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"a-Si/a-Si Tandem Solar Cells"

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a-Si/a-Si Tandem Solar Cells

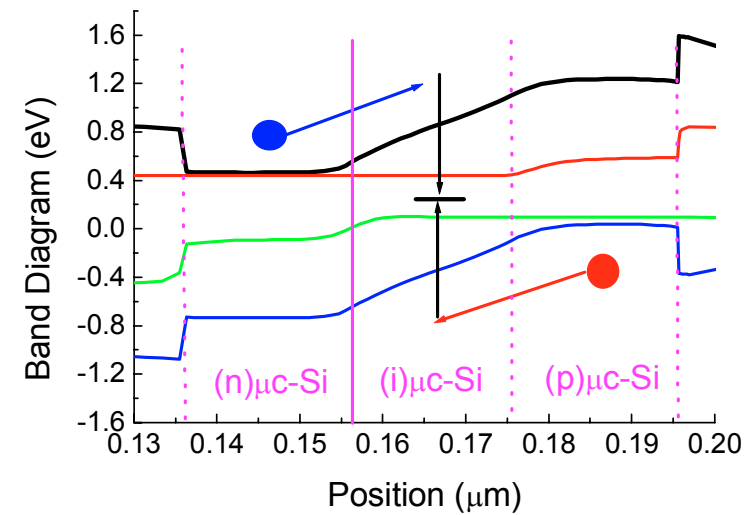
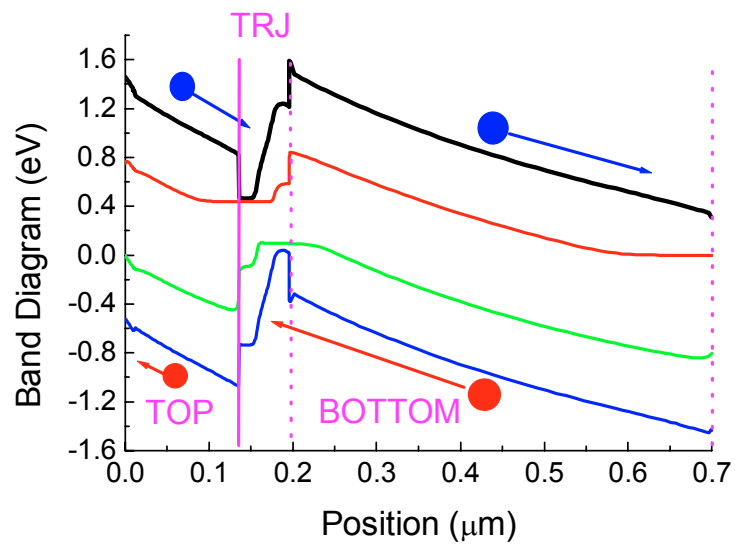
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Introduction

- a-Si/a-Si stacked tandem solar cells are more robust to light soaking than single a-Si p-i-n.
- a-Si mobility gap can be tailored at the top and bottom cells to use more efficiently the sun spectrum (ex: 1.88-1.78 eV - UU).
- S.Wieder et al. using several substrate temperatures (90 °C-190 °C) and hydrogen dilutions (1-20) reported $\eta = 9.2\%$ in the initial state with a decrease of 8% after 900 h of light soaking (1995).
- Ray used in top cell intrinsic layers with high gap ($\sim 1.9\text{eV}$) a-Si deposited at lower deposition temperatures and high hydrogen dilution rates. They reached 10.8% and FF= 0.72 in the annealed state. The degradation (1000 hrs of AM1.5 light) soaking was between 18-20%
- a-Si or combinations of a-Si and microcrystalline silicon ($\mu\text{c-Si}$) layers were used to build the tunnel recombination junction.

Tandem and TRJ Bands



TRJ Junctions

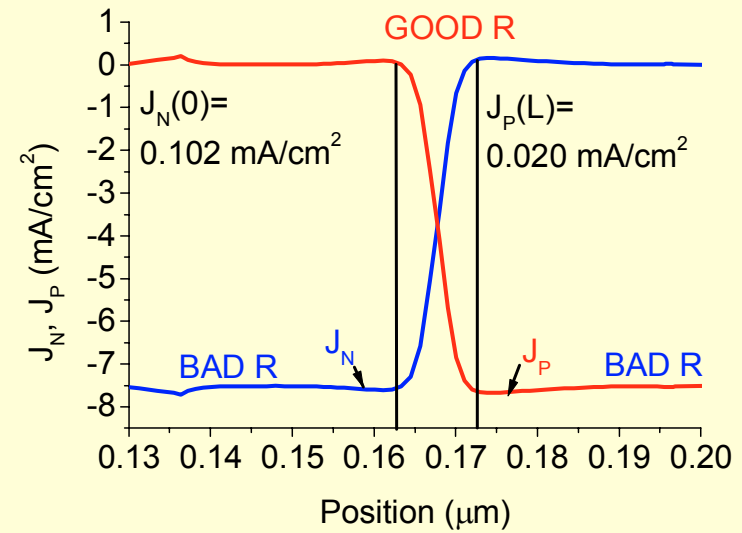
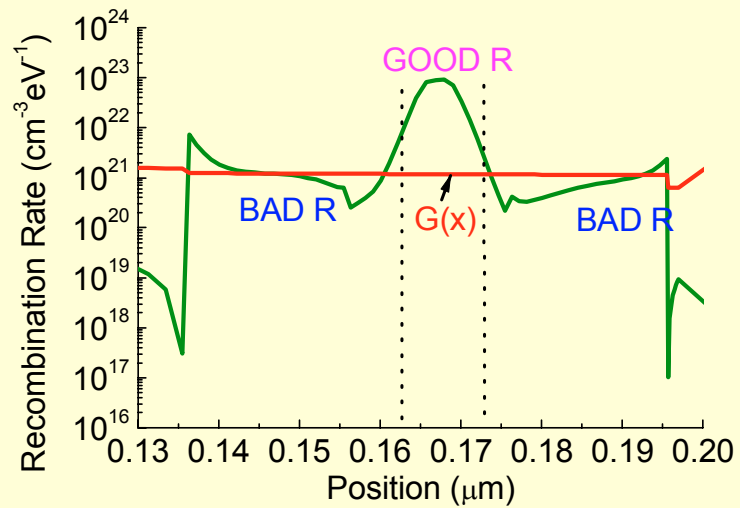
- Driving force to study $\mu\text{c-Si}$ in tandem TRJ.
 - low mobility gap favors recombination.
 - low optical absorption minimizes optical losses.
- $\text{SnO}_2\text{:F/p-a-SiC/i-a-Si/n-}\mu\text{c-Si/p-}\mu\text{c-Si/i-a-Si/n-a-Si/Ag}$.
 - record efficiency achieved at Utrecht University of **9.89%**.
- interface oxidation treatments were needed at two interfaces:
 - (a) $\text{i-a-Si/n-}\mu\text{c-Si}$ → oxide improves the crystallinity of the $\text{n-}\mu\text{c-Si}$ layer.
 - (b) $\text{n-}\mu\text{c-Si/p-}\mu\text{c-Si}$. → oxide enhances recombination.
- We present experimental results for two different TRJ:
 $\text{n-}\mu\text{c-Si/oxide/p-}\mu\text{c-Si}$ and $\text{n-}\mu\text{c-Si/oxide/i-}\mu\text{c-Si/p-}\mu\text{c-Si}$.

Good and Bad Recombination

- In tandem solar cells we have:
 - "good" recombination (GR) between electrons and holes photo-generated in the first and in the second cell respectively.
 - "bad" recombination (BR) occurring between electrons and holes photo-generated in the same cell.
- e-h pairs annihilated by GR contributes to the photocurrent.
- BR in p-, i- and n- layers reduces the total photocurrent leading to electrical losses.
- Back diffusion of electrons and holes at the front and back contact respectively are not significant loss mechanisms in tandem cells.
- High built-in potential must exist in TRJ to obtain high V_{OC} .
(~ sum of V_{OC} of both pin).

TRJ

Recombination and Currents

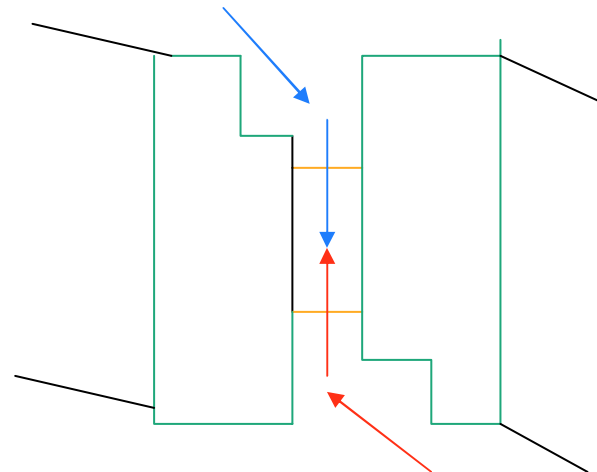


Undesired scenario

- When the TRJ (tunnel junction) cannot provide enough GR, more carriers will recombine through BR → solar cell performance will be deteriorated.
- Other undesired effect would be the creation of light induced dipoles due to the accumulation of trapped electrons and trapped holes what would weaken the electric field in the top cell and bottom cells and in the TRJ intrinsic layers.

Previous Work (1)

- TRJ junctions of a-Si based tandem cells can contain a-Si layers.
- V_{oc} is very sensitive to E_G of TRJ layers.
- Standard parameters of a-Si ($E_G = 1.72-1.8\text{eV}$) gives rise to GR $\sim 13-15$ orders of magnitudes lower than needed $\rightarrow V_{oc}$ cannot be matched by increasing DB density and capture cross sections.
- J. Hou and Bae et al enhanced GR in a-Si TRJ adding a highly defective layer with low $E_G \sim 1.0\text{ eV}$ (LMG) between the n-a-Si and p-a-Si layers and grading E_C (n-layer) and E_V (p-layer) towards the LMG region.



Previous Work (2)

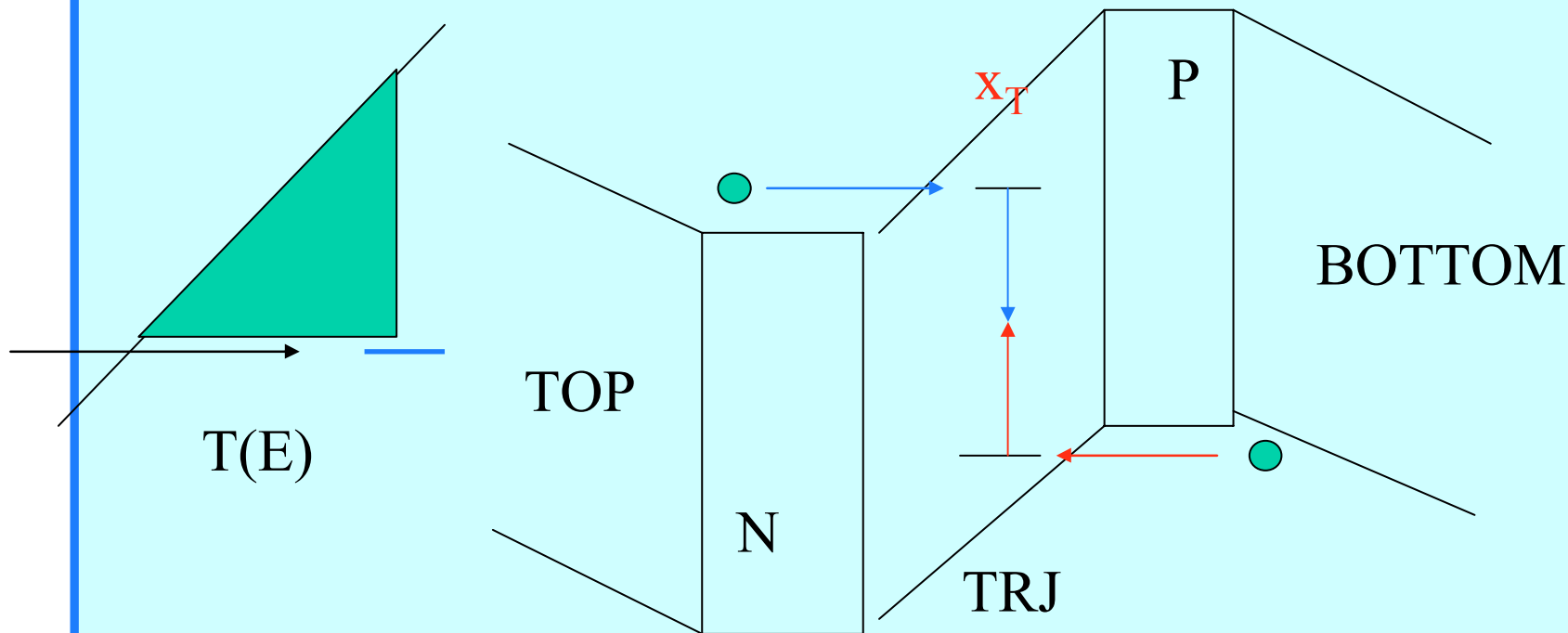
- Willeman et al. → exponential increase of the drift mobility with the electric field F

$$\mu_{\text{eff}} = \mu_0 \exp(F/F_0)$$

- Only when Hurkx 's trap assisted tunneling (TAT) and μ_{eff} models are simultaneously applied, the experimental J-V curves can be matched
- Recombination Model used in this work
 - SRH** → regular recombination through traps
 - TAT** → Hurkx 's tunnelling
 - PFT** → TAT + Pool Frenkel Effect (PFE)

Trap assisted Tunneling (TAT)

- Traps located at x_T can capture or emit free carriers from or to other locations different from x_T by tunneling.
- Tunneling transmission coefficients $T(E)$ are reduced by the presence of intense electric fields.

