NANOPHOTO Final meeting

Work Package 4
Prototyping and characterization

Outline

- Work package overview
- P-type and intrinsic layer characterisation
- PIN Solar cell fabrication process
- IV curves
  - Merten collection model
  - Results
- Conclusion

Work Package Overview

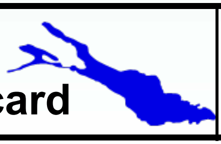
Task 4.1

Fabrication of opto-electronic devices and preliminary characterization and testing

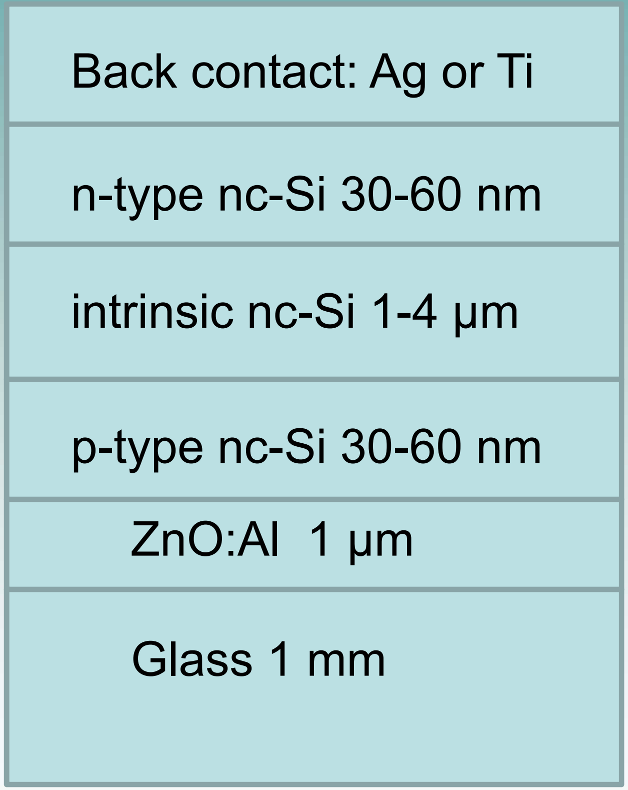
Task 4.2

Characterisation of opto-electronic devices

Remark: Focused on development and characterisation of nc-Si thin-film solar cells



PIN-Si thin-film solar cell
„Superstrate“ Configuration



Back contact: Ag or Ti

n-type nc-Si 30-60 nm

intrinsic nc-Si 1-4 µm

p-type nc-Si 30-60 nm

ZnO:Al 1 µm

Glass 1 mm

Space Charge Limited Current (SCLC) case of material with deep traps in a band tail

- If there is a density of traps >> density of free carriers
- Uniformly spatially distributed
- With an energy distribution such as: $g(E) = A * \exp((E_t-E_c)/kT_c)$ with T_c characteristic temperature of the band tail $T_c \geq T_{measurement}$

