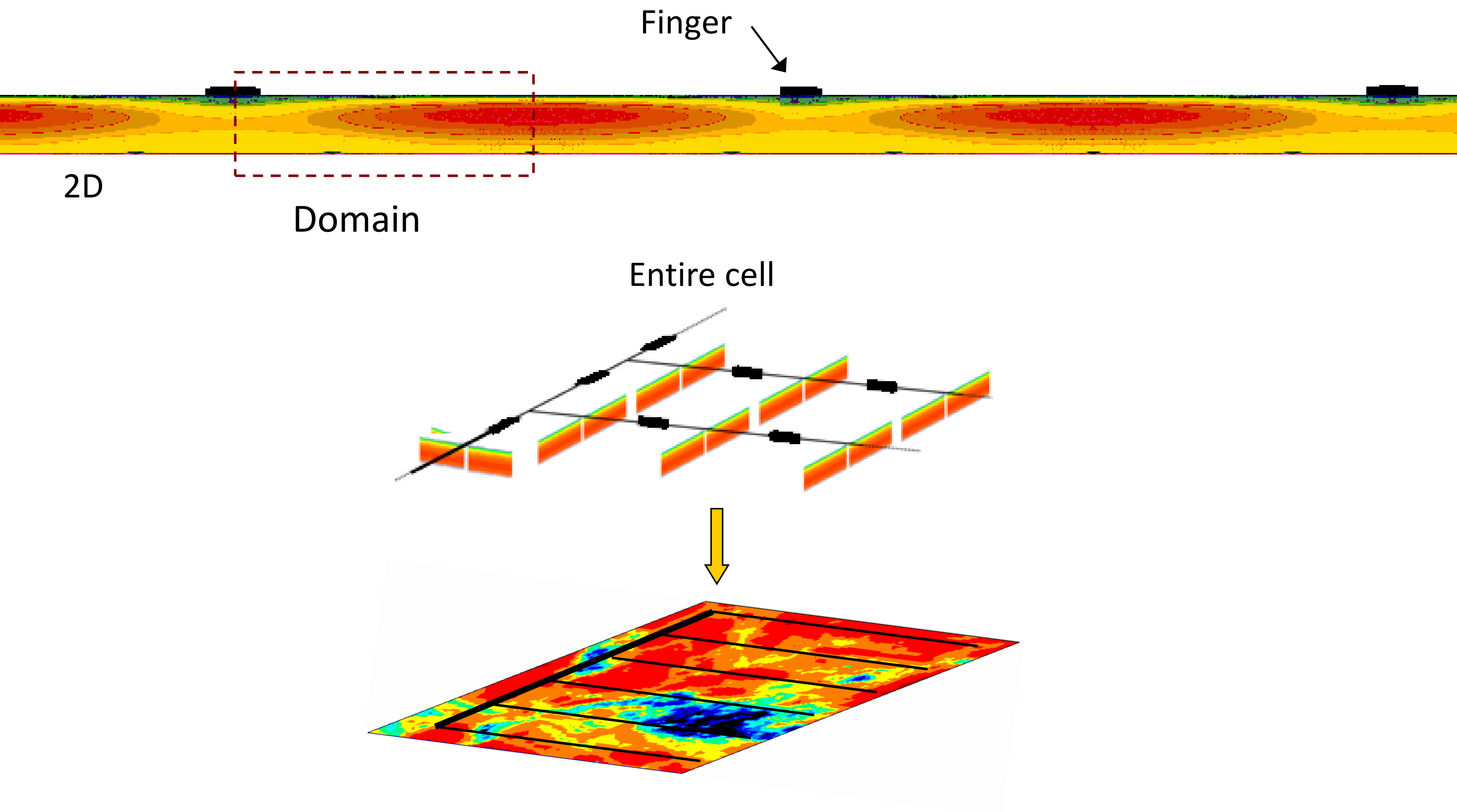
$R_s(V)$-free I-V curves
↓
Recombination losses
↓
pFF
↓
1FF