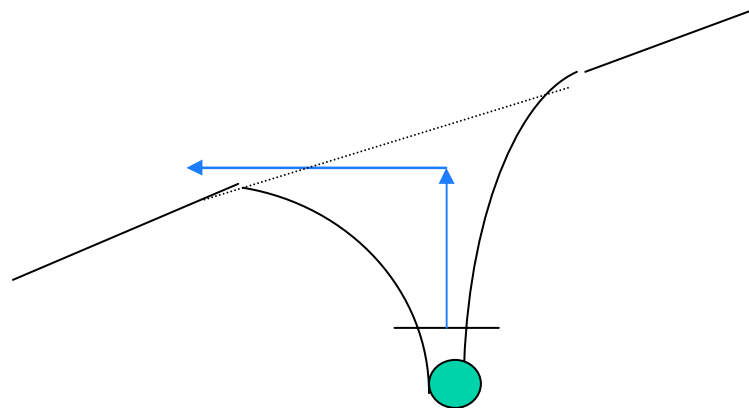


Hurkx's model (TAT)

- Capture cross sections become function of the absolute value of the electric field [F]
- The expressions of Hurkx et al.
- (a) depend only on local variables at x
- (b) can be expressed with analytical functions
- (c) adds only two new electrical parameters: the electron and the hole effective mass (m^*_E and m^*_H)
- (d) are strictly valid in regions where the electric field is constant (where tunneling currents are significant).

Pool Frenkel Effect (PFE)

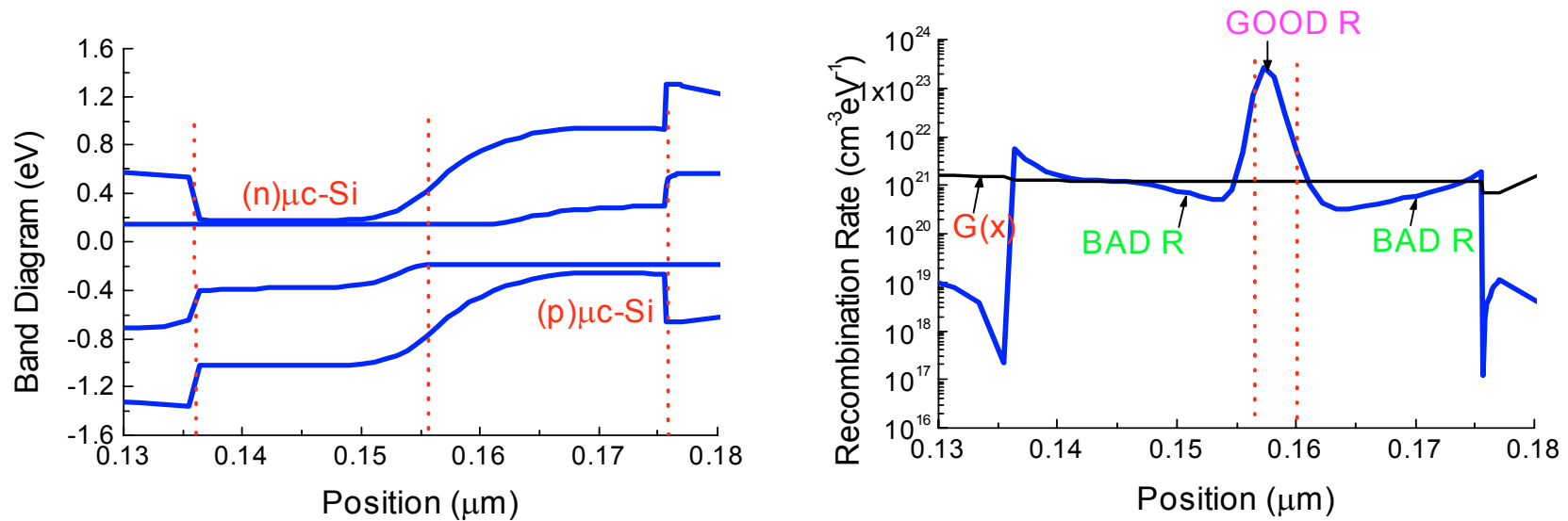
- PFE predicts an enhancement in the emissions probabilities and in the capture cross sections due to field-induced barrier lowering. The electric field in tandem TRJ could approach values near 10^6 V/cm.
- The PFE effect is only active in processes of capture and emission of electrons in donor-like states and capture and emission of holes in acceptor-like states.
- Similar statement for amphoteric states.



TRJ: all layers of $\mu\text{c-Si}$

- These TRJ have uniform electrical properties
→ electric field is almost constant (Hurkx's TAT)
- $E_G(\mu\text{c-Si})$ is assumed to be 1.2 eV.
- DB density ($\mu\text{c-Si}$) is modeled with three amphoteric-like gaussians (D^+ , D^0 , and D^-) centered at energies spaced by 0.3 eV. The correlation energy is $U=0.2$ eV. The D^0 gaussian is located $U/2$ below mid-gap.
- $\mu_N = 40 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}$ and $\mu_P = 4 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}$
- n- $\mu\text{c-Si}$ /p- $\mu\text{c-Si}$ TRJ structure →

n-p $\mu\text{c-Si}$ TRJ



The Good R takes place in a very narrow region located near the n/p interface mainly inside the p- $\mu\text{c-Si}$ layer.

The position of the GR peak is not dictated by the asymmetry existing between the electron and hole mobility.

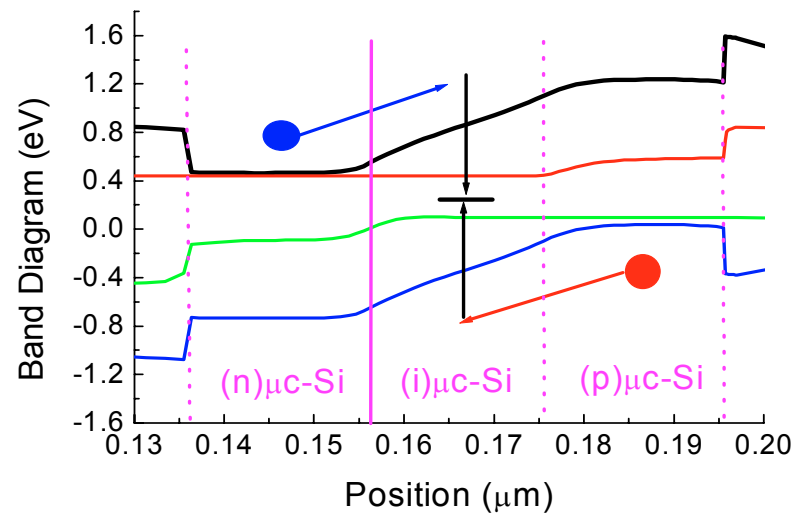
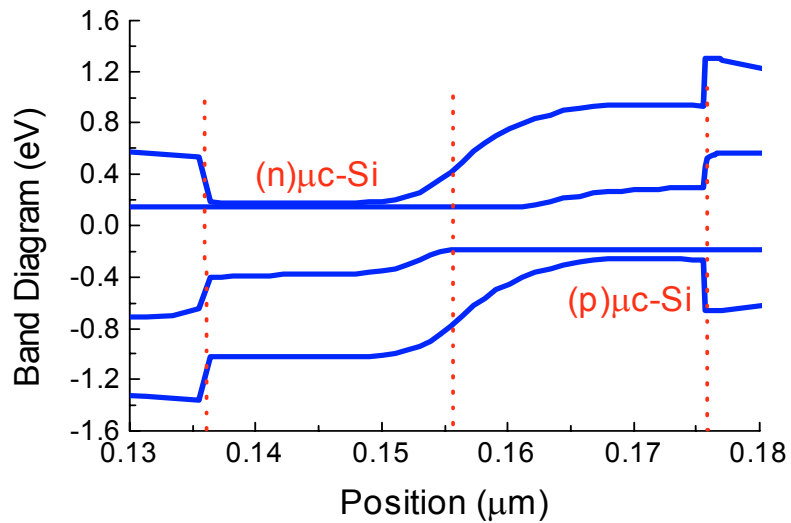
- The GR peak is sensitive to the asymmetry in the activation energies: 26 meV in n- $\mu\text{c-Si}$ and 59 meV in p- $\mu\text{c-Si}$

n-p $\mu\text{c-Si}$ TRJ

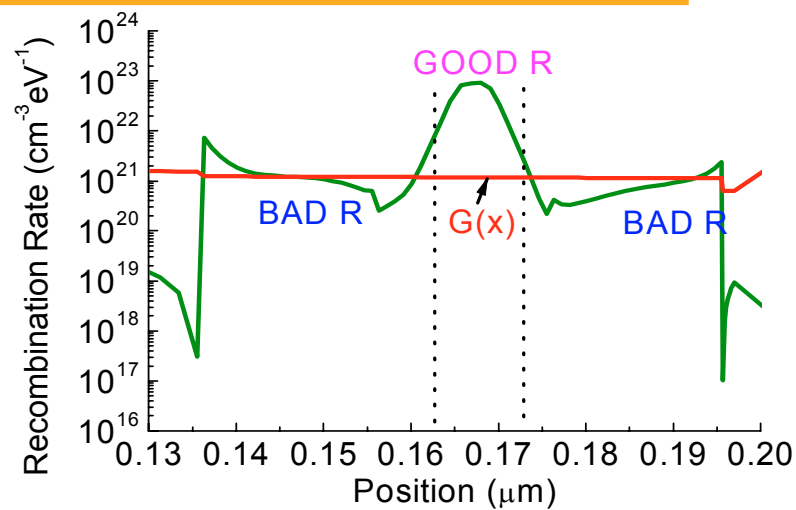
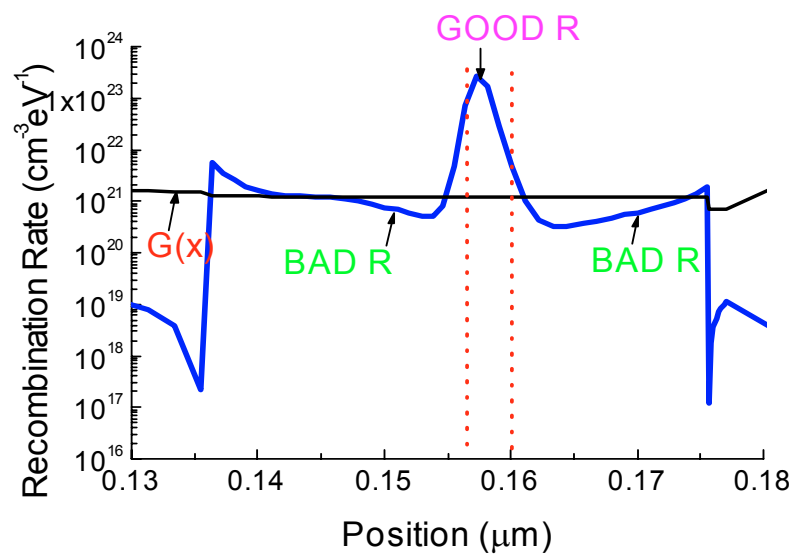
- The GR peak is approximately located where the Fermi level at thermodynamic equilibrium crosses mid-gap.
- The electric field in the TRJ of a good designed tandem solar cell is not significantly modified by light or voltage bias.
- Little dependence of V_{oc} with respect to n- $\mu\text{c-Si}$ and p- $\mu\text{c-Si}$ thicknesses (W_N and W_P) (W_N and $W_P \geq 20$ nm).
- Most of the recombination in $\mu\text{c-Si}$ layers are electrical losses.
- GR can be enhanced growing a thin oxide layer at the n- $\mu\text{c-Si}$ /p- $\mu\text{c-Si}$ interface. (~20-40 Å thick).
- Oxide modeled the by a thin, non-doped, and highly defective layer with nearly the $\mu\text{c-Si}$ mobility gap.
- Higher gaps \rightarrow Tunneling at constant energy is needed.