➡ The excess injected carriers will fill some traps of the band tail

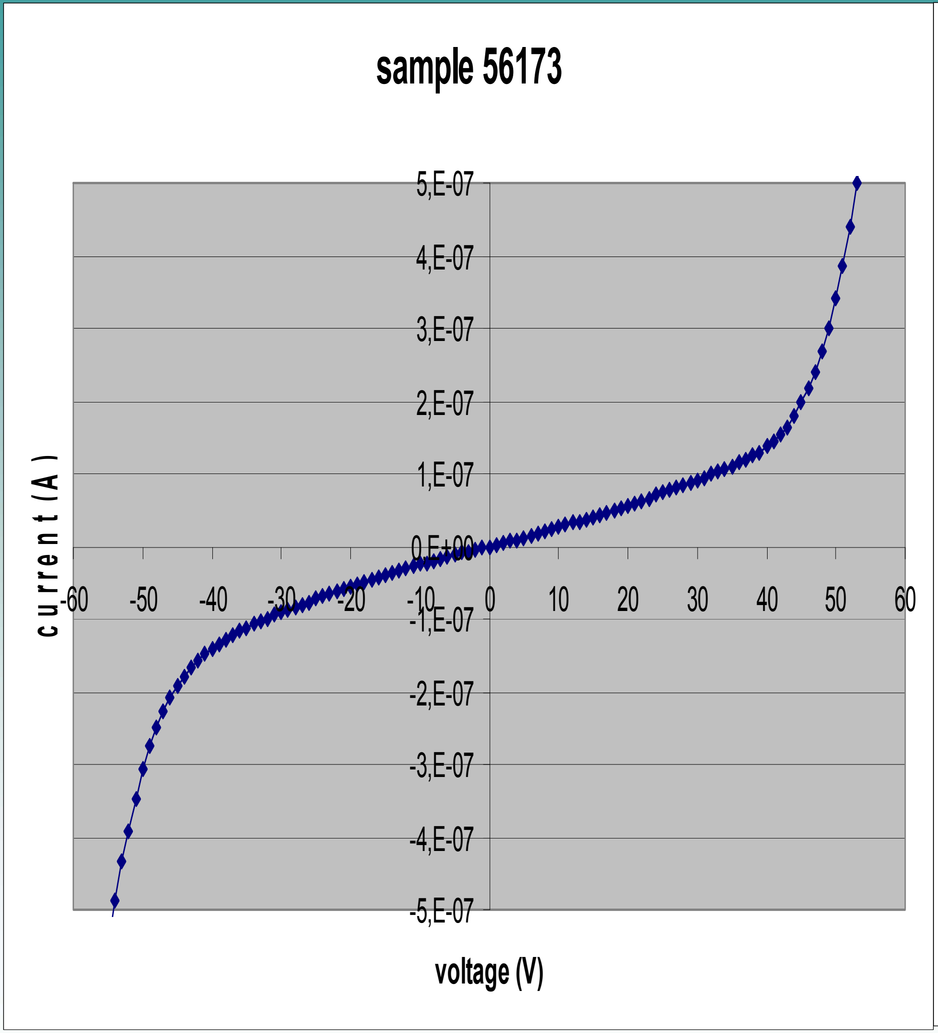
In this case it has been demonstrated that :

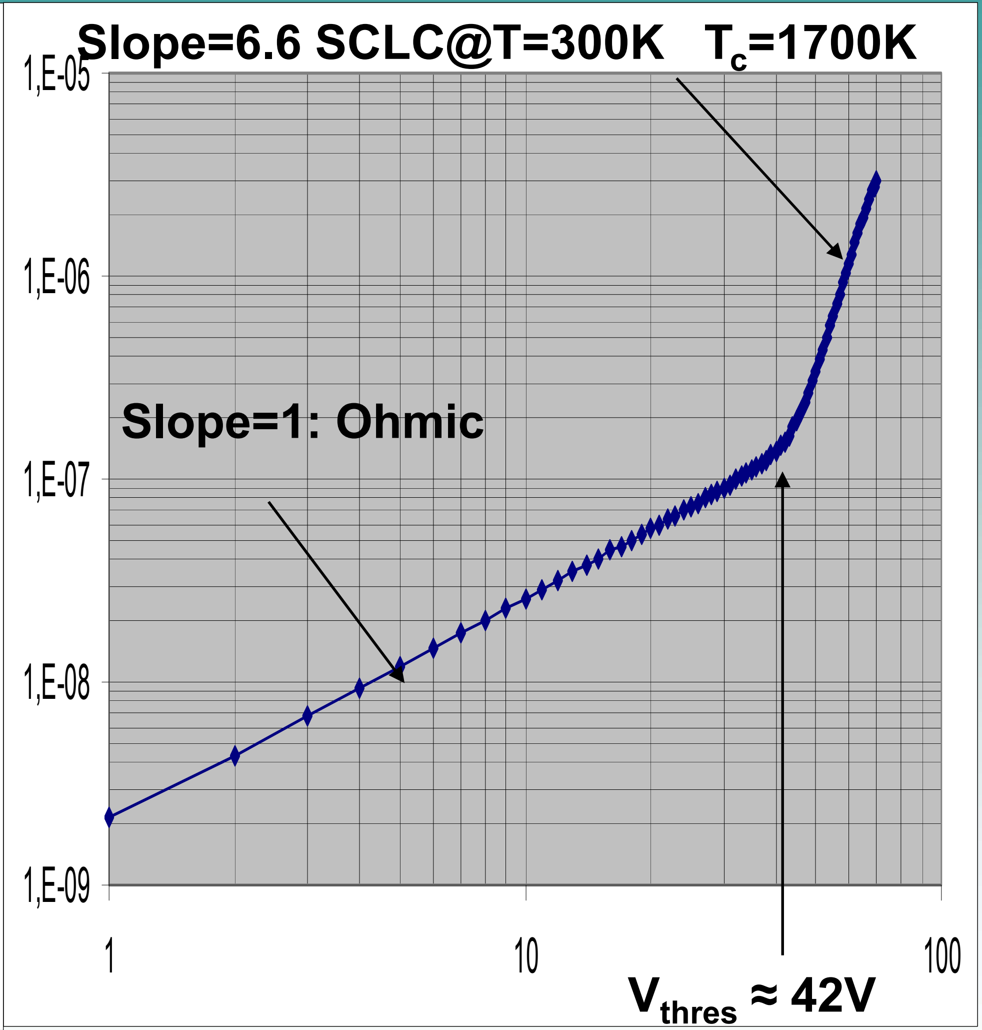
➡ $I = A * V^{\gamma}$ with $\gamma = 1 + T_c/T$