Content

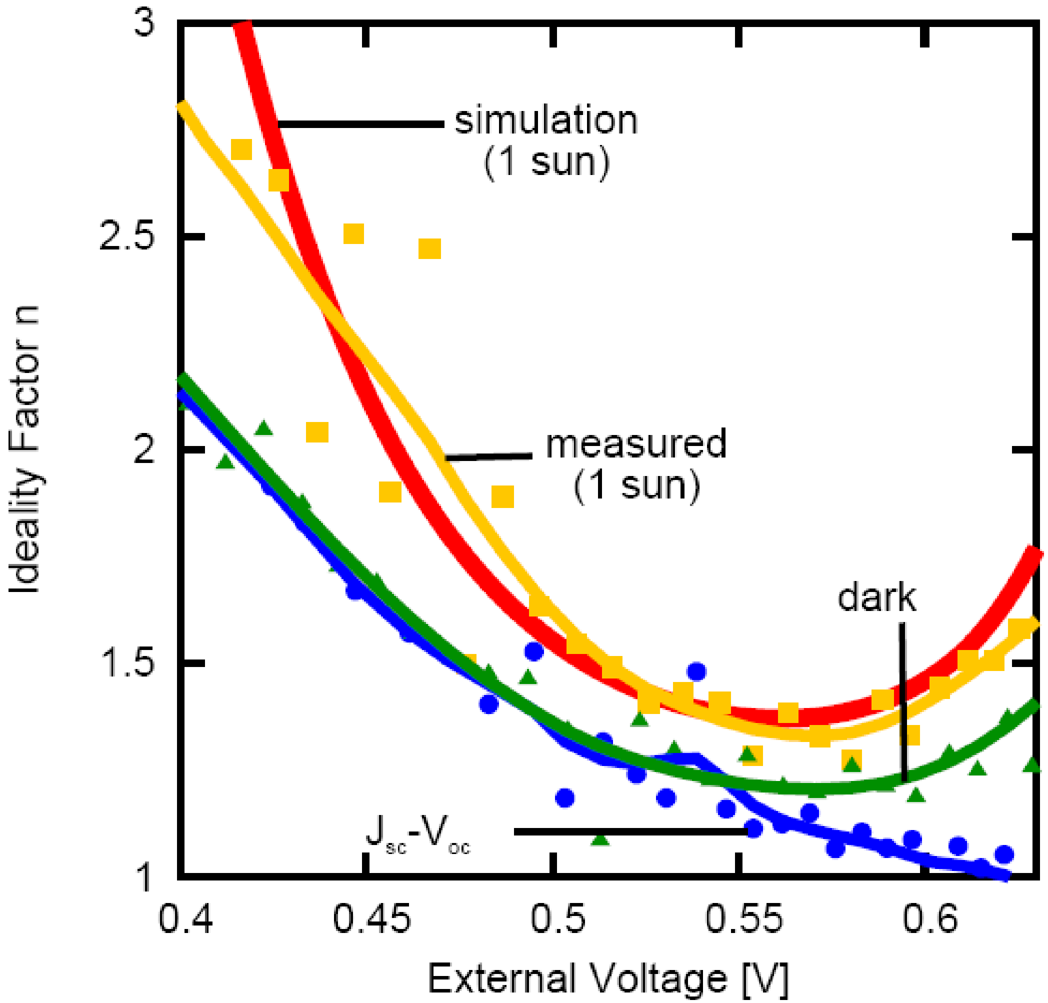
2 (Loss)-Analysis
using simulations



Domain & discretization



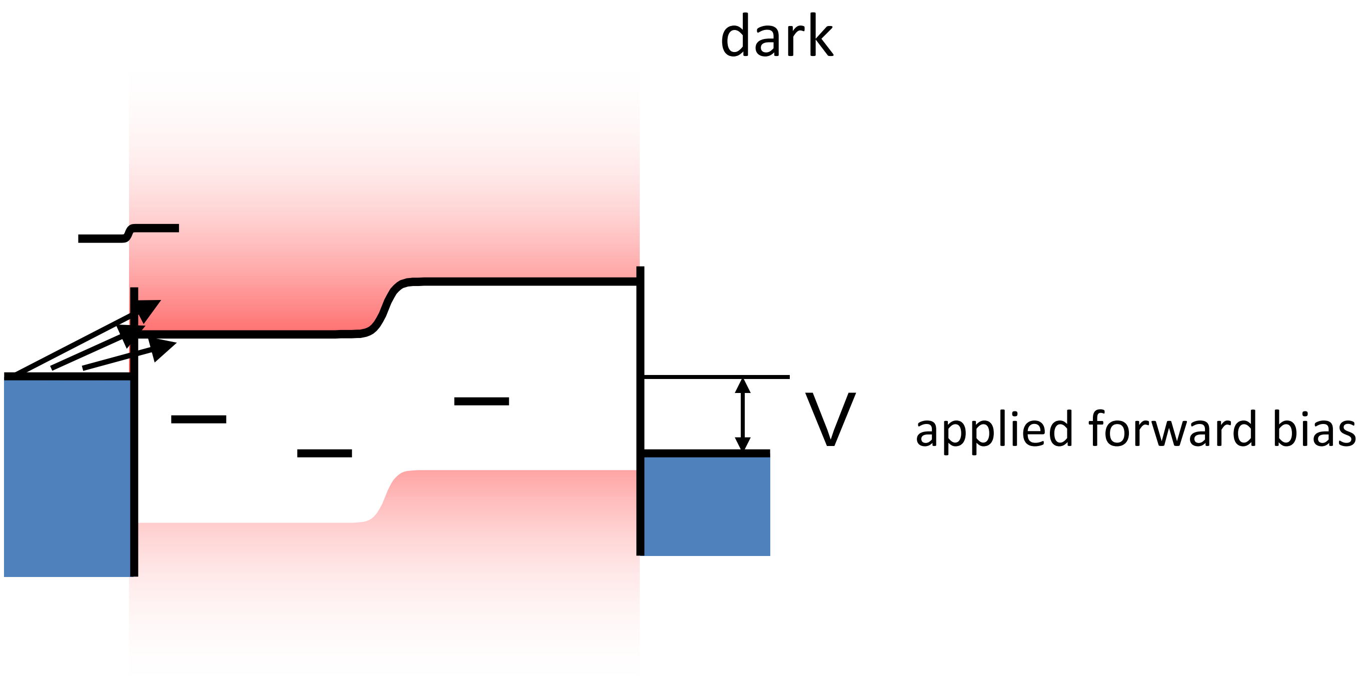
Reproduction of the ideality factor



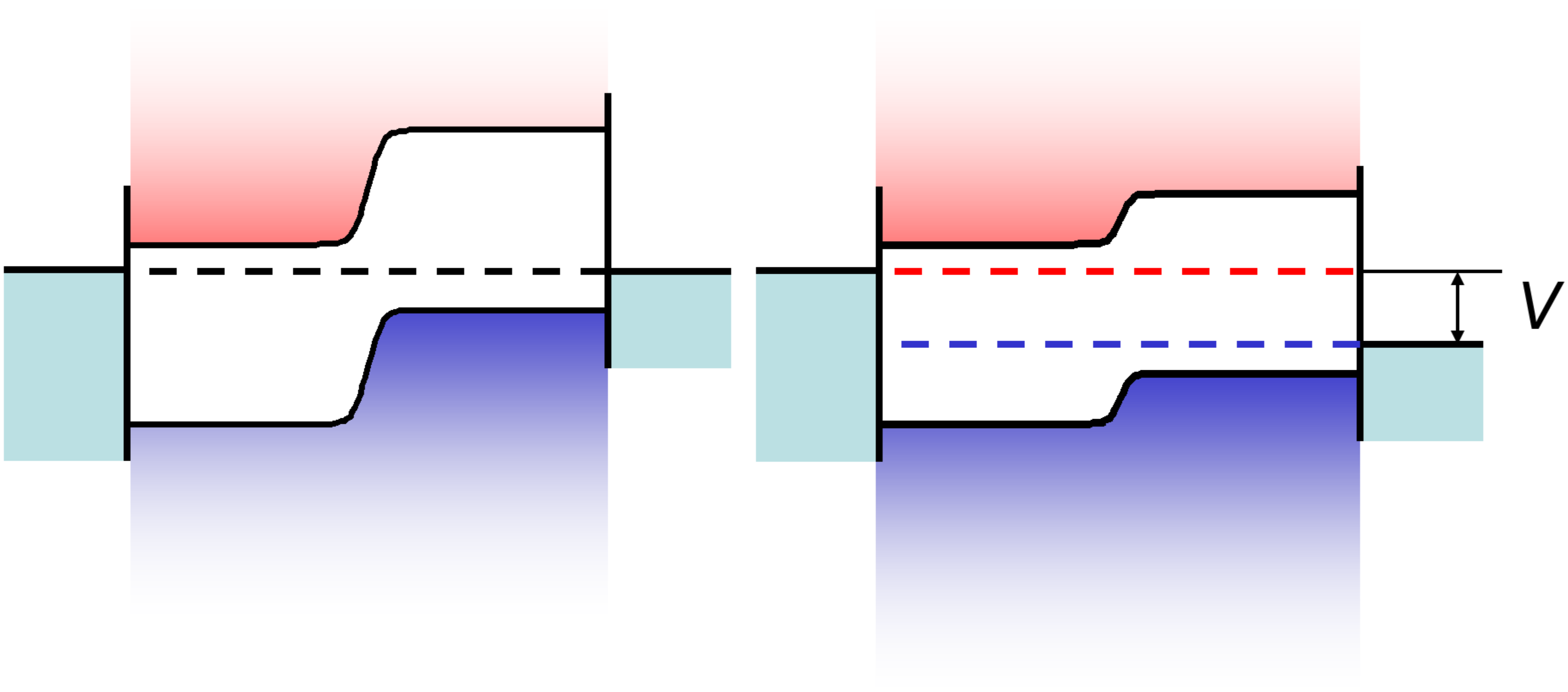
Ultimate test

S. Steingrube et al. Energy Procedia 8, 263 (2011)

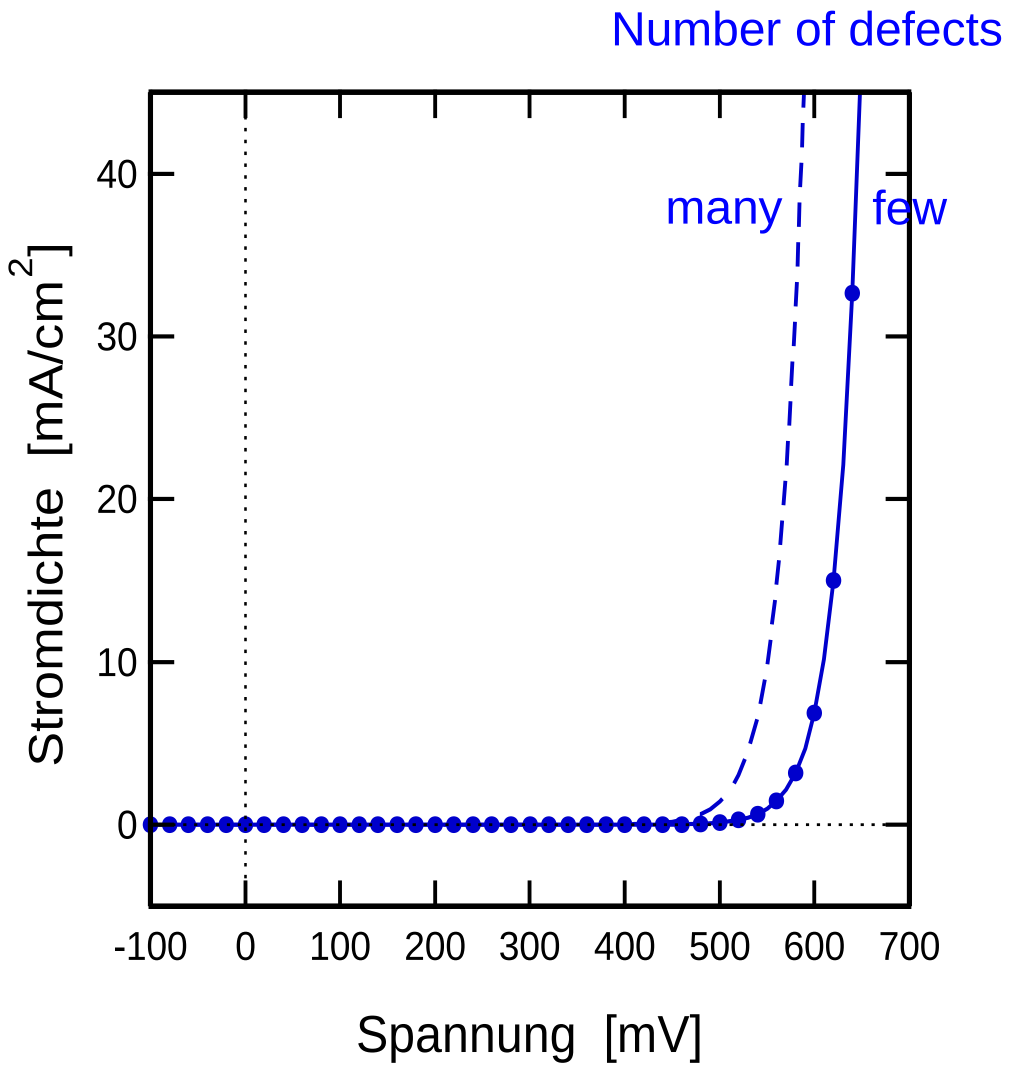
Which is the most likely current-path?