n-p vs. n-i-p $\mu\text{c-Si}$ TRJ

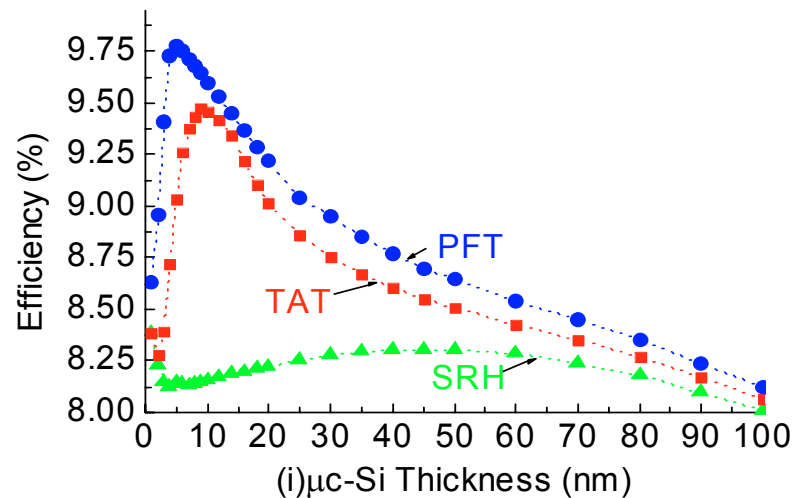
- A highly defective and low band-gap region enhances Good R shifting and pinning the Fermi level near mid-gap.
- The Good R peak moves towards the n/p interface where the high DB density favors R.
- The same effect can be introduced adding an **(i)- $\mu\text{c-Si}$** layer between the doped $\mu\text{c-Si}$ layers.
- This **(i)- $\mu\text{c-Si}$** layer forces the Fermi level to cross mid-gap inside this layer where there are high DB densities.
- At lower DB densities thicker (i)- $\mu\text{c-Si}$ layers will be required.
- In n- $\mu\text{c-Si}$ /i- $\mu\text{c-Si}$ /p- $\mu\text{c-Si}$ structures the Good R spreads over most of the intrinsic layer.



n-p vs. n-i-p



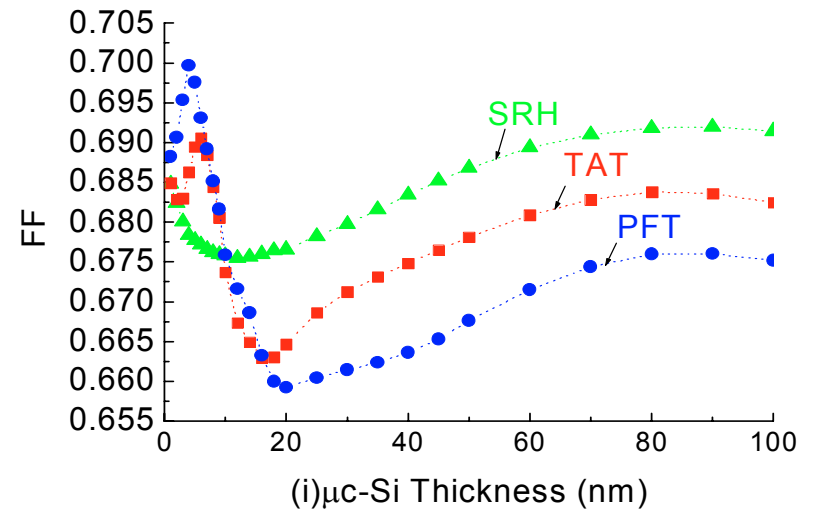
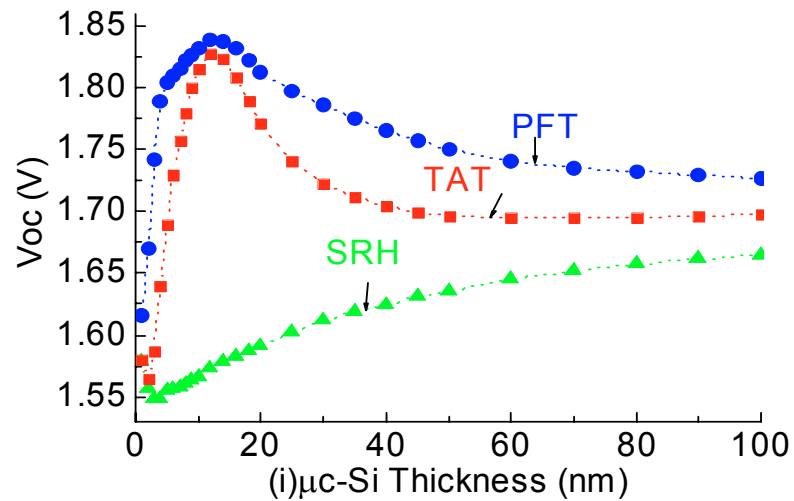
n-i-p $\mu\text{c-Si}$ TRJ $\eta(W_i)$



- DB density in $\mu\text{c-Si}$
 - Intrinsic layer $1.5 \times 10^{18} \text{ cm}^{-3}$
 - Doped layers $5.0 \times 10^{18} \text{ cm}^{-3}$
- Tail states do not contribute to recombination in $\mu\text{c-Si}$
- Thin i-layer can not host GR
- Thick i-layer → too much BR
- There is an optimum $W(I)$
- The SRH model predicts the highest efficiency when the (i) $\mu\text{c-Si}$ layer is removed (layers thinner than 10nm)

n-i-p $\mu\text{c-Si}$ TRJ

$V_{oc}(W_i)$ - FF(W_i)



J_{sc} slightly improves using the TAT and PFT

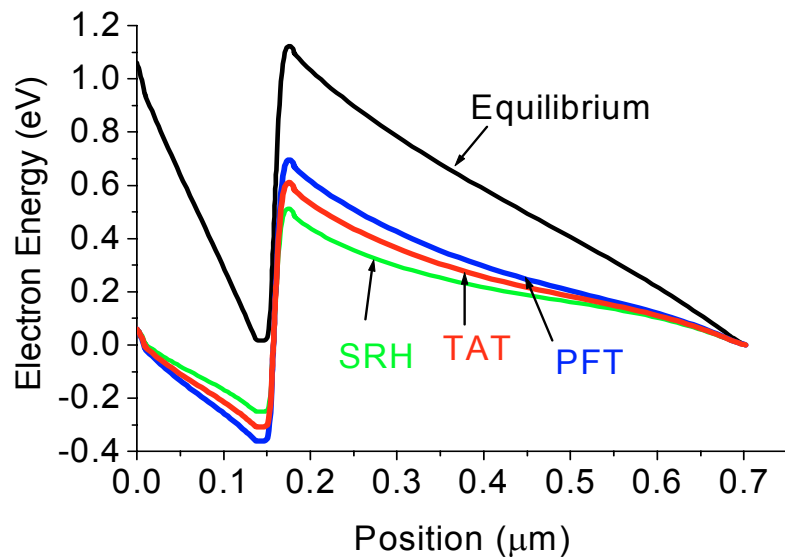
Ex: i- $\mu\text{c-Si}$ layer 5 nm thick

J_{sc} (mA/cm^2)

7.62 (SRH), 7.65 (TAT), and 7.67 (PFT).

Comparing TAT and SRH

- TAT enhances the predicted solar cell performance.
- With TAT the highest solar cell efficiency is obtained for cells with much thinner i- $\mu\text{c-Si}$ layers.
- Thinner (i)- $\mu\text{c-Si}$ layers increase F and enhance T(E).
- The maximum $\eta(\%)$ is obtained for i- $\mu\text{c-Si}$ thickness within 6-10 nm depending on the DB density present in i- $\mu\text{c-Si}$ (Lower DB densities \rightarrow Thicker i-layers).
- Thicker i- $\mu\text{c-Si}$ layers weaken F making tunneling less effective.
- For very thick i- $\mu\text{c-Si}$ layers, TAT and SRH predict the same efficiencies (we lose the electric field).



- With PFE + TAT (together) the best solar cell efficiencies are predicted at even thinner $i\text{-}\mu\text{c-Si}$ layers.

Energy potential profile at equilibrium and under AM1.5 light and $V = 1.0\text{V}$. The $i\text{-}\mu\text{c-Si}$ layer is 5nm thick.

Power loss in the TRJ

Power loss (mW/cm²) in the TRJ for different (i)- μ c-Si layer thicknesses (nm) at maximum power conditions

W(i) (nm)	2	5	10	20	30
SRH(mW/cm)	2.025	2.114	2.144	1.985	1.858
TAT(mW/cm ²)	1.964	1.067	0.826	1.212	1.413
PFT(mW/cm ²)	1.220	0.294	0.366	0.527	0.746

Advantages of n-i-p $\mu\text{c-Si}$ TRJ

- (n) $\mu\text{c-Si}$ -oxide-(p) $\mu\text{c-Si}$ is the conventional TRJ configuration used in a-Si tandem solar cells.
- However it is quite difficult to have control on the oxide thickness and on the DB density.
- Very thick oxide could prevent free electrons and holes from tunneling through.
- We have a better control on the electrical parameters of the (i) $\mu\text{c-Si}$ layer in a n-i-p($\mu\text{c-Si}$) TRJ configuration.
- We can control the DB density and thickness.

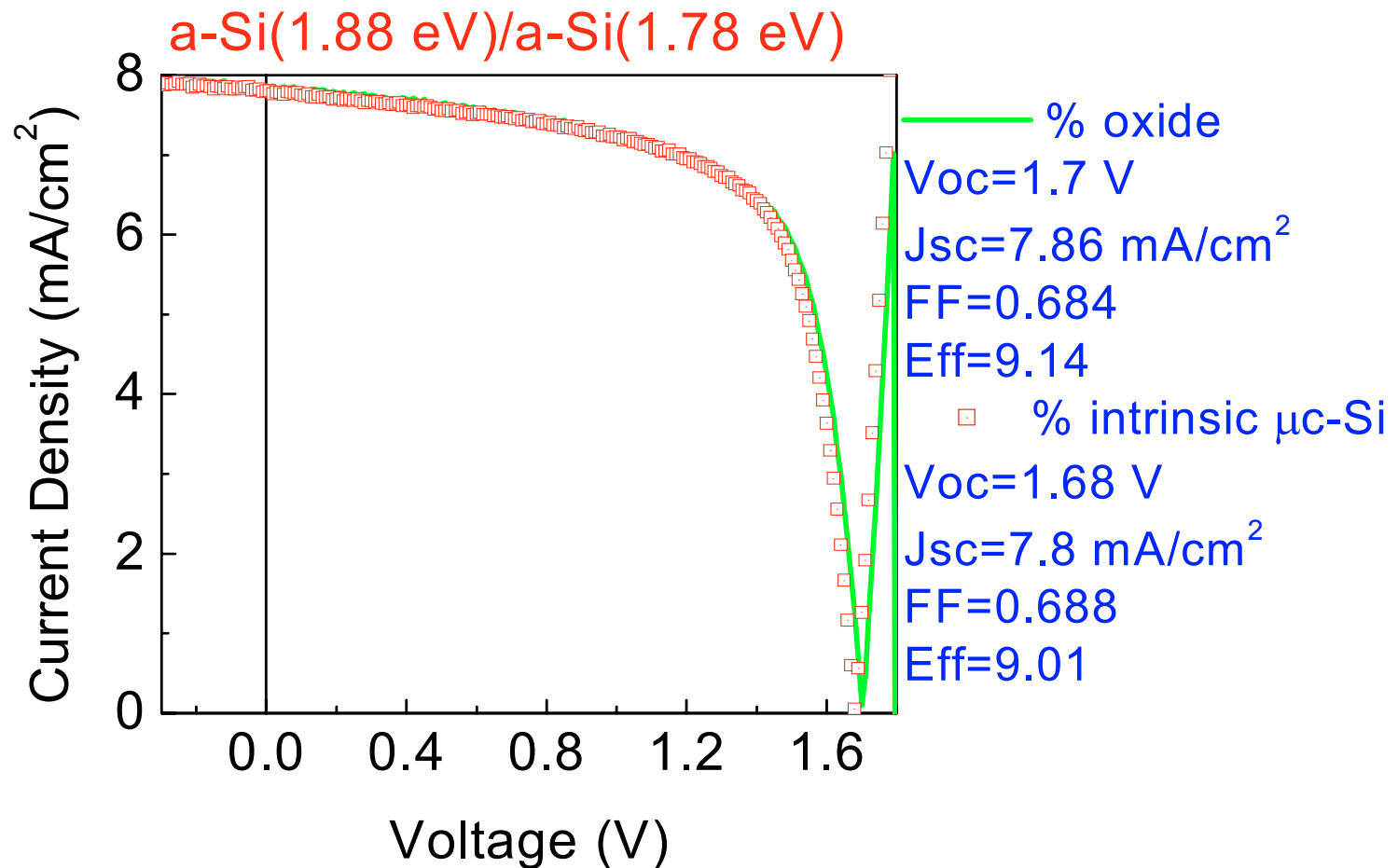
Tandem samples

- a-Si/a-Si tandem solar cells grown with PECVD.
- Superstrate: SnO₂/p-a-SiC/i-a-Si/n- μ c-Si/p- μ c-Si/i-a-Si/n-a-Si/Ag.
- a-Si tandem cell with μ c-Si n-p TRJ \rightarrow **10%** initial efficiency.
- Structural property of μ c-Si verified with XTEM micrograph.
- ERD analysis confirmed the presence of oxygen peaks at the interface before the n- μ c-Si layer and between the μ c-Si layers Bonded oxygen is not etched away due to the H plasma.
- Bonded oxygen in the μ c-Si layer increases the density of defects.
- Oxide treatment was done by CO₂ plasma at a low power (4W) to avoid damage or etching of the layer.