$\gamma \geq 2$ function of the temperature

➡ Evidenced in a $\log(I) = f(\log(V))$ diagram

- If $T_c < T_{measurement}$ $\gamma = 2$





Slope=6.6 SCLC@T=300K T_c=1700K

Slope=1: Ohmic

$V_{thres} \approx 42V$

i layer : Study of silane flow influence

D= SiH4/(SiH4+ H2)	SiH4 flux (sccm)	#num	Surface Xc (%)	Conductivity homogeneity	IV measurements observation
30%	20	7821	28	Not evaluated	High photogain, low dark current
30%	16	7823	27	Not evaluated	Medium photogain & dark current
30%	12	7824	41	Not evaluated	Low photogain, high dark current
50%	20	7825	36	Bad	High photogain, low dark current
50%	16	7826	27	Bad	Low photogain, high dark current
50%	12	7827	39	Bad	Low photogain, high dark current

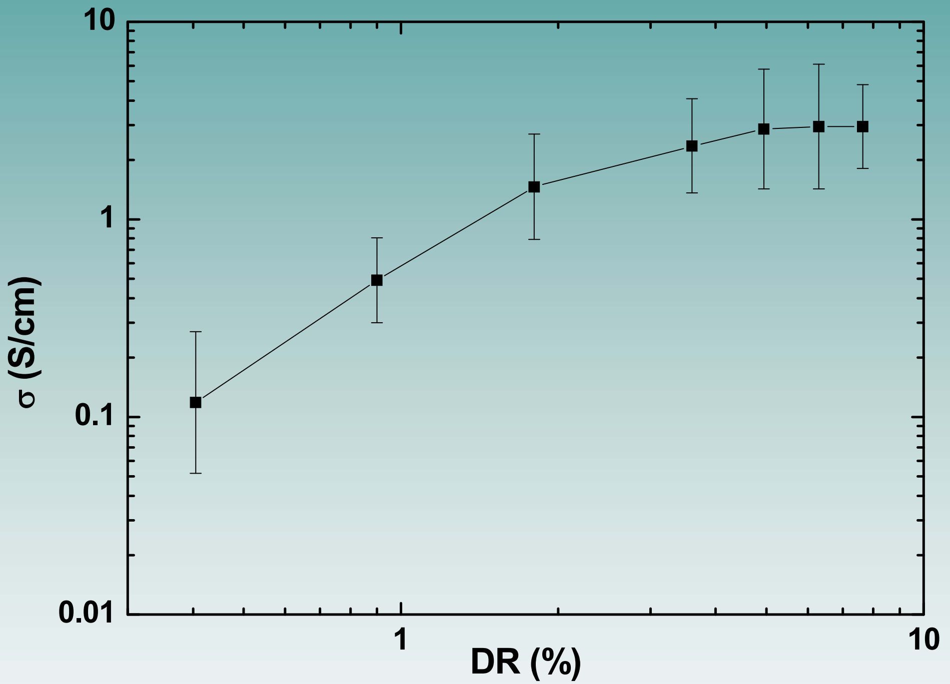
- Samples 7821, 7825 (high silane flow)
  - High photogain (1000-10000), Low conductivity (10^{-11}-10^{-9} S/cm)
    - ➡ amorphous Si dominates
- Decreasing the silane flow at the same dilution
  - Reduced photogain, increased dark conductivity
    - ➡ nc-Si dominates