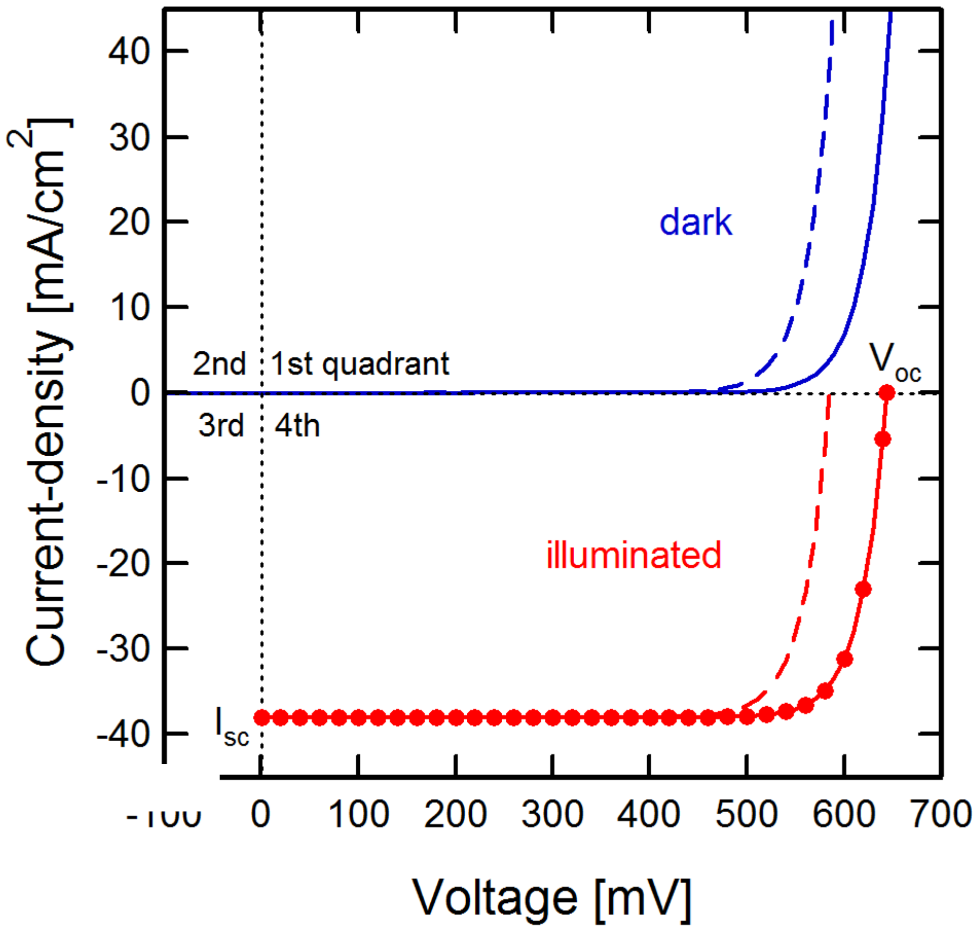
Exponentially increasing recombination rates