Comparing TRJ junctions

- In a-Si(1.88 eV)/a-Si(1.78 eV) tandem solar cells two structures were used:
- n- μ c-Si(20 nm)/i- μ c-Si(5 nm)/p- μ c-Si(20 nm).
- n- μ c-Si(20 nm)/Oxide/p- μ c-Si(20 nm).
- Oxide treatment before the n- μ c layer made on both TRJ.
- The light J-V curves of both tandem solar cells resulted very similar \rightarrow we had practically the same V_{oc} , J_{sc} , FF.
- The SR characteristics were also very similar.

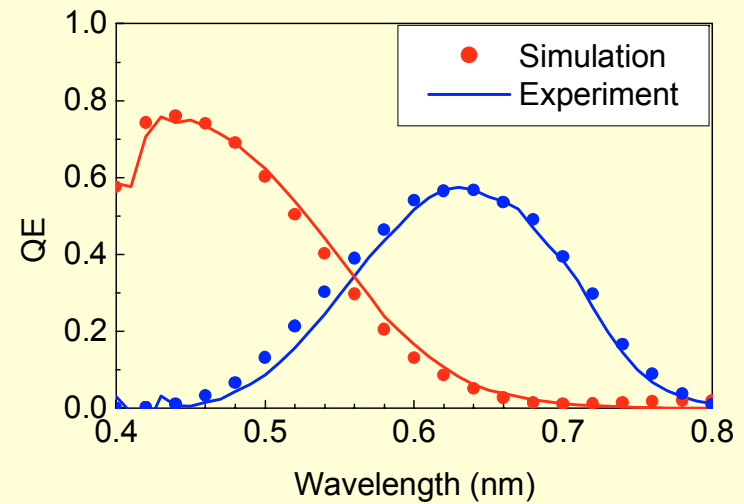
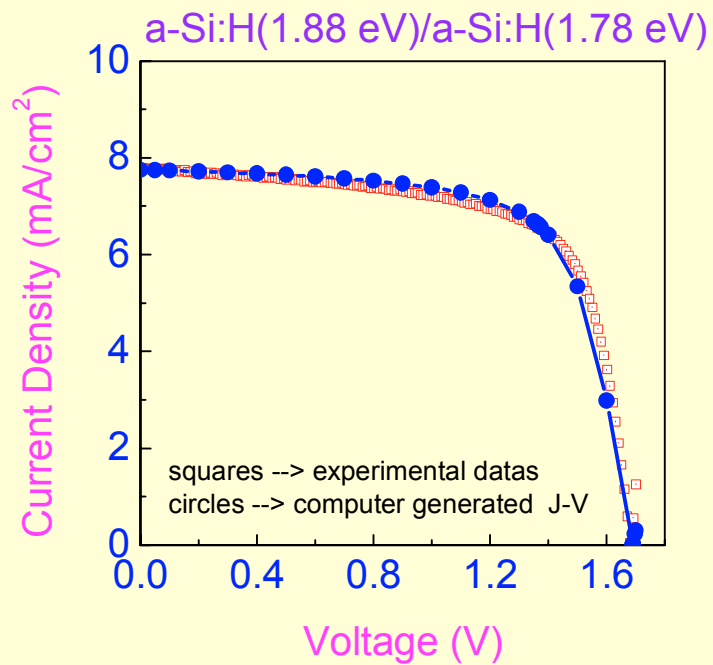
Comparing experimental J-V curves



First conclusions

- Thickness and deposition time of the intrinsic $\mu\text{c-Si}$ layers can be carefully controlled to achieve consistent results.
- Studies on three thicknesses (2.5 nm, 5 nm, 10 nm) revealed that the efficiency peaked at 5 nm in conformity with the predicted trends.
- These results give a direct confirmation to our modeling results and they are an indirect confirmation of the assumptions made in modeling the oxide layer.

Fitting J-V and SR curves



Fittings and sensitivity studies

- The light J-V and the bias light QE of tandem solar cells with a 5 nm thick i- μ c-Si were matched (n-i-p TRJ) using a DB density in the i- μ c-Si layer of.

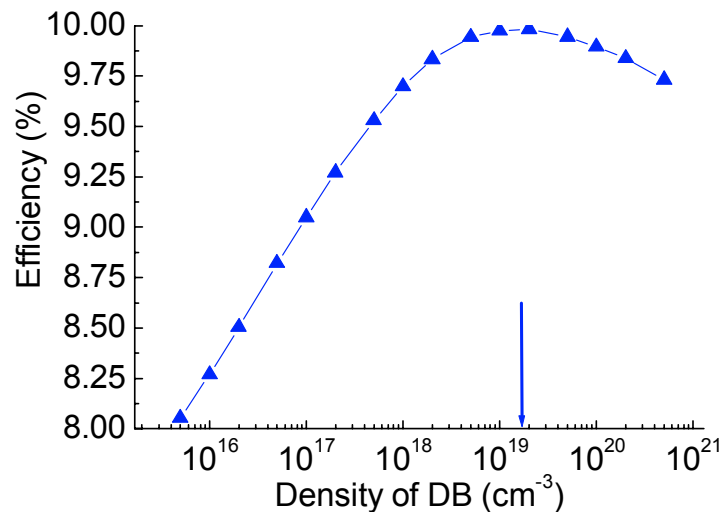
PFT $\rightarrow 1.0 \times 10^{17} \text{ cm}^{-3}$ (PFE+TAT).

TAT $\rightarrow 1.5 \times 10^{18} \text{ cm}^{-3}$.

SRH $\rightarrow 1.3 \times 10^{19} \text{ cm}^{-3}$.

- For a tandem solar cell having an n-oxide-p TRJ fittings are achieved with a DB density of $2.5 \times 10^{18} \text{ cm}^{-3}$ when the oxide is 2 nm thick (PFT model).

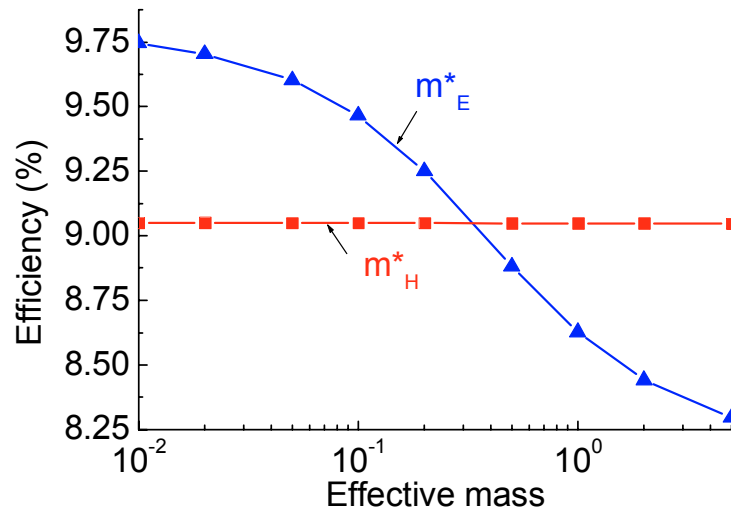
$\eta(\text{tandem})$ vs. DB density in (i)- $\mu\text{c-Si}$



Thickness of the (i)-layer= 5nm
PFT model

- Very high DB densities distort and could even collapse F in the i- $\mu\text{c-Si}$ layer bulk reducing T(E).
- **Rule:** the product.
DB density x W(i- $\mu\text{c-Si}$) that gives rise to the maximum efficiency in tandem solar cells is almost constant.

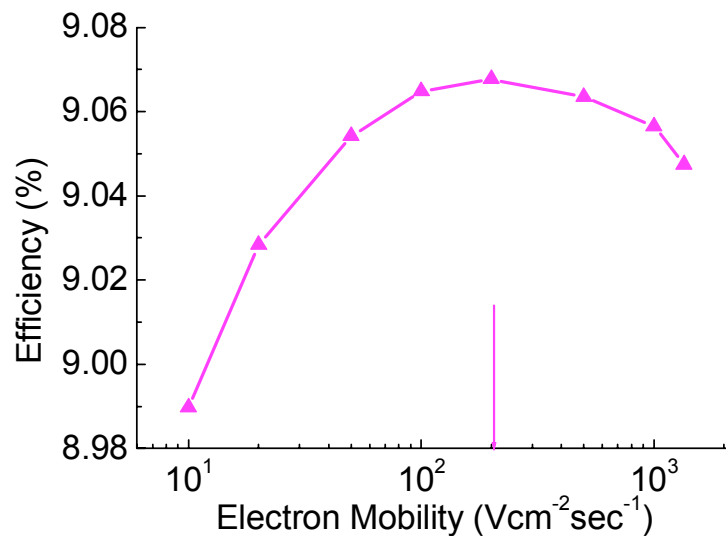
$\eta(\text{tandem})$ w.r.t. Effective masses in (i)- $\mu\text{c-Si}$



Thickness of the (i)-layer= 5nm
DB density= 10^{17}cm^{-3} (PFT)

- The lower activation in n- $\mu\text{c-Si}$ places the Good R peak closer to the i/p than to the n/i interface \rightarrow the barrier to be tunneled by electrons (holes) is thicker (thinner).
- The electron supply is limiting the Good R $\rightarrow \eta(\text{tandem})$ is a strong function of m^*_E .
- When the activation energies in n- and p- $\mu\text{c-Si}$ are exchanged $\eta(\text{tandem})$ is a strong function of m^*_H .

η (tandem) vs. mobilities in (i)- μ c-Si



Thickness of the (i)-layer= 5nm
DB density= 10^{17}cm^{-3} (PFT)

- The ratio electron-hole mobility is kept 10 (except for the highest mobility corresponding to c-Si free carrier mobilities).
- Higher mobilities on both doped μ c-Si layers in conjunction with higher mobilities in i- μ c-Si do not result in better solar cell performances.

Limitations of our PFT model

V_{oc} , FF and η for different E_G ($\mu\text{-Si}$). The DB density is $1.0 \times 10^{17} \text{ cm}^{-3}$.
Last row \rightarrow DB density needed to have $\eta = 9.02\%$ for different E_G ($\mu\text{-Si}$)

Gap (eV)	1.20	1.25	1.30	1.35	1.40	1.45	1.50
V_{oc} (V)	1.690	1.652	1.632	1.603	1.574	1.538	1.496
FF	0.689	0.686	0.681	0.674	0.666	0.657	0.648
Efficiency	9.021	8.775	8.604	8.367	8.117	7.824	7.505
DB (cm^{-3})	1.0×10^{17}	2.5×10^{17}	5.0×10^{17}	1.75×10^{18}	$5.0 \times 10^{18*}$	-	-

(*) The efficiency achieved for E_G ($\mu\text{-Si}$) = 1.4eV was 8.99
 J_{sc} does not change much with E_G ($\mu\text{-Si}$)

E_G (i)- $\mu\text{-Si}$ can not be higher than 1.4eV

Non – uniform $\mu\text{c-Si}$ properties

- Raman spectroscopy \rightarrow thin layers of $\mu\text{c-Si}$ grown on a-Si have non-uniform electrical and optical properties.
- First few nm show an amorphous character.
- Above $\sim 40\text{-}50$ nm a fully crystalline phase is achieved.
- Most important features of the kinetics and transport physics of $\mu\text{c-Si}$ TRJ can still be captured assuming that $\mu\text{c-Si}$ layers with uniform electrical properties.
- Using non-uniform electrical properties we also observe that the peak of Good R is located in the doped layer with the higher activation energy.
- Recombination (bad and good) goes mainly through the regions where the $\mu\text{c-Si}$ mobility is minimum.
- V_{oc} becomes more a function of doped layer thicknesses.
- TAT and PFT models predict that the highest tandem solar cell efficiencies are achieved for intrinsic $\mu\text{c-Si}$ layers with few nm.