Ideal i layer conductivity characteristics for solar cells

- Bibliographic study establish that the best compromise between
  - Amorphous
    - Poor dark conductivity 10^{-11}-10^{-9} S/cm (high recombination)
    - High photogain :1000-10000 : very good light absorption
  - And Crystalline silicon
    - High dark conductivity 10^{-4}-10^{-5} S/cm (low recombination)
    - Low photogain :1-5 : low light absorption
  - Should be nc-Si with:
    - Medium dark conductivity 10^{-7} S/cm
    - Medium photogain : 100
- The best samples already grown show a dark conductivity of 10^{-8} S/cm for a photogain around 100

  ➔ These samples will have lower electrical performance than the recommended ones from literature

Conductivity of p-type layers of series 8135-8144



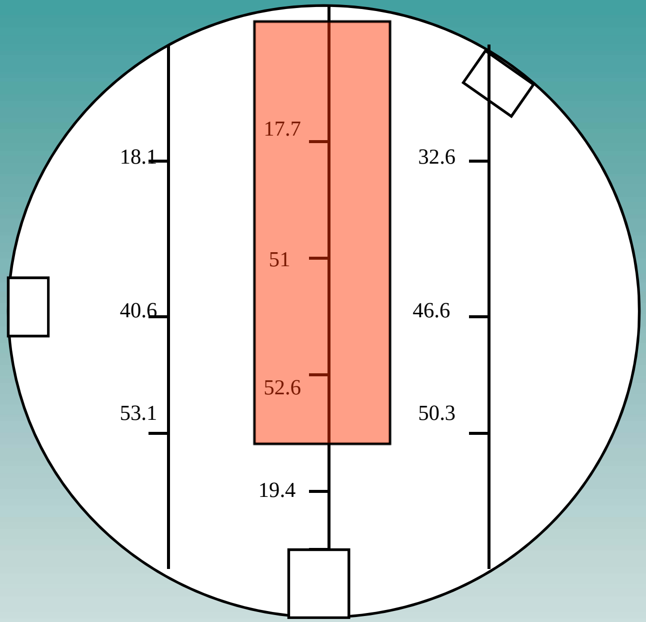
- As expected the conductivity increases with doping ratio to reach a maximum of 5-6 S/cm at **DR 6.3%!!!**

  In the literature the optimum DR is between 0.4 and 0.8% for VHF-PECVD or HWCVD
- The conductivity on one wafer varies for a factor 3 to 6
- With the averaging the maximum is not very pronounced

Microsharp environmental tests on samples coming from the wafer 7665 (Si substrate, T=300°C, d=30%)

- 14 days @ 70°C and 95% Relative Humidity
- placed in dry oven @ 245°C for 14 days
- thermal shock from -35°C to 200°C for 3 days + thermal shock from -20°C and -30°C to 200°C for 3 days
- 14 days @ -40°C.

Results



- No crystallinity variation after tests
- hydrogen content decrease after
  TT in dry oven @ 245°C for 14 days

  falls below the detection limit after
  thermal shock from -35°C to 200°C for 3 days + thermal shock from -20°C and -30°C to 200°C for 3 days.

PIN-Si thin-film solar cell
„Superstrate“ Configuration

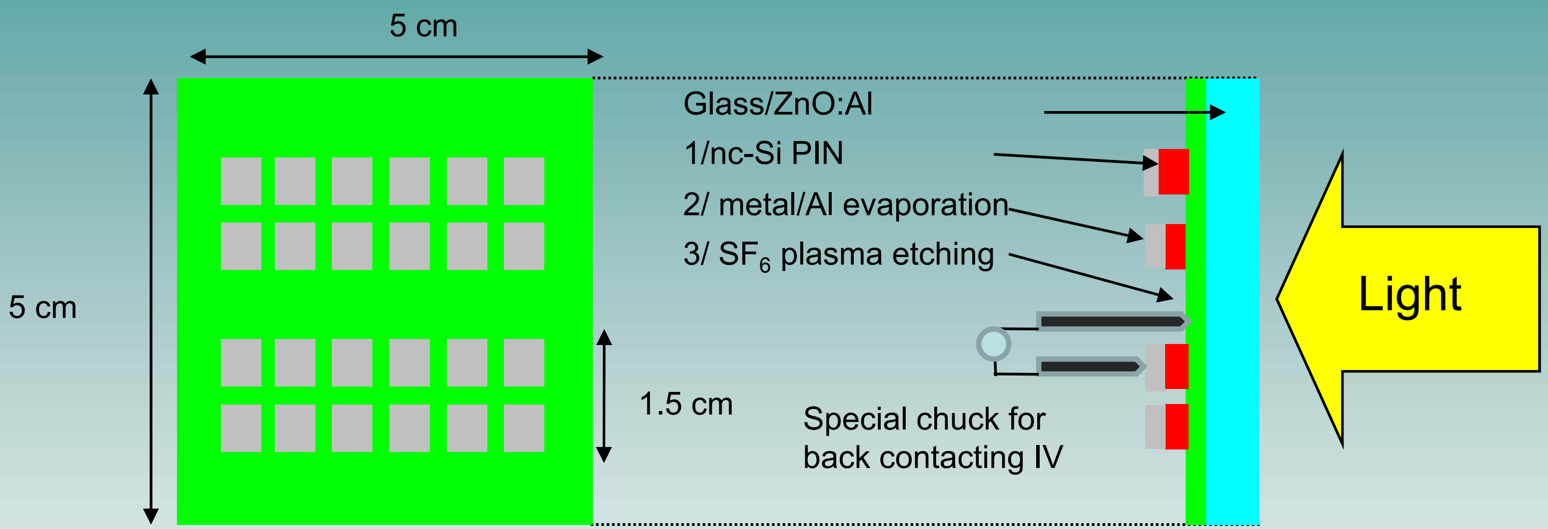
- Back contact: Ag or Ti
- n-type nc-Si 30-60 nm
- intrinsic nc-Si 1-4 µm
- p-type nc-Si 30-60 nm
- ZnO:Al 1 µm
- Glass 1 mm