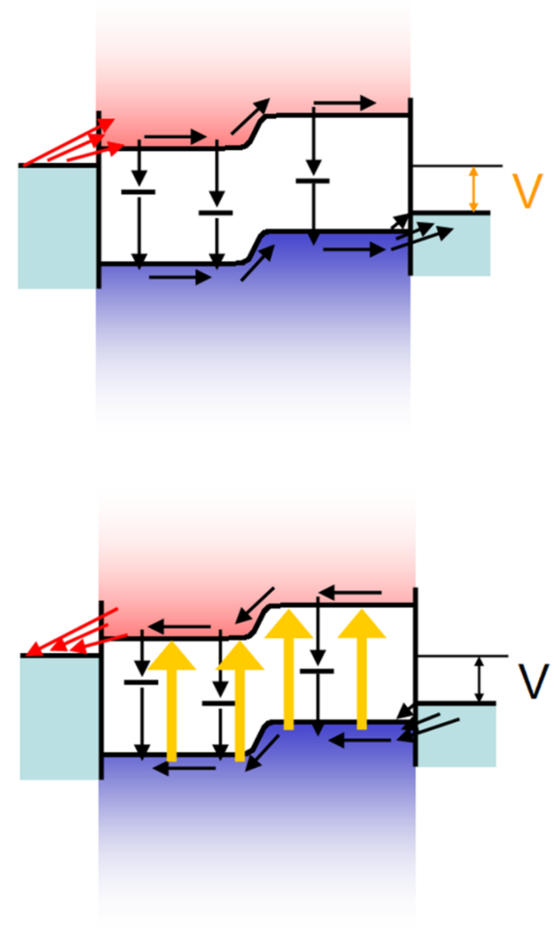


Dark I-V curve = recombination rate

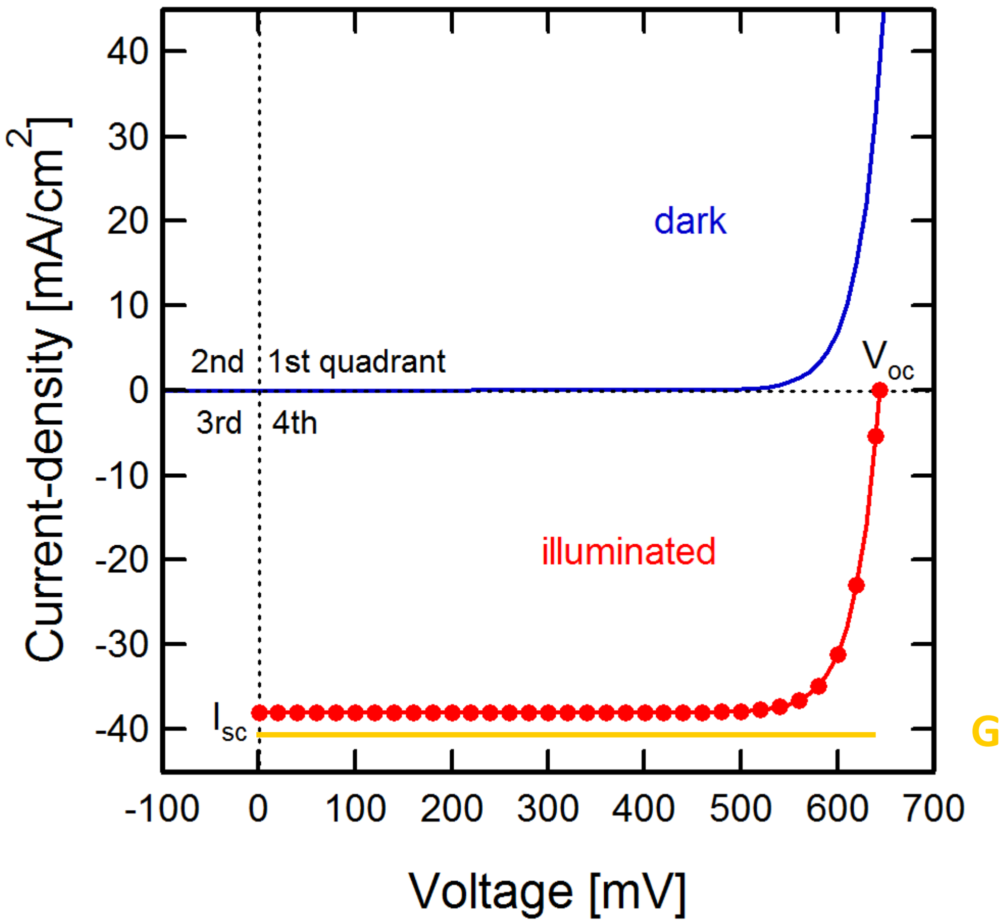


Illuminated I-V curve is shifted to 4th quadrant



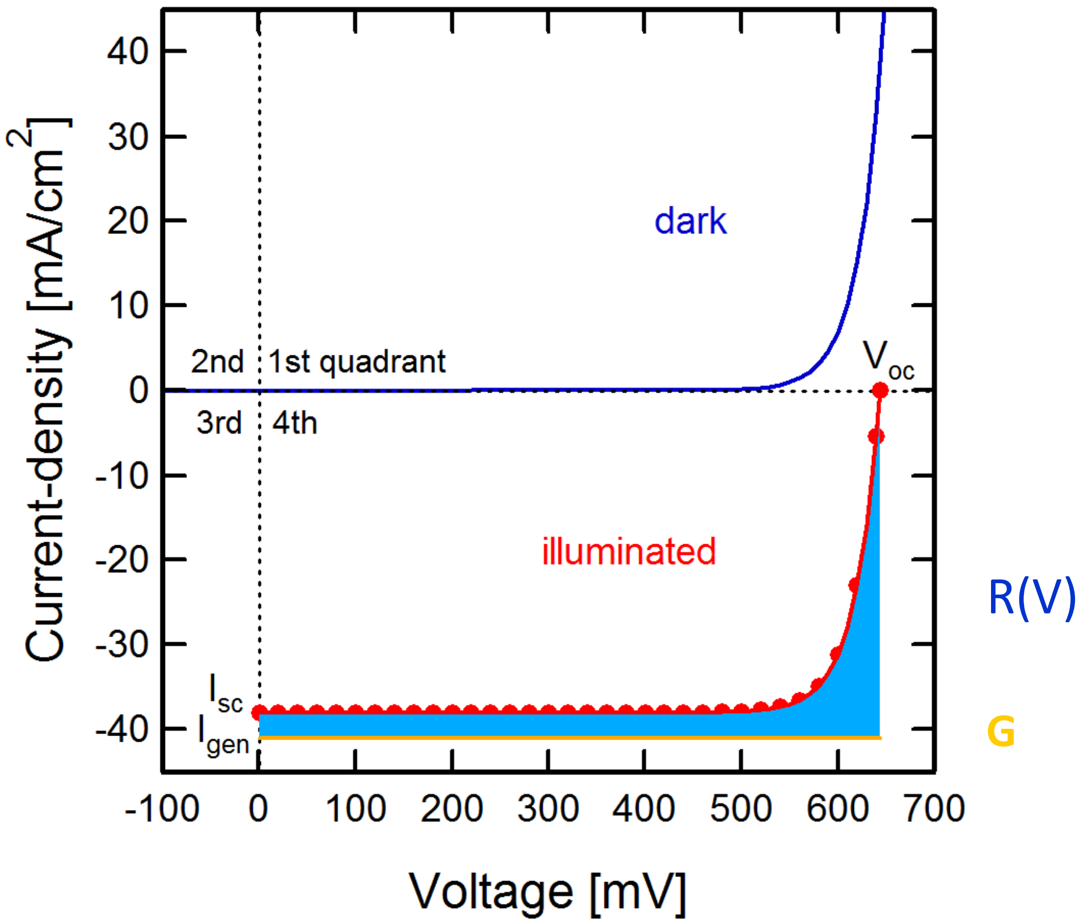


Think of G – R



Current-density [mA/cm²]
40
30
20
10
0
-10
-20
-30
-40
dark
2nd
1st quadrant
3rd
4th
V_{oc}
illuminated
I_{sc}
G
-100
0
100
200
300
400
500
600
700
Voltage [mV]

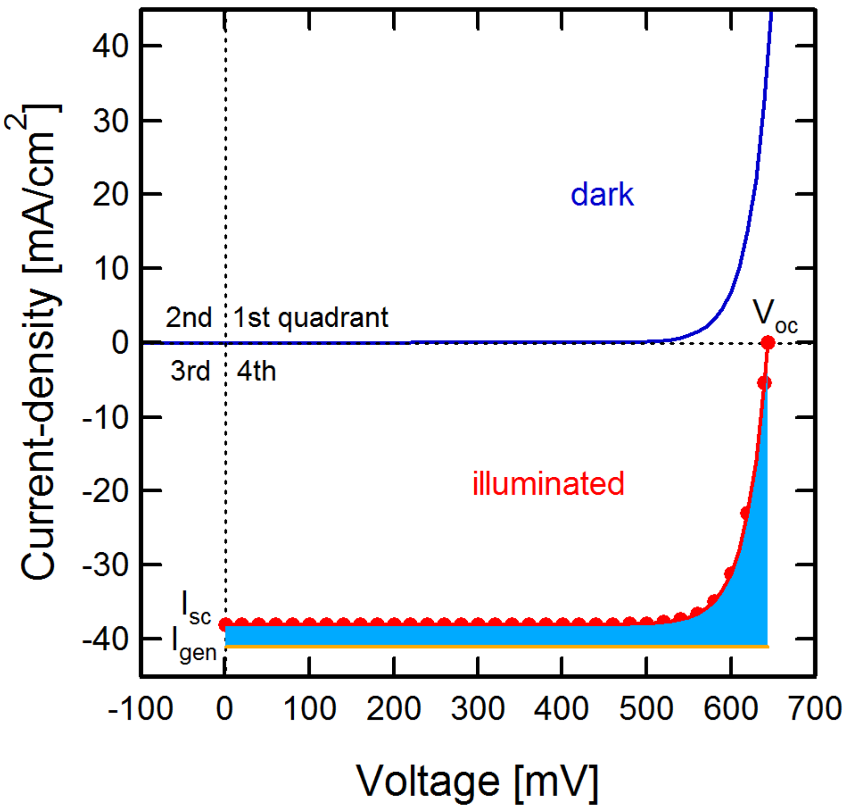
J(V) = G – R(V)



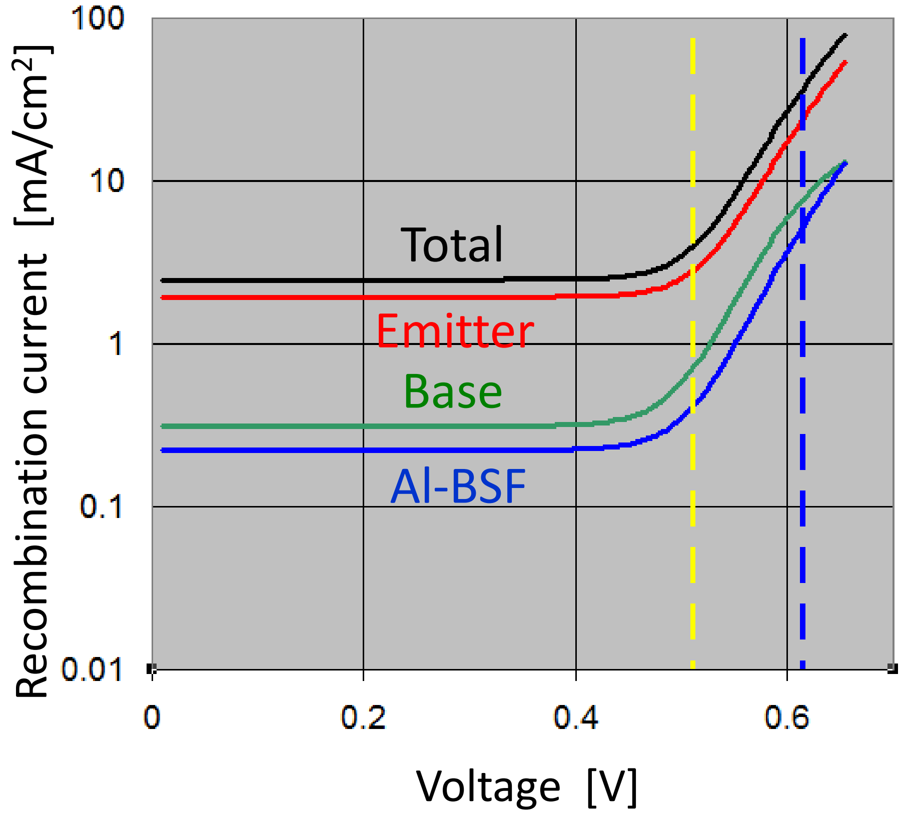
Current-density [mA/cm2]
40
30
20
10
0
-10
-20
-30
-40
dark
2nd
1st quadrant
3rd
4th
Voc
illuminated
Isc
Igen
-100
0
100
200
300
400
500
600
700
Voltage [mV]
R(V)
G

J(V) = G – R(V)

Losses in the various cell regions



R(V)