Conclusions

- Tandem solar cells $\text{SnO}_2\text{:F/p-a-SiC/i-a-Si/TRJ/i-a-Si/n-a-Si/Ag}$ were modeled and made with two different TRJ structures:
(a) n- $\mu\text{c-Si/oxide/p-}\mu\text{c-Si}$ and (b) n- $\mu\text{c-Si/i-}\mu\text{c-Si/p-}\mu\text{c-Si}$.
- Modeling and experiments confirmed that physical properties of the oxidized $\mu\text{c-Si}$ interface and of a highly defective (i) $\mu\text{c-Si}$ layer are similar.
- Comparable efficiencies can be reached with either TRJ.
- We found an alternative and more reproducible method to make TRJ
→ using an intrinsic silicon interface layer.
- The experimental tandem solar cell efficiency depends strongly on the (i) $\mu\text{c-Si}$ layer thickness in agreement with the predictions of TAT or PFT models.
- The experimental tandem illuminated J-V characteristics can not be successfully fitted for $E_G(\mu\text{c-Si}) > 1.4$ eV.

D-AMPS - ASPIN

- PFT was integrated in ASPIN and in D-AMPS. Hurkx's Tunnelling + Poole Frenkel Effect.
- Based on analytical functions that due to suitable approximations depends on local variables only.
- Only one new independent parameter - the effective tunnelling mass (m_{tun}) is introduced.
- Capture cross sections (σ) and emission coefficients of trap states become field-dependent and they are enlarged for more intense fields.
- PFT converges to SRH equations when the electric field approaches zero.

What about TRJ with $E_G > 1.4\text{eV}$?

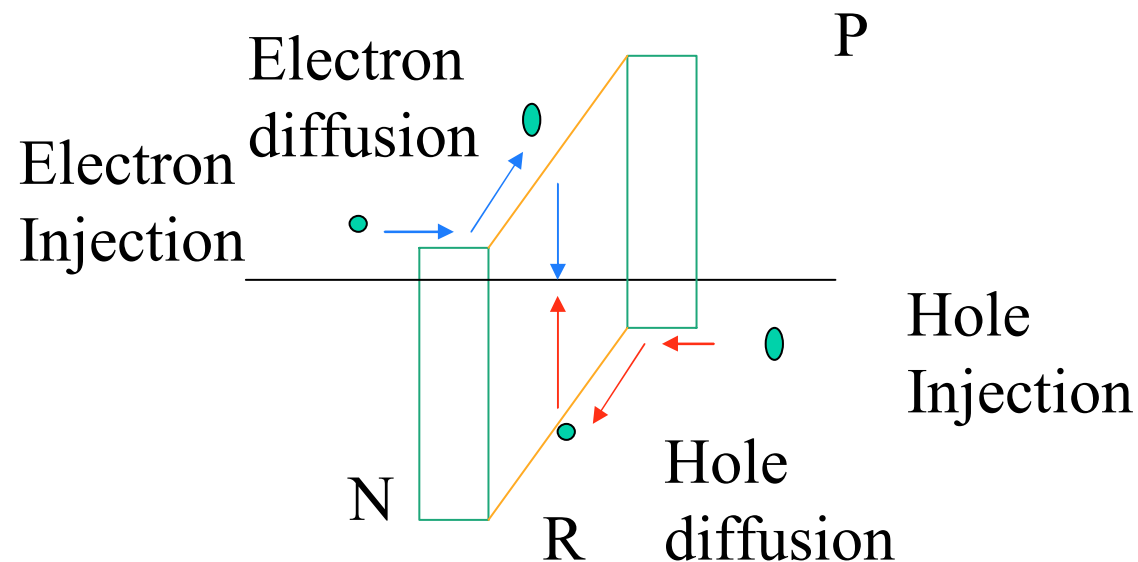
- Willemen et al. (Delft Univ.) could fit light J-V curves of a-Si based tandem solar cells where the TRJ has mobility gaps between 1.7 and 2.0 eV.
- They implemented Hurkx's TAT mechanism and established that it was not enough to match the experimental V_{OC} .
- V_{OC} could be reproduced by making the extended state mobilities to increase with the electric field F .
- $\mu_{eff} = \mu_0 \exp(F/F_0) \rightarrow$ Enhanced Field Mobilities (EFM).
- F_0 is a free parameter that determines the magnitude of the dependence with respect to the electric field strength.
- Only when TAT and EFM are simultaneously applied, the experimental J-V curves could be matched.
- Their mobilities were calculated only at thermal equilibrium and they were assumed temperature independent.

General considerations

- In tandem cells the TRJ is a forward biased n-p or n-i-p.
- The voltage drop over the TRJ junction has to be very small (not higher than 0.05 V in a-Si/a-Si tandem solar cells to have efficiencies over 10%).
- Using SRH in TRJ we predict current levels from 2×10^{-7} mA/cm² to 5×10^{-6} mA/cm² at 0.05 V ($J_{sc} \sim 8$ mA/cm²).
- Hegedus et al. reported experimental J-V curves of several TRJ with currents from 1 mA/cm² to 3 mA/cm² at 0.05 V.
- Calculated current levels have to be increased by seven orders of magnitude ?? → we have to include an extra transport mechanism to enhance recombination.
- Computer J-V curves of n-p and n-i-p TRJ are rectifying.
- Measured J-V of TRJ show similar current levels for reverse and for forward voltages ???.

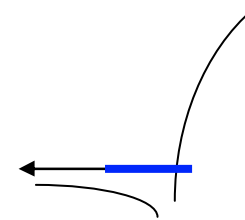
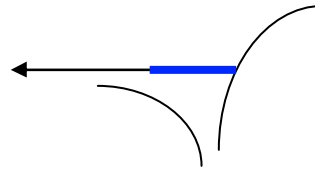
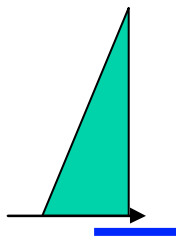
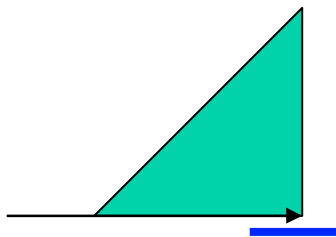
Electric transport in TRJ

- In single TRJ junctions electrons (holes) injected into the n-layer (p-layer) move by diffusion against the field. They cannot surmount the built-in potential and recombine
- The dark current supply is not limited by doped layer conductivities or by contacts under normal conditions → recombination or diffusion is limiting??



TAT and PFE

- **TAT** capture cross sections and emission coefficients are field-dependent. Strong electric fields ($F > 10^4$ V/cm) increase transparency of potential barriers for tunnelling. **Recombination is enhanced**
- **PFE** effective cross sections of charge defects only are field-dependent. They are enhanced by the factor $E_H = \exp(\Delta E_l/kT)$ where $\Delta E = q \sqrt{qF/\pi\epsilon}$ (\sim image lowering). **Recombination is enhanced**



Gu's model

- The attempt-to-escape frequency is assumed field-dependent:

$$\nu = \nu_0 \exp(F/F_0).$$

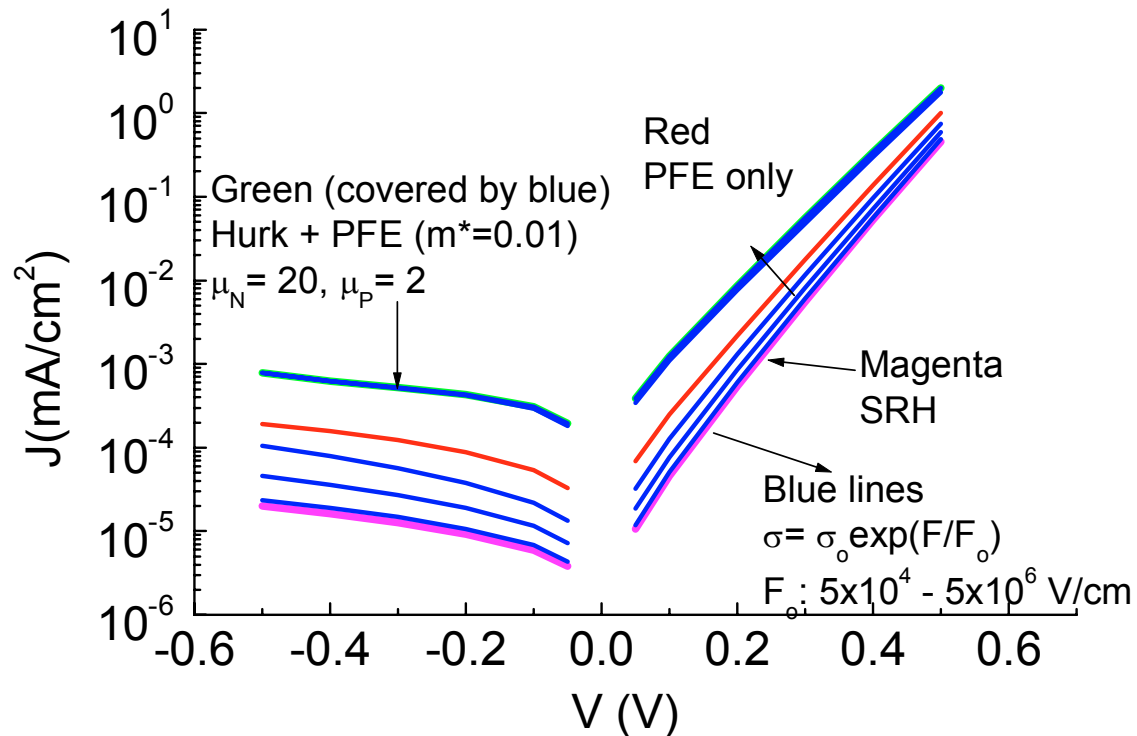
- This is equivalent to assume that.
 - $\sigma(F) = \sigma_0 \exp(F/F_0)$ all cross sections.
 - $N_C = N_{C0} \exp(F/F_0)$ and $N_V = N_{V0} \exp(F/F_0)$.

First we assume $\sigma(F) = \sigma_0 \exp(F/F_0)$ only (CSE).

Recombination will be enhanced with CSE (as in PFT).

First TRJ under analysis \rightarrow n-p⁺-p (a-Si/a-Si/a-SiC).

n-p⁺-p (a-Si/a-Si/a-SiC) dark J-V



Dark J-V characteristics of the n-p⁺-p (a-Si/a-Si/a-SiC) TRJ obtained with different models enhancing the capture cross sections and emission coefficients

Limitations of our modeling

- Pushing simulation to the limit.

TAT → lowering m^* .

PFE → charged and neutral traps are F dependent.

CSE → lowering F_0 .

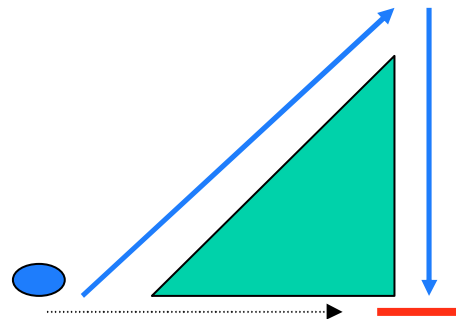
We increase the forward and the reverse currents.

The total current in the $n-p^+-p$ (a-Si/a-Si/a-SiC) TRJ goes up to 4×10^{-4} mA/cm² at 0.05 V.

- The current cannot be increase further by decreasing F_0 below 5×10^4 V/cm.
- **J-V curves remain rectifying!!**
 - contradiction with measurement results.
 - It is not just a matter of increasing recombination!!

Why can we not reach the experimental current levels?

- In all of these models (SRH, TAT, PFE, and CSE) we are really working on a single grid point.
- There is no connection between the regions where the recombination is maximum and the regions where free carrier concentrations are high.
- Recombination is enhanced for increasing electric fields but electrons and holes still have to move to the physical position where recombination is taking place.