Selection of **T**ransparent **C**onductive **O**xide

Requirement:
TCO must withstand plasma deposition of Si layers

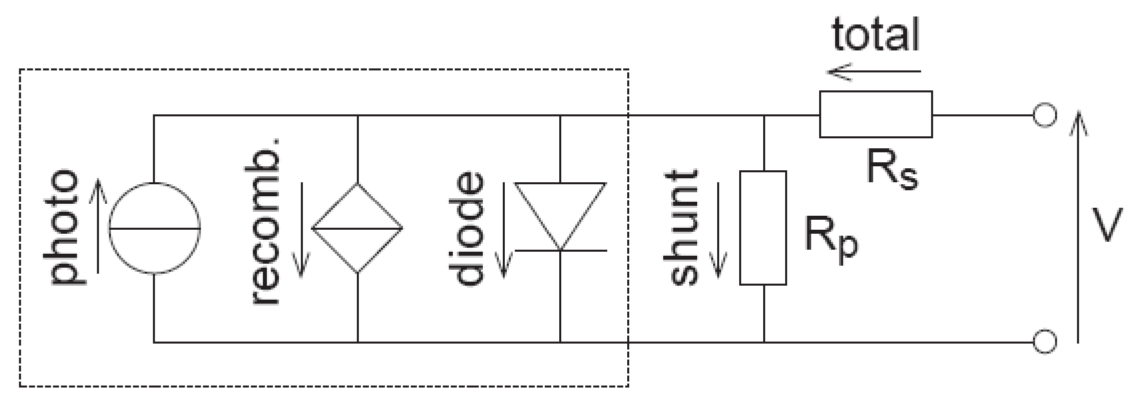
Results:
Indium tin oxide not stable against hydrogen
ZnO stable in plasma

PIN solar cell global macroscopic structure elements and fabrication process



- Step 1/ pin nc-Si deposition at LNESS on glass/ZnO
- Step 2/ metal/Al evaporation (with mask)
- Step 3/ SF_6 plasma etching: removal of nc-Si between Al-contacts