Predictions

Measurement

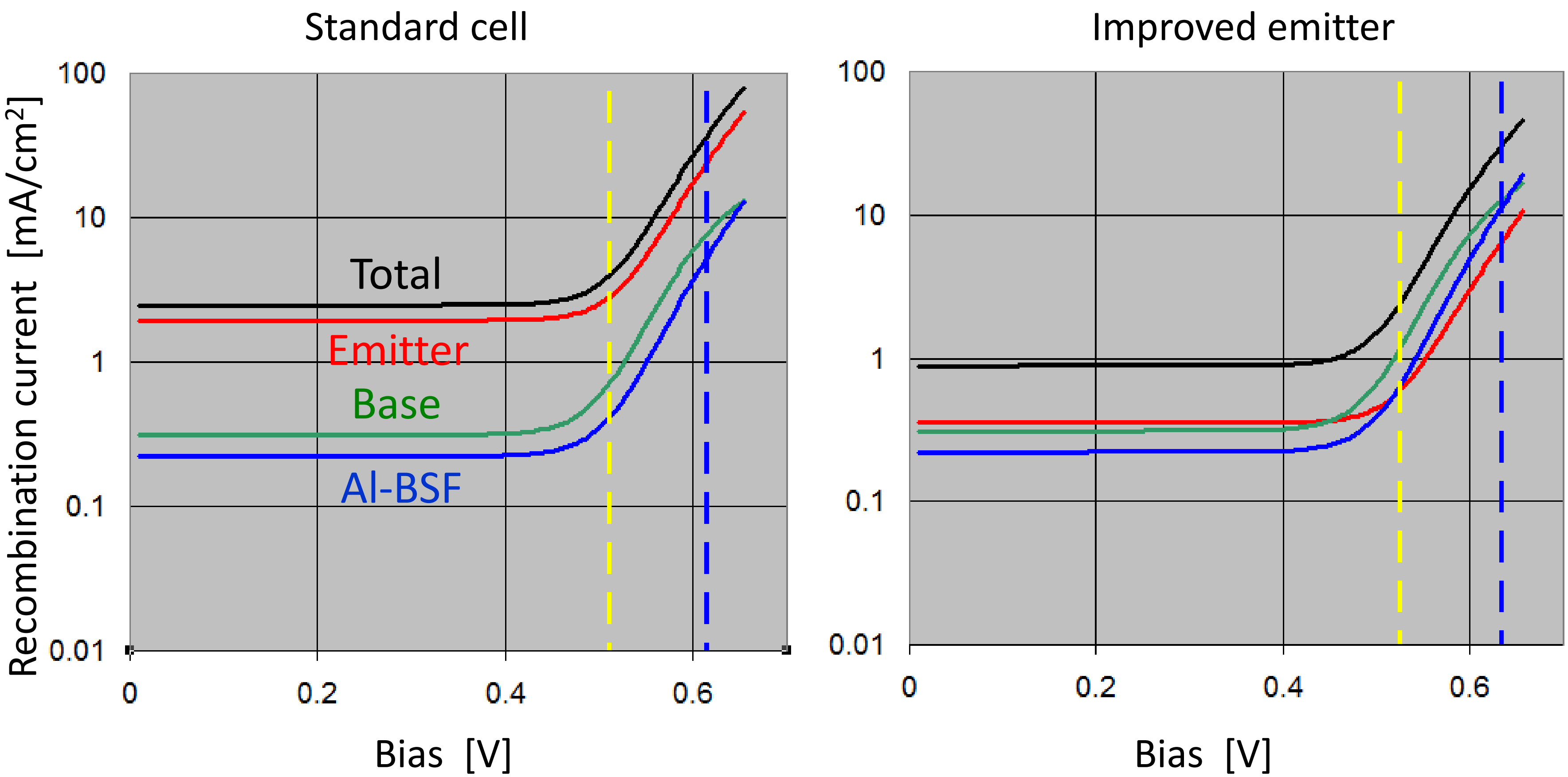
Extraction of R_s

Parametrization of $R_s(V)$

$R_s(V)$-free I-V curves

Loss analysis
Predictions

After improvement of the emitter in a PERC cell



V_{oc} = 614 mV
FF = 76.3

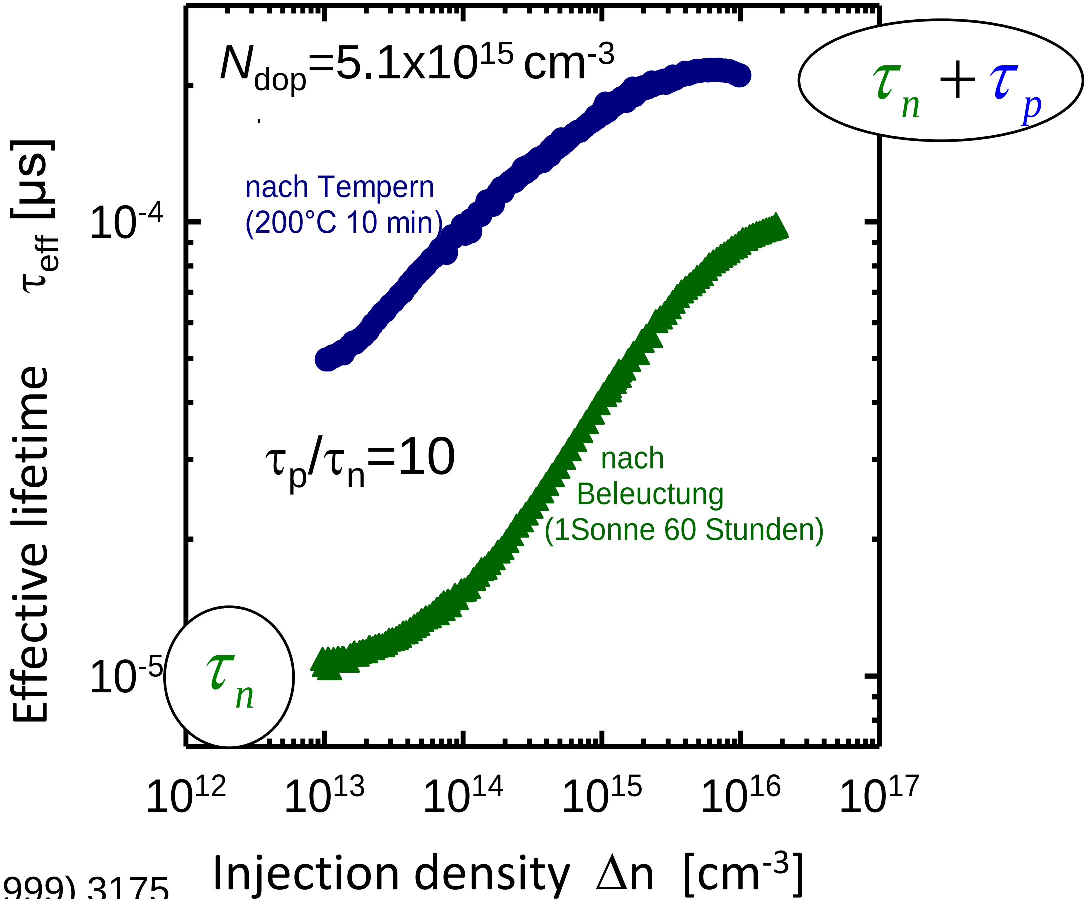
V_{oc} = 633 mV
FF = 75.4

Losses in the p-type Cz base

Injection dependent lifetime in the p-type base

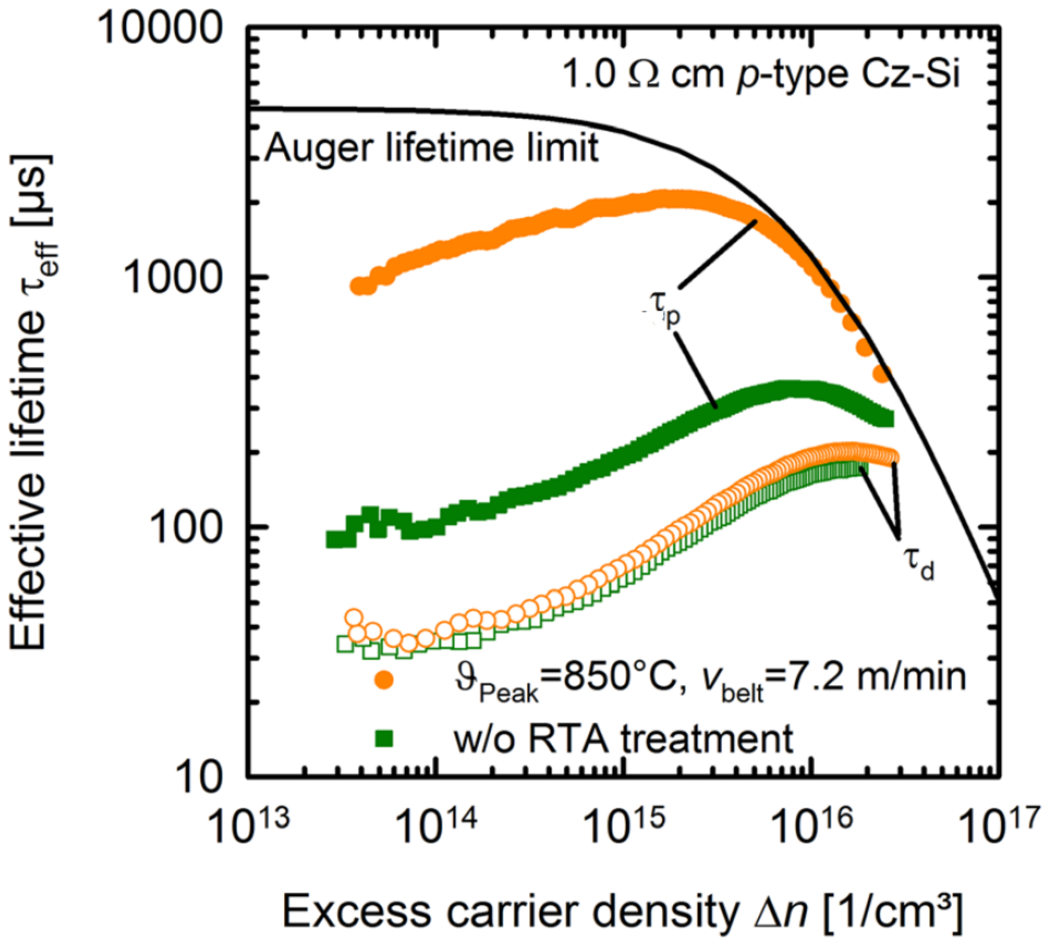
$$\tau_{SRH}(\Delta n) = \frac{\tau_p(n_0 + n_1 + \Delta n) + \tau_n(p_0 + p_1 + \Delta n)}{n_0 + p_0 + \Delta n}$$