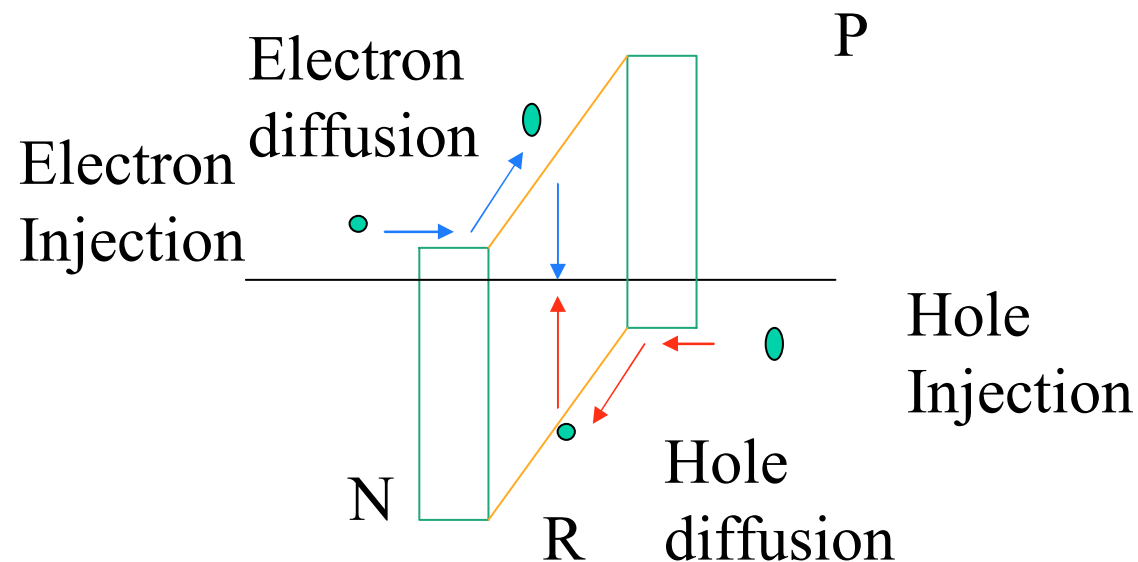


Field enhanced mobilities

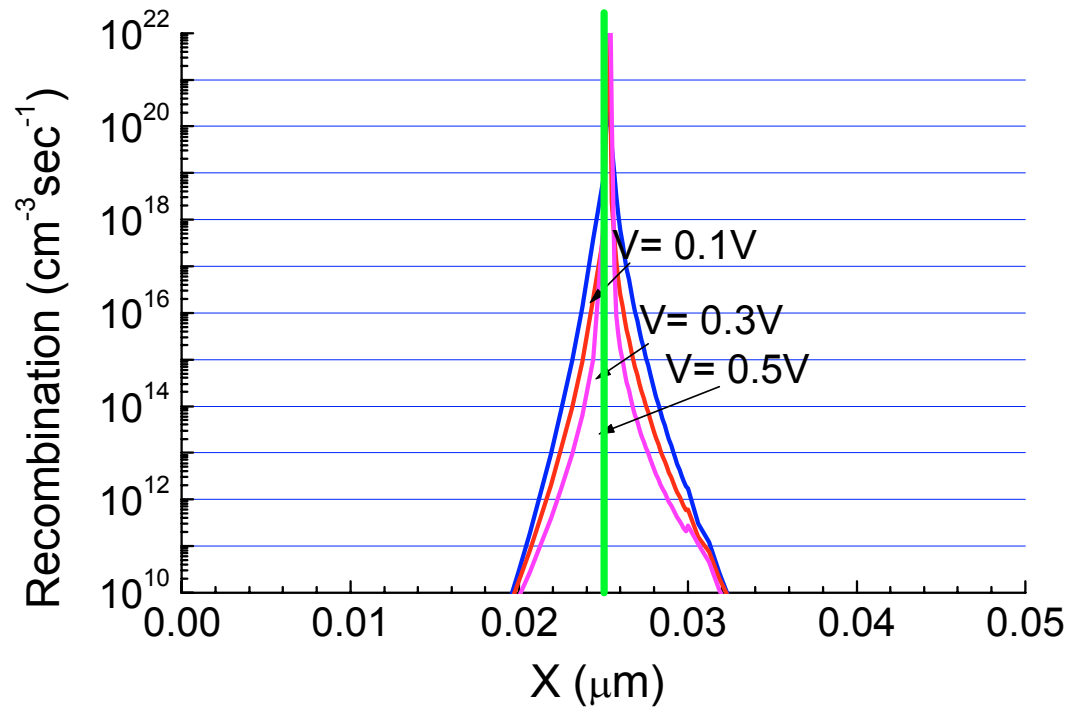
- The increase of free carrier mobilities helps diffusion of majority free carriers against the electric field to the region where they actually recombine (J. A. Willemen Ph. D. thesis).
- The same conclusions were drawn for D-AMPS and for ASPIN. Enhancement of extended state mobilities eases the charge flow.
- Total current does not change increasing mobilities in the n-type (a-Si) and p-type (a-SiC) layers near the front and back contacts (n-a-Si/p-a-SiC structure).
- The total current rises when mobilities are increased within the region where R reaches 10^{-3} of its peak value.

Diffusion transport in TRJ

- Single TRJ junctions electrons (holes) injected into the n-layer (p-layer) move by diffusion against the field.
- Higher mobilities helps the barrier climbing.
- The dark current supply is not limited by the bulk mobilities of doped layers.
- The dark current supply is limited by the mobilities present in the regions near where the Good R peak is formed.



Recombination in n-p (a-Si/a-SiC, 25/25 nm)



Recombination rates (R) in a n-p (a-Si/a-SiC, 25nm / 25 nm) TRJ for different forward biases.
The vicinity of the metallurgic junction is shown
 $R < 10^{12}\ \text{cm}^{-3}\text{s}^{-1}$ elsewhere

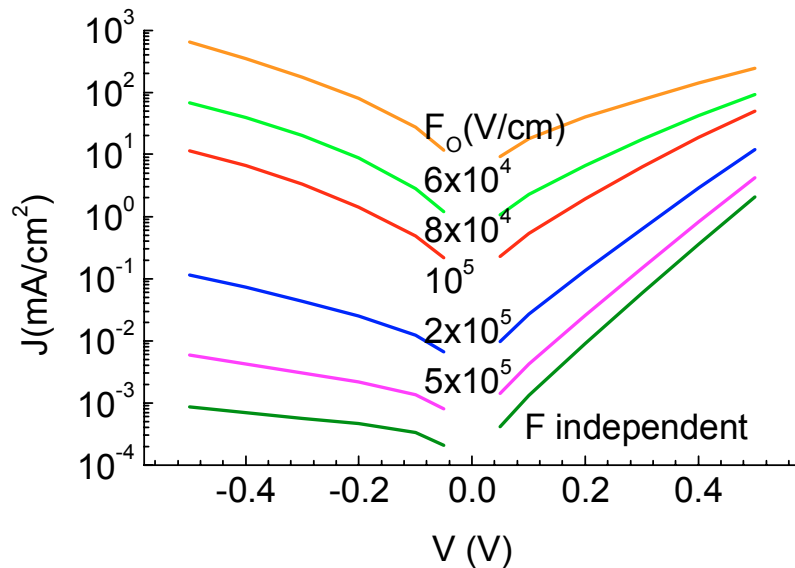
Diffusion currents

- μ_N ($\sim 20 \text{ cm}^2/\text{V}/\text{s}$) and μ_P ($\sim 2 \text{ cm}^2/\text{V}/\text{s}$).
- Enlarging $\mu_N - \mu_P$ by $\mu_N \times \text{Fac} - \mu_P \times \text{Fac}$ in the whole TRJ:
 $J \rightarrow J \times \text{Fac}$ in the voltage range (-0.3V, +0.3V) \rightarrow electron and hole diffusion currents are increased.
- For $\text{Fac} > 10^5$ contacts or doped layer conductivities could start limiting J .
- Experimental evidence: conductivity and drift mobility in a-Si exponentially increase with the electric field F .
- Transport in TRJ is by diffusion (but mobilities and diffusion coefficients are connected by Einstein's relation).

Refining Willemens' model

- Willemen assumed that both **extended state electron and hole mobilities** are exponentially dependent on F as $\mu(F) = \mu_0 \exp(F / F_0)$ (FDM).
- Willemen's uses the electric field $F = F_{TE}$ at thermal equilibrium, i.e. $\mu(F_{TE}) = \mu_0 \exp(F_{TE} / F_0)$.
- We implemented a similar model but recalculating mobilities for each grid point "x", voltage V and iteration: $\mu(F)$ takes into account the real field F .
- The feedback effect of the FDM model in the device properties was not neglected.

n-p⁺-p (a-Si/a-Si/a-SiC) dark J-V



Dark J-V obtained in the n-p⁺-p (a-Si/a-Si/a-SiC) TRJ using the expression

$$\mu = \mu_0 \exp(F(V,x) / F_0)$$

(FTM model) for different values of F_0

$J \sim 3 \text{ mA/cm}^2$ ($V = 0.05 \text{ V}$, Hegedus) $\rightarrow F_0 \leq 8 \times 10^4 \text{ V/cm}$.

- The dark J-V curve is practically Ohmic as the experimentally observed J-V (at $F_0 \leq 8 \times 10^4 \text{ V/cm}$).

Five TRJ structures were studied

- 1) n-p⁺-p (a-Si/a-Si/a-SiC).
- 2) n-p (a-Si/a-SiC).
- 3) n-p⁺-p (μ c-Si/a-Si/a-SiC).
- 4) n-i-p (μ c-Si/ μ c-Si/ μ c-Si) and
- 5) n-p (μ c-Si/ μ c-Si).

Uncertainty in μ c-Si electrical parameters.

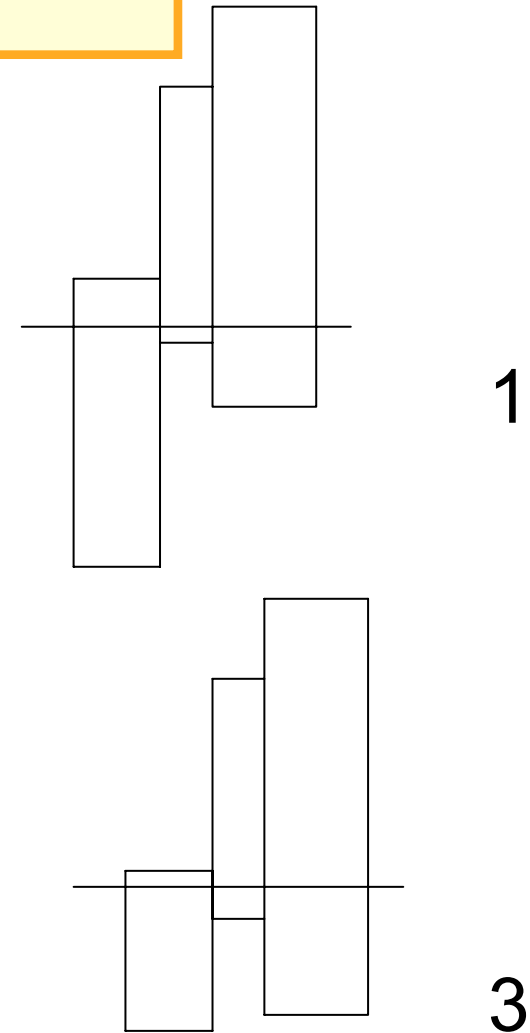
→ two different set of inputs are used.

more defective material.

(high DB density, steep tails).

less defective material.

(low DB density, wide tails) .