IV curve model: Difference to wafer solar cells



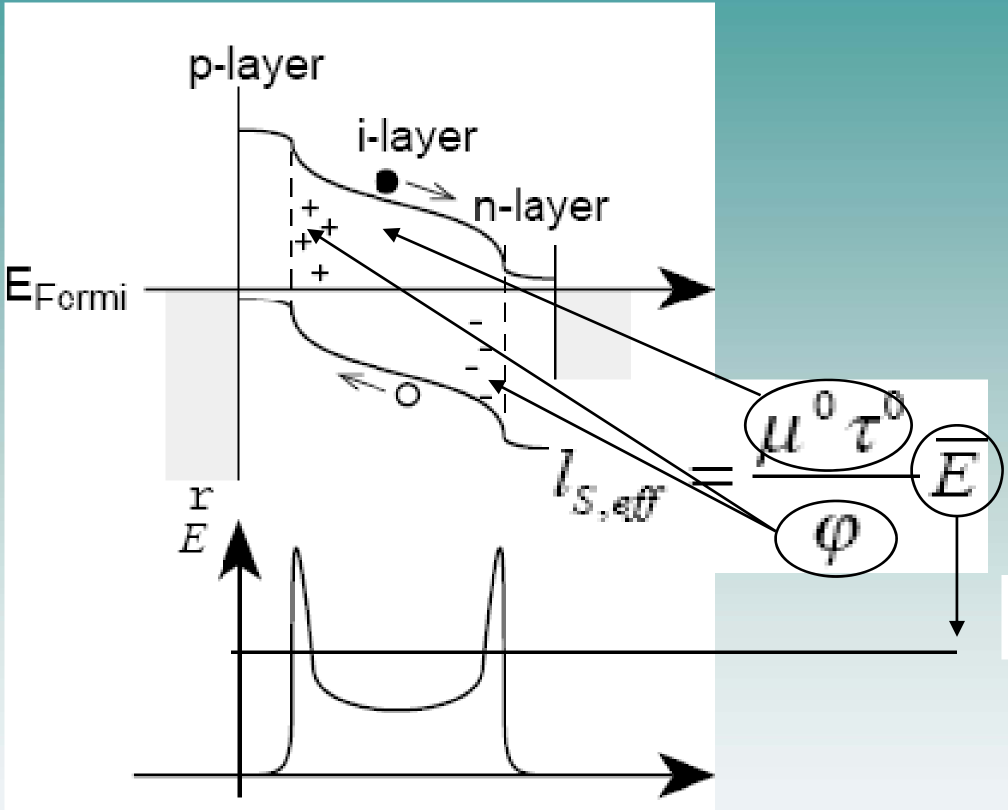
- Drift device: Carrier collection dependent on electric field between p-type and n-type layer

  ➔ ideal diode factor = 2 (not 1)

  ➔ diode saturation current $J_{on} \propto 1/\tau$ (not $1/\sqrt{\tau}$)
- Recombination current function of V

  ➔ Merten collection model

Transport properties of the i-layer: Merten Model (1)



Assuming all that the diffusion is negligeable Merten Hubin Crandall and Rech have express differently the **collection probability function** due to differing additional approximations

Hof remarked that these 4 models lead to similar results with different relative value of μ.τ :

$$\mu^0\tau^0\big|_{Crandall} \div \mu^0\tau^0\big|_{Rech} \div \mu^0\tau^0\big|_{Hubin} \div \mu^0\tau^0\big|_{Merten} \approx 1 \div 2 \div 3.73 \div 4$$

(Phd Hof University of Neuchatel)

➔ Therefore these model are very suitable qualitatively while differing in the evaluation of μ.τ by a maximum factor of 4

Transport properties of the i layer: Merten Model (2)

$$I(V) = \underbrace{-I_{photo} \cdot \frac{1}{1 + \dfrac{L^2 \cdot \varphi}{\mu^0 \tau^0 \cdot (V_{bi} - [V - IR_s])}}}_{generated\ current - recombination\ term} + \underbrace{I_0\left(e^{q\frac{V-IR_s}{nkT}} - 1\right)}_{injection\ term\ (dark\ current)} + \underbrace{\frac{V - IR_s}{R_p}}_{shunt\ losses}$$

$\mu_0.\tau_0$: Normalized mobility lifetime product: depend on electron and hole mobility and lifetime describes quality of the i layer