B-O complex



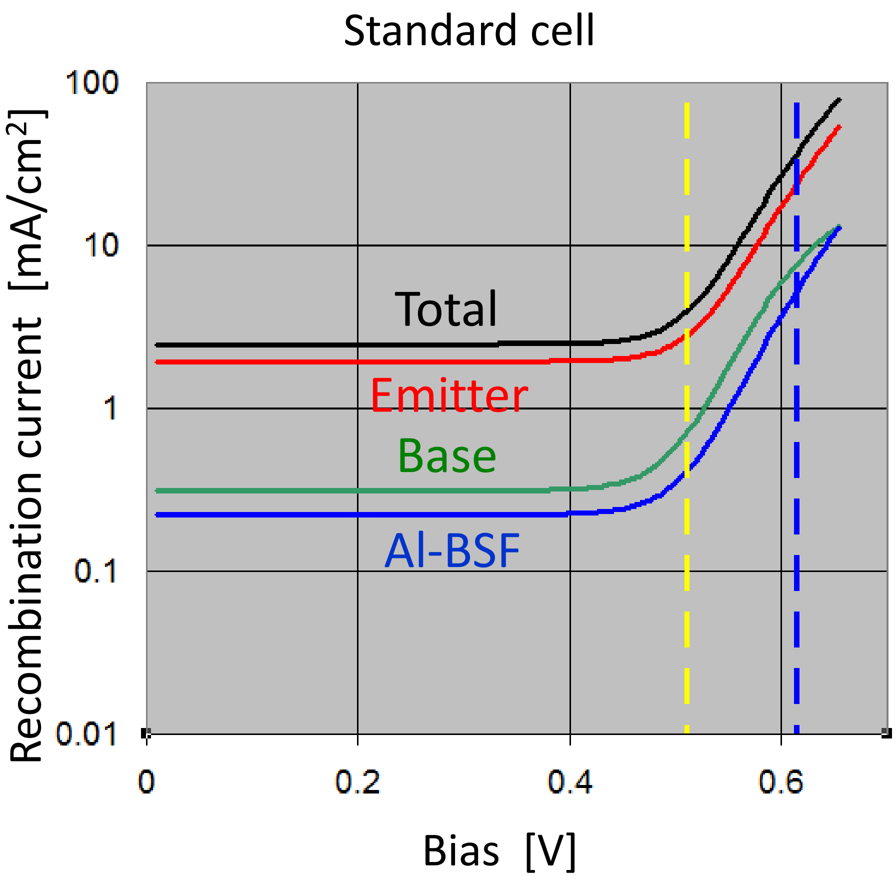
J. Schmidt, A. Cuevas, J. Appl. Phys. 86 (1999) 3175
S. Rein, S.W. Glunz, Appl. Phys. Lett. 82 (2003) 1054
K. Bothe R. Sinton, J. Schmidt, Prog. PV 13 (2005) 287

Deactivated B-doped Cz wafers



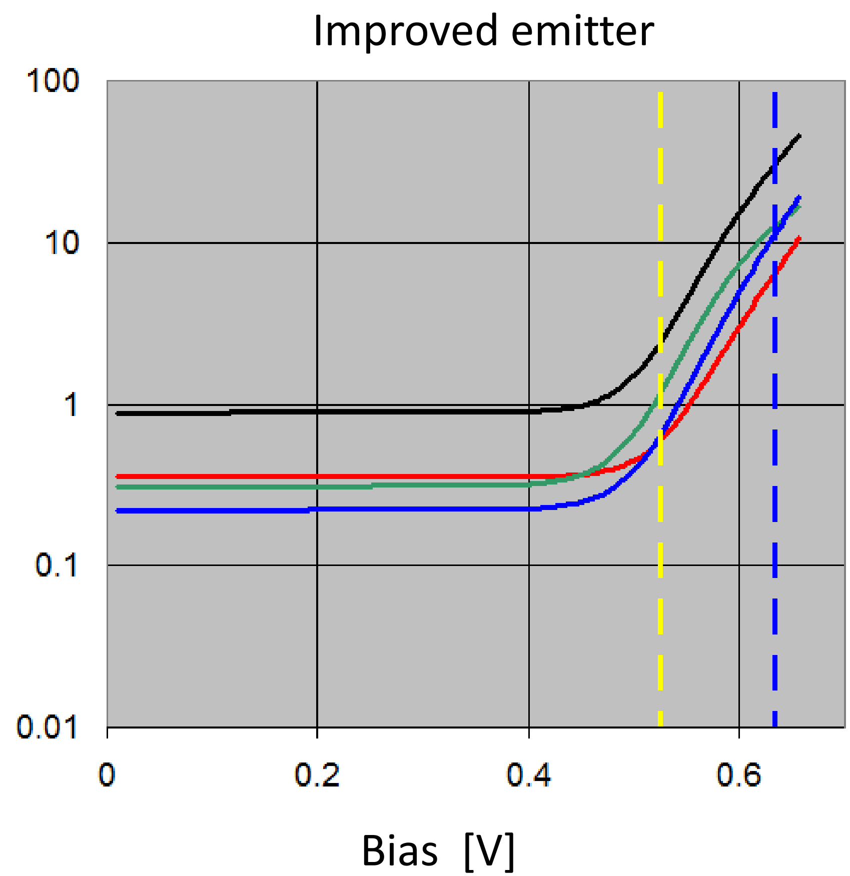
D. Waler et al, Appl. Phys. Lett. 104, 042111 (2014)

Improved emitter → smaller FF because of base!



V_{oc} = 614 mV

FF = 76.3



V_{oc} = 633 mV

FF = 75.4

FF, pFF und 1FF

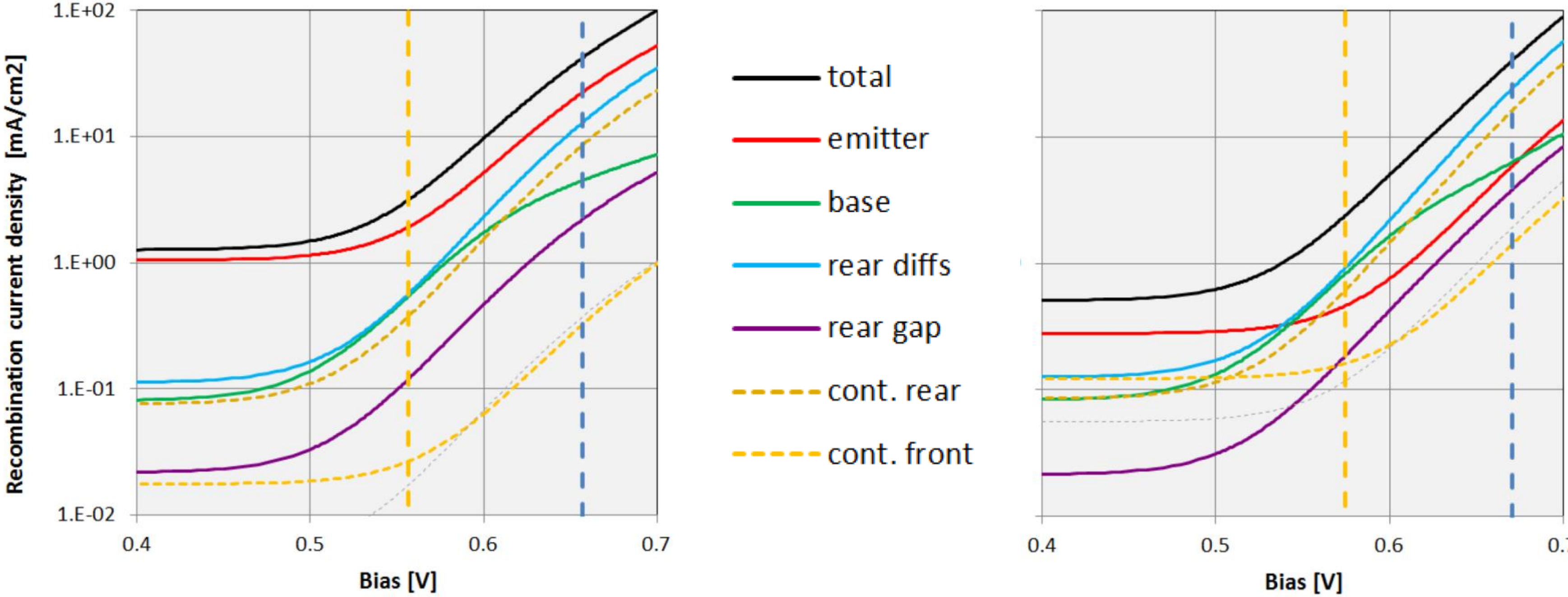
Two cells with low FF

1) Mainly due to $R_s \rightarrow$ pFF is close to 1FF
2) Mainly due to $n \rightarrow$ pFF is far from1FF

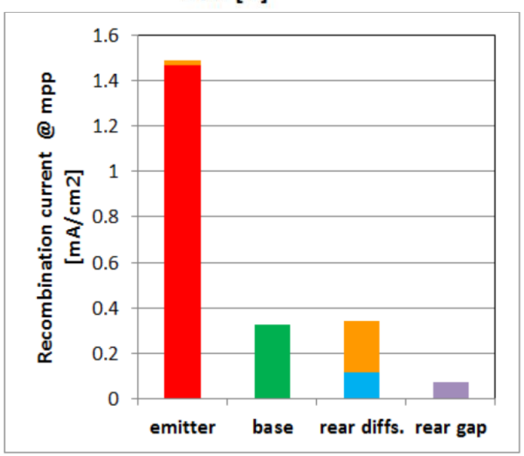
$\Rightarrow$ Determine FF and pFF, if possible using $R_s(V)$, and 1FF