Simulation parameters of the five TRJ structures

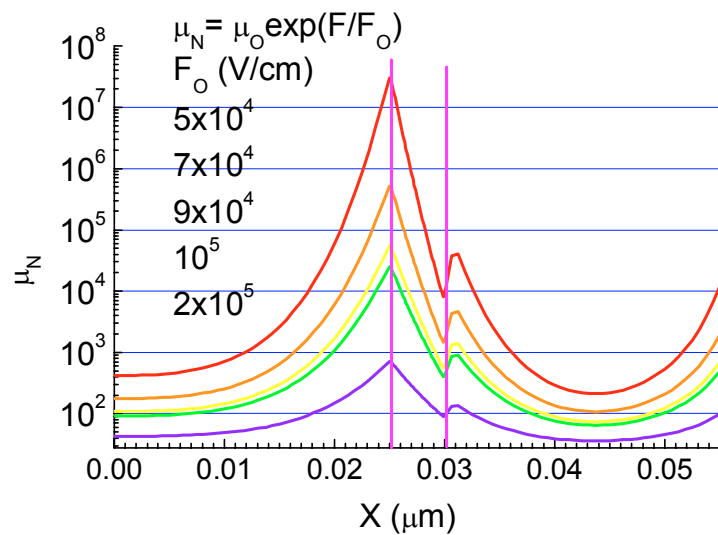
	n (a-Si)	p ⁺ (a-Si)	p (a-SiC)	n (μ c-Si)	i (μ c-Si)	p (μ c-Si)
Thickness (nm)	25	10*	25	20	5	20
Activation energy (eV)	0.27	0.2*	0.47**	0.026	0.73	0.059
Mobility Gap (eV)	1.76	1.72	1.98	1.54	1.54	1.54
DB density (cm ⁻³)	5x10 ¹⁸	6x10 ¹⁸	5x10 ¹⁸	5x10 ¹⁸ 5x10 ¹⁶	1.5x10 ¹⁸ 5x10 ¹⁵	5x10 ¹⁸ 5x10 ¹⁶
Tail slope E _a /E _d (meV)	30/50	40/60	45/80	10/10 20/30	10/10 20/30	10/10 20/30
G _{do} , G _{ao} (cm ⁻³ eV ⁻¹)	10 ²¹	10 ²¹	10 ²¹	2x10 ²⁰ 10 ²¹	2x10 ²⁰ 10 ²¹	2x10 ²⁰ 10 ²¹
Mobilities (cm ² /Vs)	20/2	20/2	20/2	40/4	40/4	40/4

Band offsets half - half conduction and valence bands.
Tunnelling effective mass = 0.01m_e.
Flat band conditions at both contacts

Built-in potentials of TRJs and Potential barriers at each interface

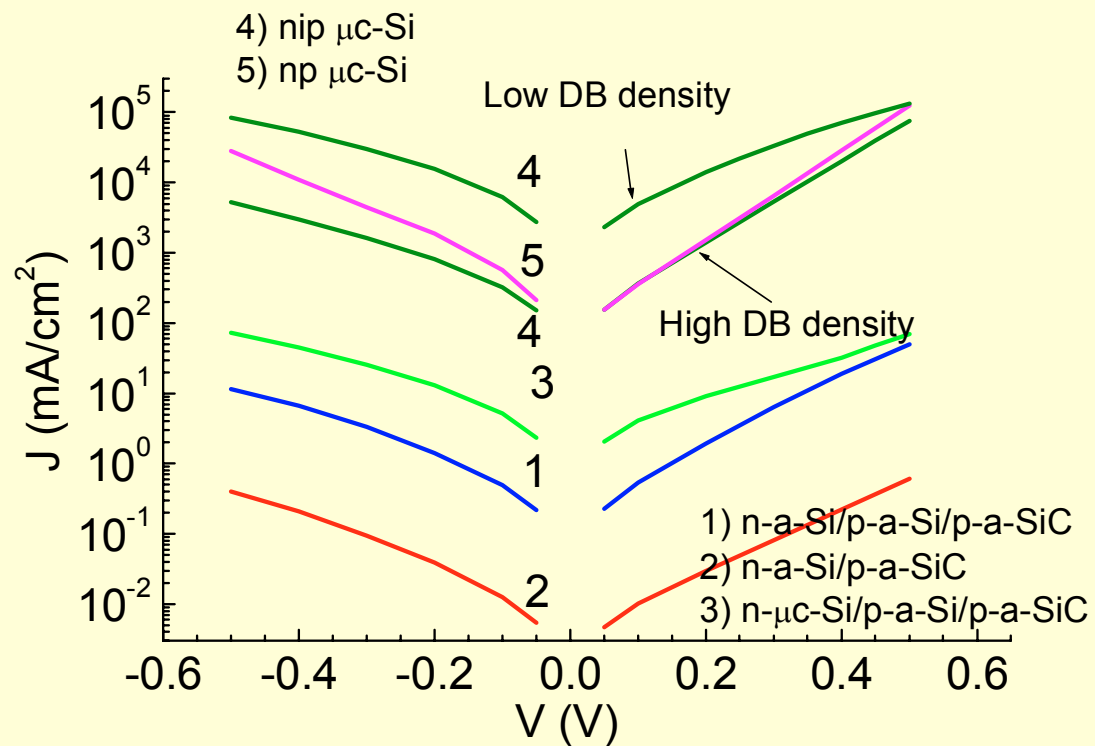
	1	2	3	4	5
Structure	n-p ⁺ -p	n-p	n-p ⁺ -p	n-i-p	n-p
Materials	a-Si/a-Si/a-SiC	a-Si/a-SiC	μc-Si/a-Si/a-SiC	μc-Si	μc-Si
Overall V _{BI} (eV)	1.1	1.1	1.244	1.455	1.455
Left V _{BI} (eV)	1.29		1.424	0.77	
Right V _{BI} (eV)	-0.18		-0.18	0.685	

Similarities and differences



- First two structures
- Same total V_{BI}
- Different F profiles reinforced at n-p+ weakened at p-p
- Differences between the F profiles of structures (1) and (2) are minor in comparison to the F profiles of other 3 structures where V_{BI} is higher

Dark J-V of the five TRJ under study



Limiting mechanisms

Simulations - Experiments

- In the five TRJ (assuming HD_{μc} layers) the same mechanism is limiting the total current: diffusion against the electric field.
- Free carrier concentrations and low mobilities are the bottlenecks.
- Hole diffusion is limiting more than electron diffusion.
- Computer trends obtained for the J-V (TRJ) agree with experimental results (in the first 3 TRJ studied by Hegedus).
The same value of F_0 was used ($\sim 10^5$ V/cm).
- The quantitative reproduction of Hegedus' J(TRJ) requires of certain dispersion in F_0 .
- 8×10^4 V/cm n-p⁺-p (a-Si/a-Si/a-SiC),
- 5.5×10^4 V/cm n-p (a-Si/a-SiC),
- 1×10^5 V/cm n-p⁺-p (μc-Si/a-Si/a-SiC) .

Comments on our results

- We have assumed E_A (p-a-SiC)= 0.47 eV
- TRJ performance can be improved by lowering E_A (p-a-a-SiC) to 0.33 eV and Hegedus' measurement can be matched with lower activation energy (0.33 eV) with minor changes in the parameter F_0 :
- 8×10^4 V/cm in n-p⁺-p (a-Si/a-Si/a-SiC)
- 1×10^5 V/cm in n-p (a-Si/a-SiC)
- 1×10^5 V/cm in n-p⁺-p (μ c-Si/a-Si/a-SiC)
- In n-i-p (μ c-Si/ μ c-Si/ μ c-Si) and n-p (μ c-Si/ μ c-Si) TRJ our simulation predicts higher total currents due to the larger supply of free holes provided by the p (μ c-Si) layer compared to the p (a-Si) layer

Comparing different TRJ in a-Si/a-Si tandem cells

- a-Si/a-Si with mobility gaps of 1.88 eV and 1.78 eV produced, characterised, and modelled at UU.
- Achieved experimental efficiency above 9%.
- TRJ used: n-i-p ($\mu\text{c-Si}$) or n-ox-p ($\mu\text{c-Si/oxide}/\mu\text{c-Si}$).
- The $\mu\text{c-Si}$ mobility gap was initially adopted 1.2 eV.
- Effective m^* = extended state effective mass of c-Si.
- Lowering m^* to $0.01 m_e$ tandem solar cell efficiencies up to 10 % can be simulated with $E_G(\mu\text{c-Si}) = 1.2$ eV.
- $E_G(\mu\text{c-Si})$ was increased to 1.54 eV.
- Field-dependent mobility physics requested a new optimisation of the TRJ intrinsic layer thickness.

a-Si/a-Si tandem solar cell η for different TRJ and F_0

F_0 (V/cm)	Tandem solar cell efficiency (%) with respect to the TRJ used				
	¹ n-p (HD _{μc})	¹ n-p (LD _{μc})	¹ n-i-p (HD _{μc})	¹ n-i-p (LD _{μc})	² n-p ⁺ -p (LE _a)
8×10^4	11.46	11.62	11.45	11.57	11.40
1×10^5	11.45	11.62	11.43	11.57	11.32
5×10^5	9.52	9.87	9.25	9.70	8.59
1×10^6	9.20	9.27	8.96	9.27	8.30
FTM off	8.87	8.74	8.68	8.87	8.04

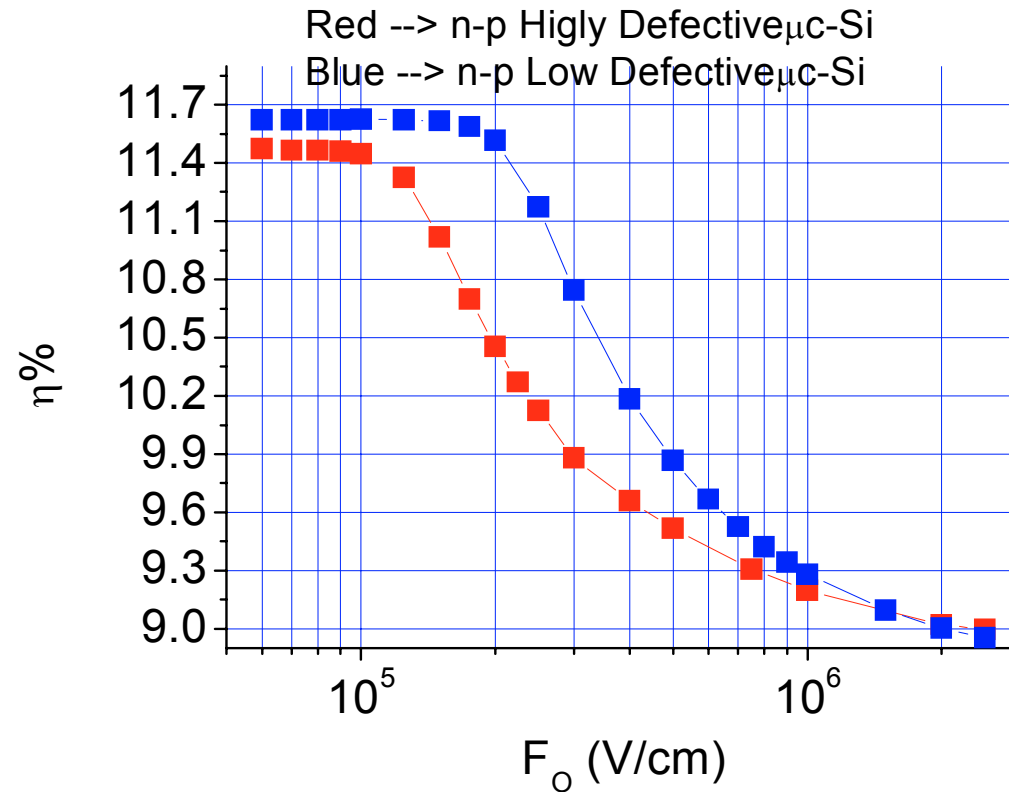
F_0 (V/cm)	Tandem solar cell efficiency (%) with respect to the TRJ used				
	² n-p ⁺ -p (HE _a)	³ n-p ⁺ -p (HE _a)	³ n-p ⁺ -p (LE _a)	³ n-p (HE _a)	³ n-p (LE _a)
6×10^4	9.98	8.05	9.40	5.58	8.33
8×10^4	9.75	7.21	8.53	5.20	7.38
1×10^5	9.17	6.93	8.10	5.03	6.96
5×10^5	7.31	6.03	6.86	4.61	6.03
1×10^6	7.11	5.91	6.74	4.57	5.88
FTM off	6.95	5.80	6.63	4.52	5.86

- ¹ all layers made of $\mu\text{c-Si}$ (either HD_{μc} or LD_{μc})
- ² n made of $\mu\text{c-Si}$, p⁺ of a-Si, p of a-SiC (either HE_a or LE_a)
- ³ n and p⁺ made of a-Si, p of a-SiC (either HE_a or LE_a)

Results

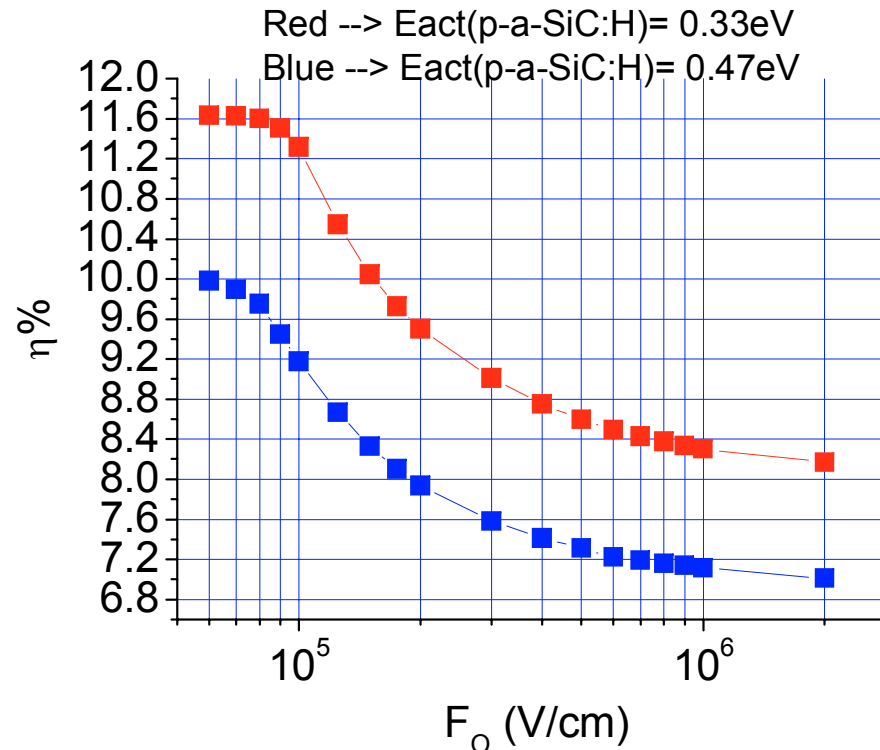
- The highest η were obtained with TRJ made entirely of $\mu\text{c-Si}$.
- The η of these tandem cells saturate for F_0 lower than 10^5 V/cm.
- For low F_0 free carriers can easily diffuse to recombine.
- FF is strong function of F_0 .
- J_{SC} and V_{OC} change very little with respect to F_0 .
- The optimum (i) $\mu\text{c-Si}$ thickness is independent of the DB density for low values of F_0 .
- Inspecting the experimental achieved efficiencies we can only say that F_0 should be lower than 5×10^5 V/cm.
- The dependence of the tandem solar cell η w.r.t F_0 can be neglected only for very high values of F_0 ($>10^6$ V/cm).