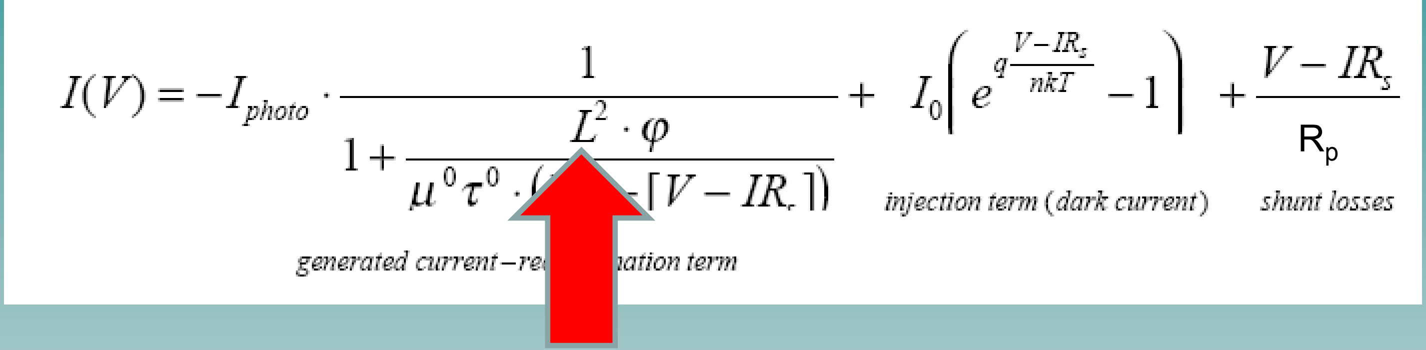
L: thickness of the i layer

φ:form factor: depend on the deformation of the electric field at the interface: quality of p/i and n/i interfaces (normaly between 1 and 2)

V_{bi}: build in voltage: depend on the activation energy of n and p layer :doping efficiency of n and p layer (assumed to be around 1V)

current increasing linearly in reverse bias, independently from the parallel resistance due to increased collection of generated carriers

Transport properties of the i-layer: Dependance of I_{photo} on L



$$I(V) = -I_{photo} \cdot \frac{1}{1 + \frac{L^2 \cdot \varphi}{\mu^0 \tau^0 \cdot (\quad -[V - IR_s])}} + I_0 \left(e^{q \frac{V-IR_s}{nkT}} - 1 \right) + \frac{V - IR_s}{R_p}$$

generated current – re ation term *injection term (dark current)* *shunt losses*

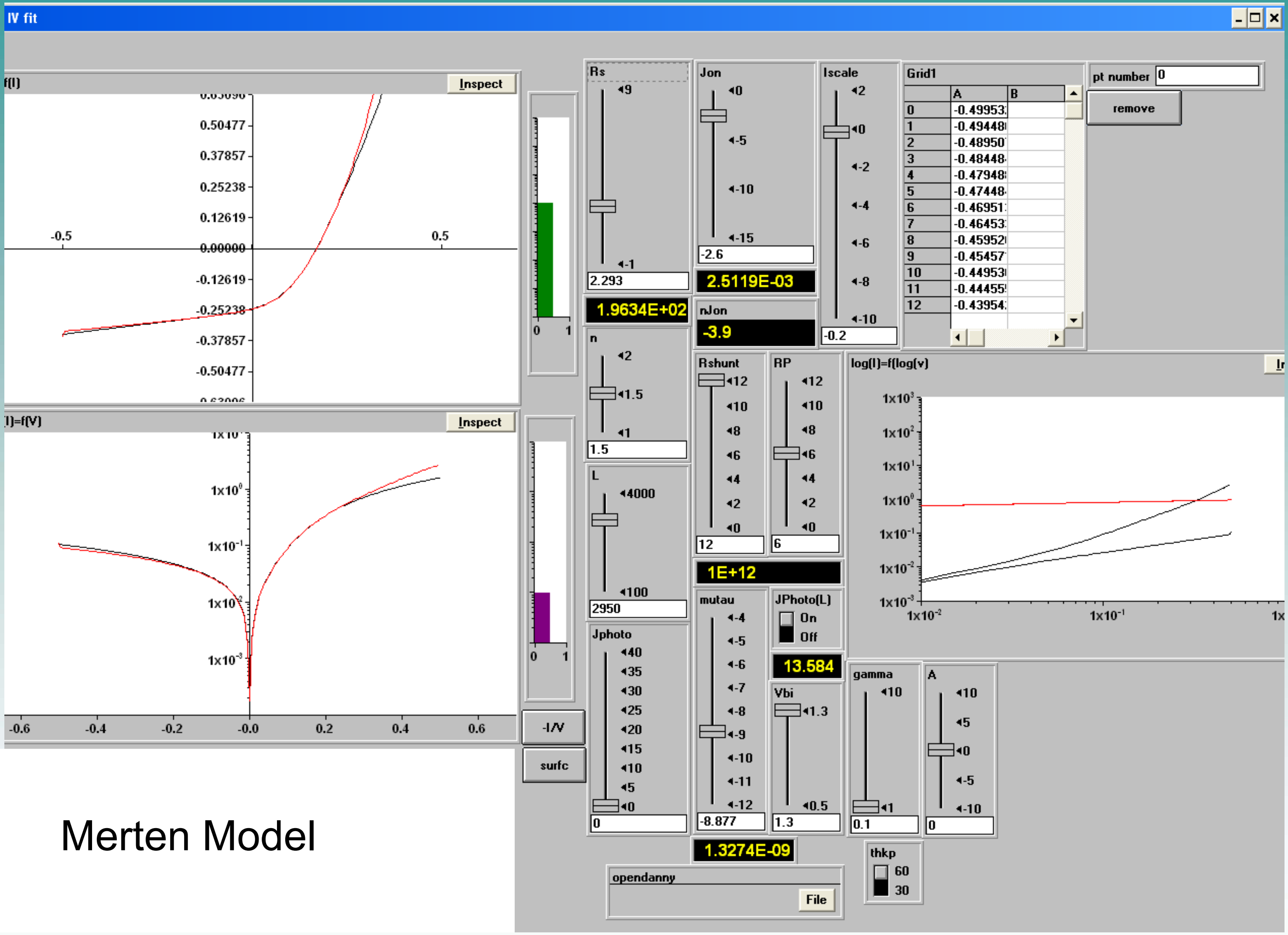
The recombination increase with L however the generation increase also with L