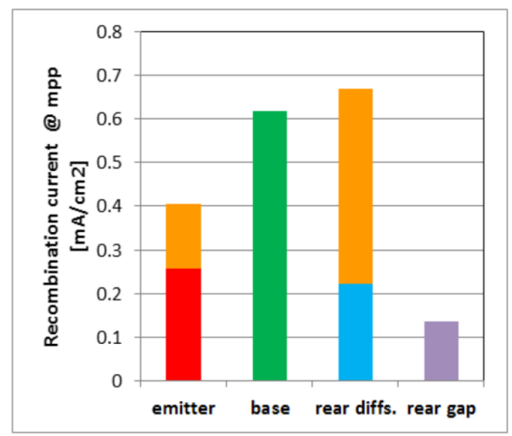
More recent progress of PERC cells (1)

Inital | Improved emitter



79.69

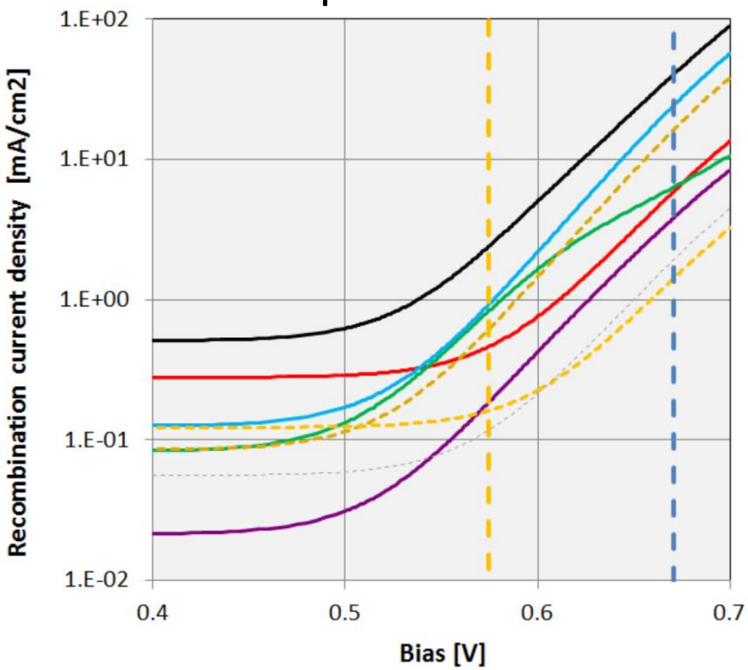




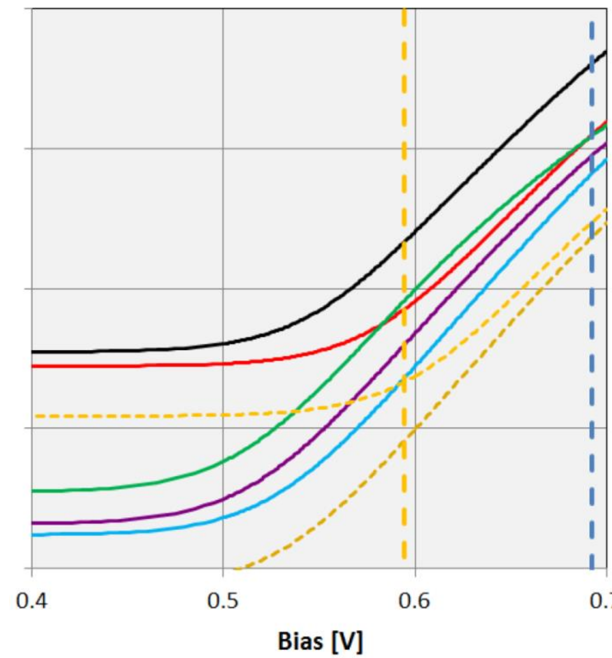
80.38

More recent progress of PERC cells (2)

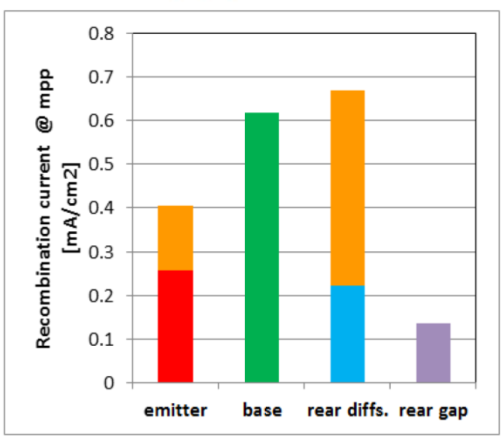
Improved emitter

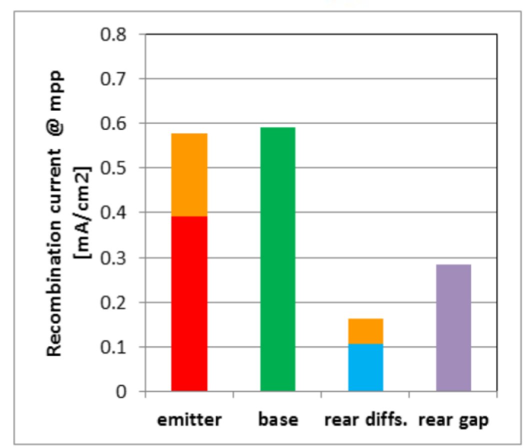


Improved base and rear



80.38



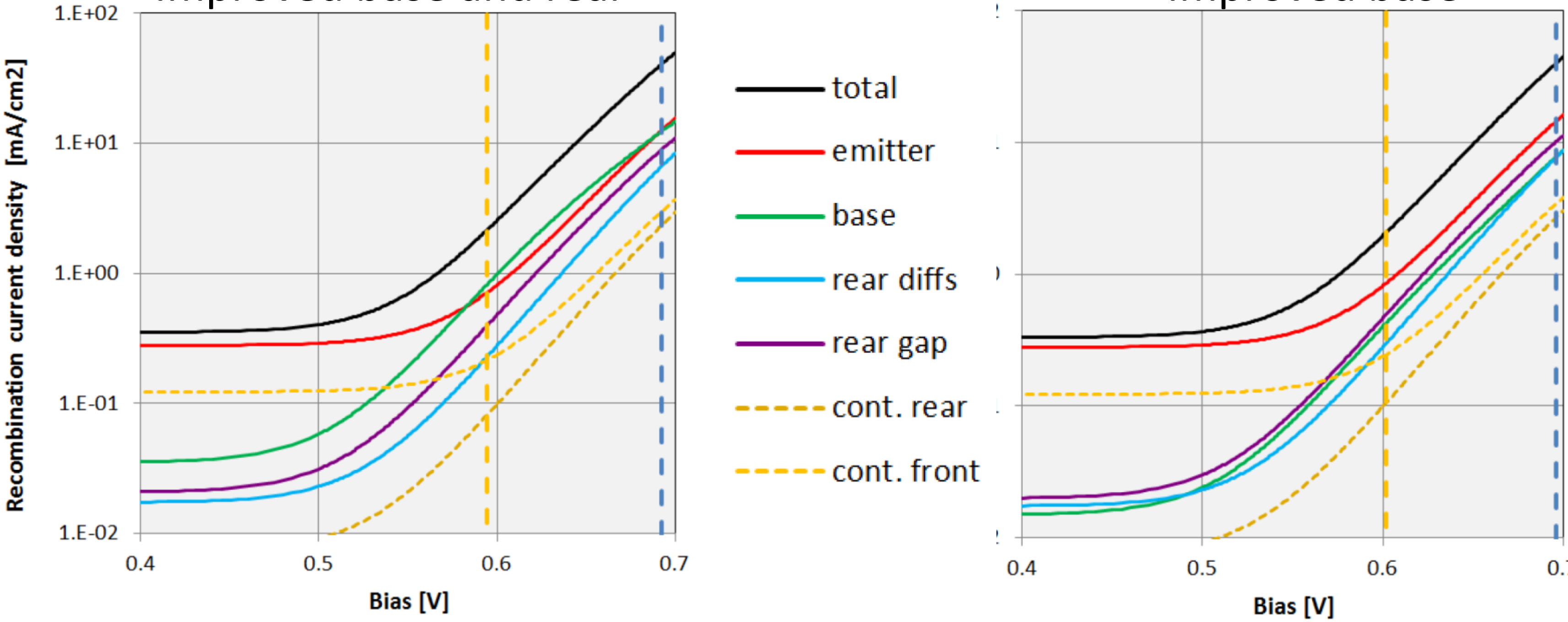


80.80

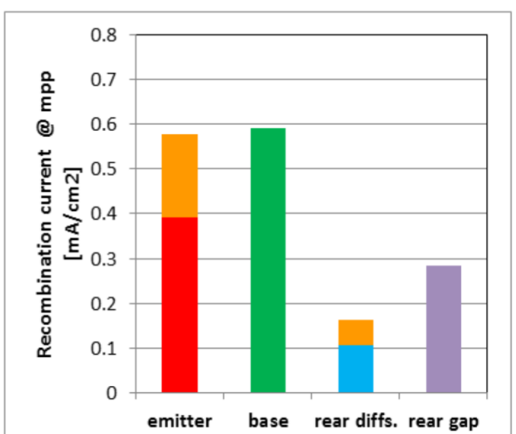
LUH

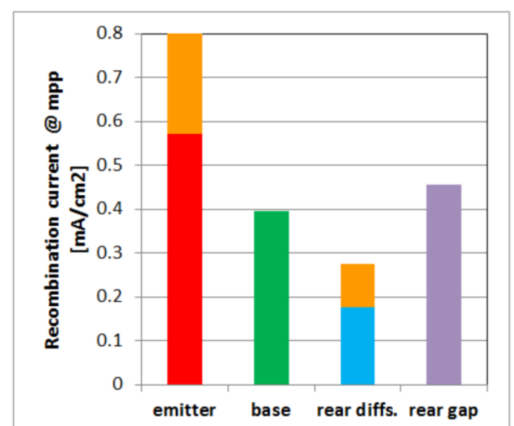
More recent progress of PERC cells (3)