➔Simulation of the absorption of the i layer varying L with ***Optical*** considering:

- Low roughness for all layers : 5nm
- X_c 50%

➔Convolution with solar spectrum lead to I_{photo}:

Fitted with very good accuracy by an empirical law: $I_{photo} = A+B*\log(L+C)$



Rs: 2.293

1.9634E+02

Jon: -2.6

2.5119E-03

nJon: -3.9

Iscale: -0.2

n: 1.5

L: 2950

Jphoto: 0

Rshunt: 12

RP: 6

1E+12

mutau: -8.877

JPhoto(L): ☐ On ■ Off

13.584

Vbi: 1.3

gamma: 0.1

A: 0

thkp: ☐ 60 ■ 30

1.3274E-09

pt number: 0

Grid1

	A	B
0	-0.49953	
1	-0.49448	
2	-0.48950	
3	-0.48448	
4	-0.47948	
5	-0.47448	
6	-0.46951	
7	-0.46453	
8	-0.45952	
9	-0.45457	
10	-0.44953	
11	-0.44455	
12	-0.43954	

Merten Model

First series of pin nc-Si devices

Device design

Ag/Al contact, *pin* Si layer thickness: 30 nm / 1 µm / 80 nm

Technological results:

Contact metal defoliates, hardly any contact to Si

Electrical results

Supralinear behaviour in reverse bias

- Can be modelized by power law > 2

➡ SCLC(T_c correct, correct layer)

➡ i-layer is contacted directly, non existing p layer

Next series

- Thicker p-type and n-type layers as well as different i-layer thicknesses

- Ti / Pd / Ag / Al contact

Second series of pin nc-Si devices

Device design

Ti / Pd / Ag / Al contact, *pin* Si layer thickness: 60 nm / 1 or 2 µm / 150 nm

Technological results:

Contacts OK, thickness check by transmission: 1.475 and 2.950 µm

Electrical results

1 µm i-layer: all cells shunted, no SCLC

2 µm i-layer: 4/10 not shunted

$\mu^0\tau^0/\phi$: improved, p-type and n-type doping OK as deduced from V_{BI} fits

J_{0n} significantly lower than in series 1

Next series

- ➡ Keep device design
- ➡ Slower growth for higher Si layer quality, introduce p/i and n/i buffer

Third series of pin nc-Si devices „16 sccm“

Device design

Ti / Pd / Ag / Al contact, *pin* Si layer thickness: 60 nm / 1 or 2 µm / 150 nm

Technological results:

Contact resistance high

Electrical results

Higher V_{OC} corresponding to lower crystalline fraction

$\mu^0\tau^0/\phi$: improved further, material has higher quality

J_{0n} significantly lower than in series 2

Shunt problems: may be due to pin holes

Third series of pin nc-Si devices „3 sccm“

Device design

Ti / Pd / Ag / Al contact, *pin* Si layer thickness: 60 nm / 1 or 2 µm / 150 nm

Technological results:

Contact resistance high

Electrical results

Lower V_{OC} corresponding to higher crystalline fraction

$\mu^0\tau^0/\phi$: improved further, material has higher quality

J_{0n} significantly lower than in series 2

Shunt problems: may be due to pin holes

Conclusion

- Electrical properties of i-layer and p-type layer determined
- Environmental testing on LE-PECVD Si layers carried out
- First LE-PECVD based PIN Solar cells are fabricated
- New input for further layer and interface optimization gained by in depth characterisation