Improved base and rear | Improved base



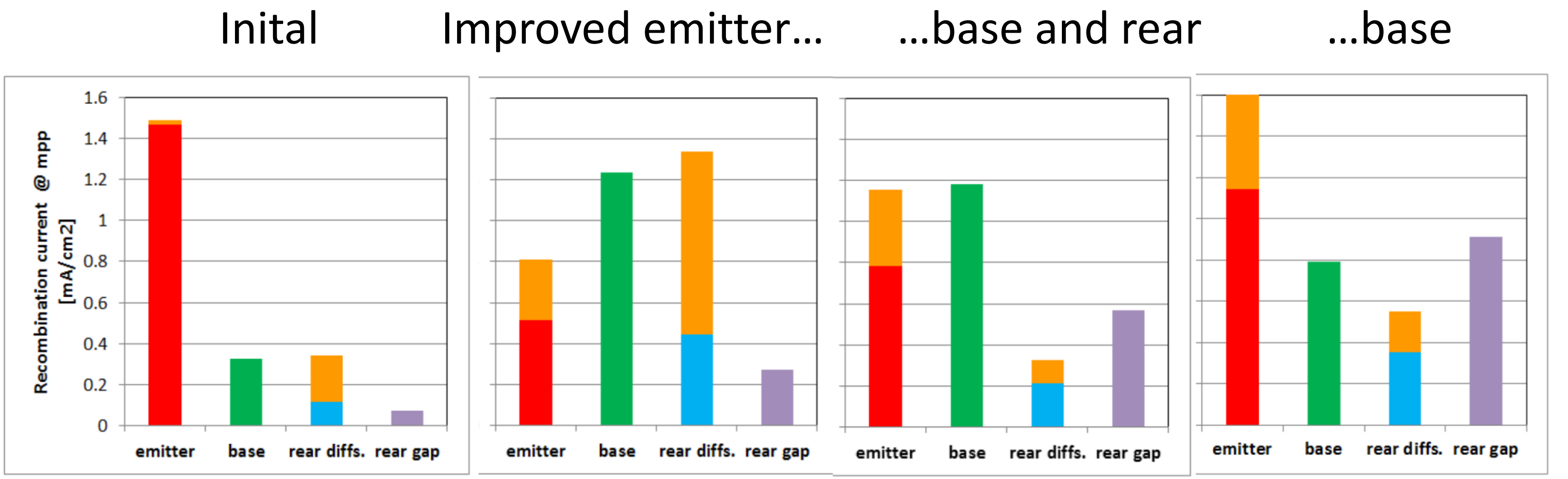
80.80





81.46

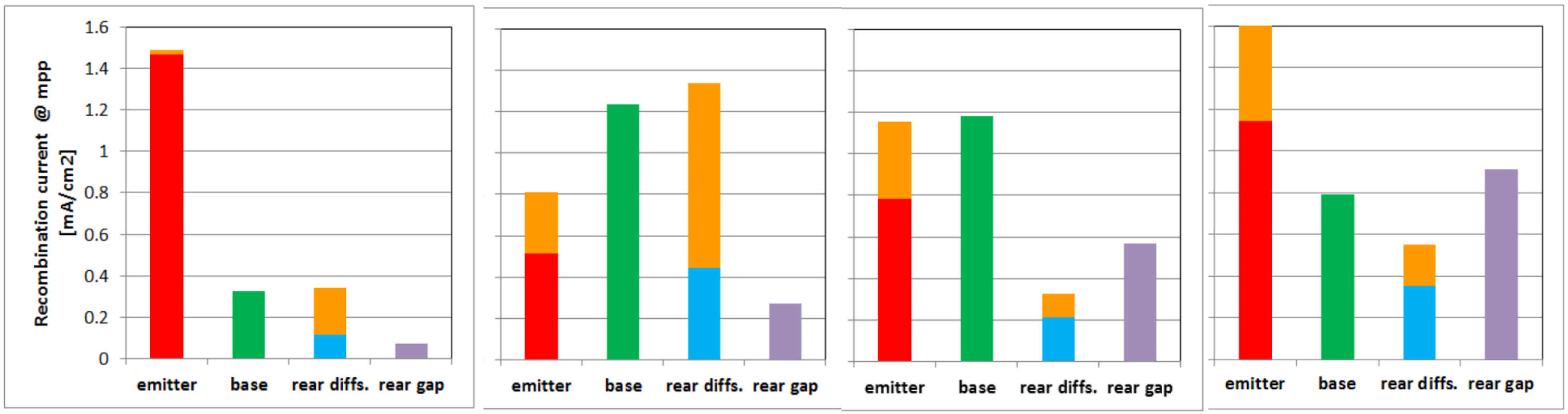
Emitter losses increase…

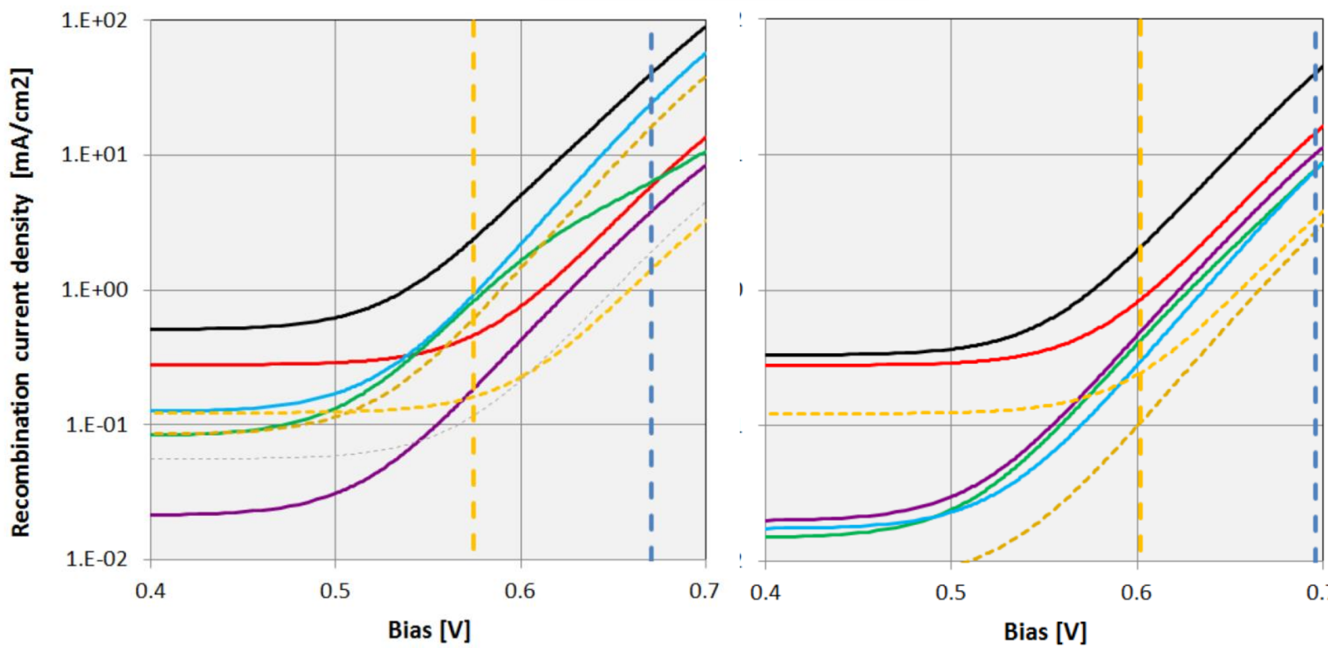


LUH

…because V_{mpp} increases

Inital | Improved emitter… | …base and rear | …base





Main points

- Extraction of $R_s(V)$ from three I-V curves (TLL method)
- Clear distinction between $R_s(V)$ and recombination losses
- $R_s(V)$-corrected I-V curve

  → pFF < 1FF ?

- Further analysis and prediction with simulations

FF is not only determined by R_s,
but also by the ideality factor, i.e.by recombination,
especially in good cells (where the base or the rear surface dominates)

Thank you!

altermatt@solar.uni-hannover.de