Tandems with n-p and n-i-p ($\mu\text{c-Si}$) TRJ



- When the n-p and the n-i-p ($\mu\text{c-Si}$) TRJ are described with low values of F_0 ($< 10^5$ V/cm) the top and bottom cells limit the carrier supply and the TRJ no longer influences the solar cell η .

Tandems with n-p⁺-p (μ c-Si/a-Si/a-SiC) TRJ



All the parameters (V_{OC} , FF, and J_{SC}) result lower in tandem cells where the p-a-SiC activation energy is higher (0.47eV).

We do not reach the 10 % efficiency mark even for very low values of F_0

We get better results when the p-a-SiC activation energy is 0.33 eV.

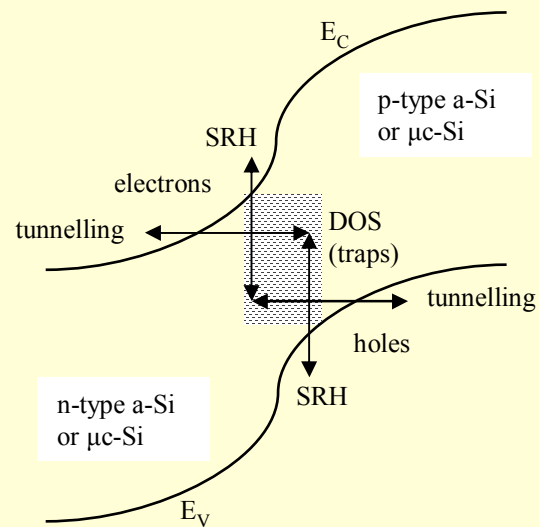
Tandem solar cells

Final Comments

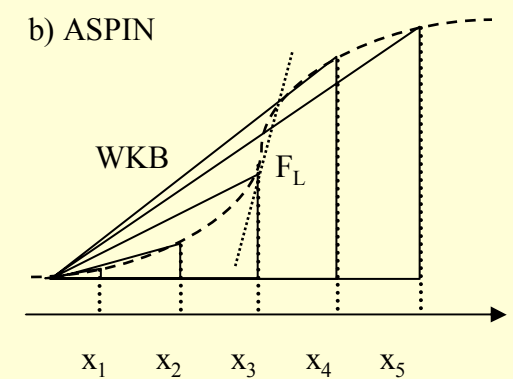
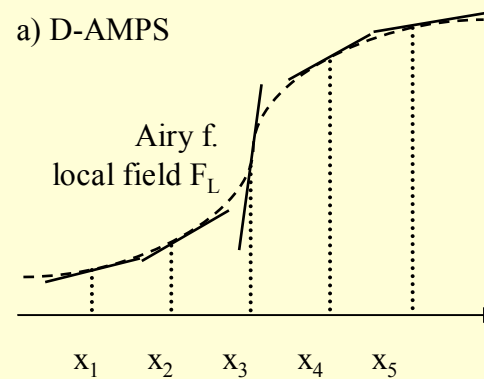
- a-Si tandem solar cells perform worse when no $\mu\text{c-Si}$ layers are included in the TRJ structure.
- We can not reach the experimental efficiencies reported in a-Si tandems for the TRJ n-p-p (a-Si/a-Si/a-SiC) or n-p (a-Si/a-SiC) for high a-SiC activation energies.
- We need at least one layer of $\mu\text{c-Si}$ or low activation energies in a-SiC layers in the TRJ to achieve the reported a-Si/a-Si tandem solar cell efficiencies (above 9%) using realistic values of F_0 .
- Clear correspondence between higher forward dark currents in TRJ and higher efficiencies in a-S/a-Si tandem cells.

D-AMPS - ASPIN

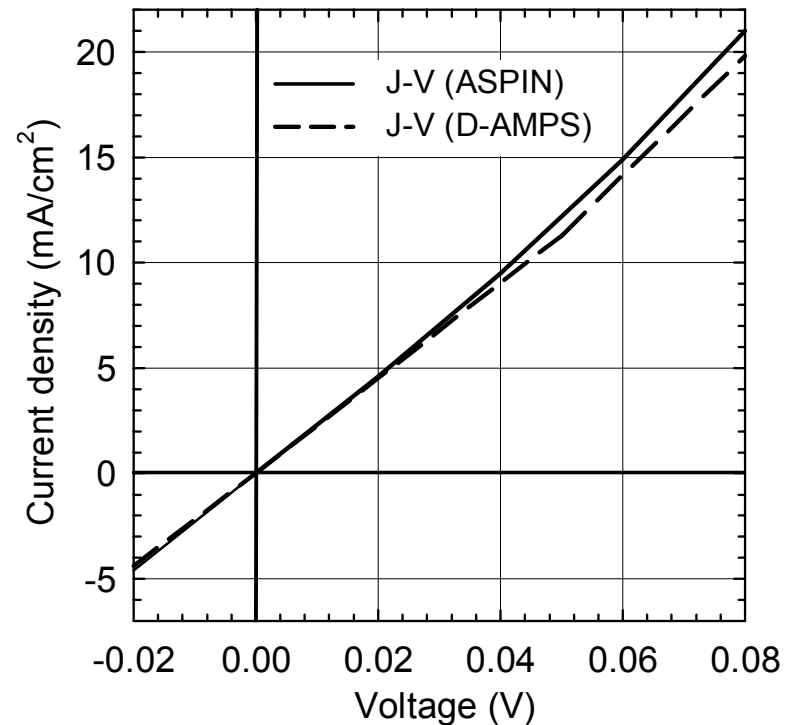
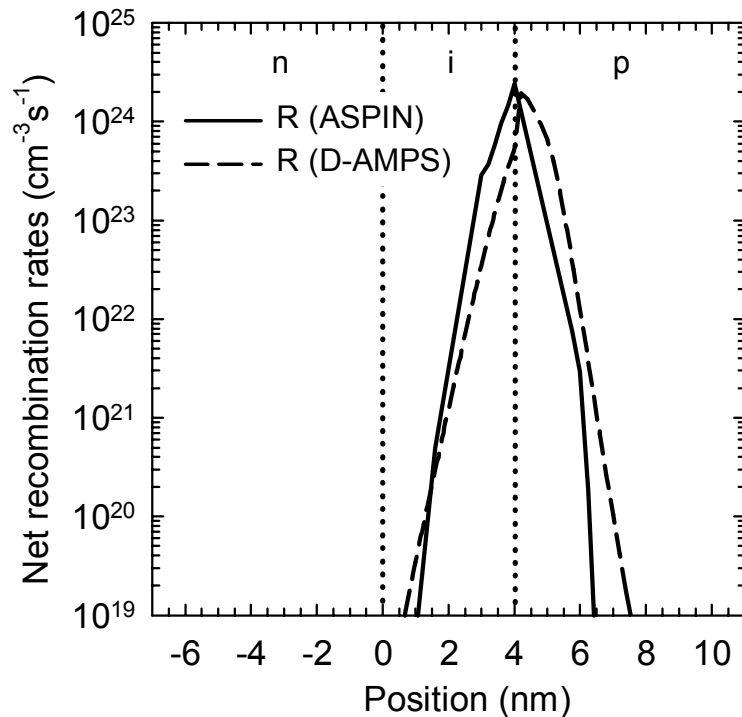
- In the PFT approach the electric field and the barrier (conduction band for electrons, valence band for holes) are required



- D-AMPS uses exact local values. ASPIN uses only the local value of electric field while the barrier is averaged for the WKB approximation
- Similar results are obtained



n-i-p ($\mu\text{c-Si}/\mu\text{c-Si}/\mu\text{c-Si}$) TRJ ASPIN and D-AMPS Similar simulation results



Net recombination rates at 0.1 V in a n-i-p $\mu\text{c-Si}$ single junction
J-V characteristics of a n-i-p $\mu\text{c-Si}$ single junction (linear scale).

Temperature dependence of dark J-V curves in TRJ

- Hegedus et al. published changes by less than one order of magnitude in J when T varies between 200-400 K (V= -0.1 V).
- Assuming electron and hole mobilities field-dependent $\mu(F) = \mu_0 \exp(F/F_0)$, we obtain changes of J by more than 9 orders of magnitude in the range of 200-400 K (V=-0.1V)!
- J is controlled by diffusion a highly T dependent mechanism.
- To reduce this dependence we can assume that field-enhanced mobilities are also highly temperature dependent (Juska et al).

- $\mu(F) = \mu_0 \exp(qAF/kT_F) \rightarrow$ Gill's law.

A is an input parameter expressed in nm.

T_F is given by : $1/kT_F = 1/kT - 1/kT_{CR}$.

T_{CR} is also an input parameter (expressed in K).

Reducing T dependence of dark J-V in TRJ

- The expression $\exp(qAF/kT)$ counterbalance the temperature dependence of free carriers n and p.
- The temperature dependence of the J-V curves can be adjusted with the parameters A and T_{CR} .
- The most appropriate parameter values were:
 - $T_{CR} = 450$ K.
 - A = 11 nm n-p (a-Si/a-SiC).
 - A = 10 nm n-p⁺-p (a-Si/a-Si/a-SiC).
 - A = 8 nm in the n-p⁺-p (μ c-Si/a-Si/a-SiC).
- Juska et al proposed A = 1.6 nm and $T_{CR} = 430$ K to fit the temperature dependence of the measured drift mobility.
- Alternative equations proposed by Juska were tested without success.

Gill's law applied to Tandem Solar Cells

Efficiency of a-Si/a-Si tandem solar cells with regard to TRJ type and parameter (A, T_{CR}). Gill's law was applied to calculate carrier mobilities

A (nm) / T_{CR} (K)	Tandem solar cell efficiency (%) with respect to the TRJ used				
	¹ n-p (HD _{μc})	¹ n-i-p (HD _{μc})	² n-p ⁺ -p (LE _a)	³ n-p ⁺ -p (LE _a)	³ n-p (LE _a)
11 / 450	-	-	-	-	7.73
10 / 450	-	-	-	8.60	7.46
8 / 500	11.59	11.55	11.60	8.51	7.36
8 / 450	11.57	11.54	11.40	8.16	7.01
8 / 400	11.37	11.34	10.44	7.71	6.64

¹ all layers made of HD_{μc} μc-Si

² n made of μc-Si, p⁺ of a-Si, p of LE_a a-SiC

³ n and p⁺ made of a-Si, p of LE_a a-SiC

Straightforward correlation between F_0 (FTM)
and Gill's law parameters: $F_0 = kT_F/qA$.

Reduces the temperature dependence of the FTM model

Appropriate for single TRJ, and tandem solar cell simulations

Conclusions

- Simulation trends in agreement with experiments.
- TRJ with at least one $\mu\text{c-Si}$ layer show a better performance.
- Realistic performances of a-Si/a-Si tandem solar cells can be achieved with simulations assuming that the extended state mobility increases exponentially with the electric field.
- Analysis of the temperature dependence of the J-V characteristics of single TRJ indicates that the field-enhanced mobility also decreases exponentially with the temperature.
- Proper application of Gill's law reduces simulated TRJ current temperature dependence in agreement with experimental observations.
- Further revisions of the field-enhanced mobility model coupled to the trap-assisted tunnelling to predict reasonable tandem solar cell efficiencies are advisable.

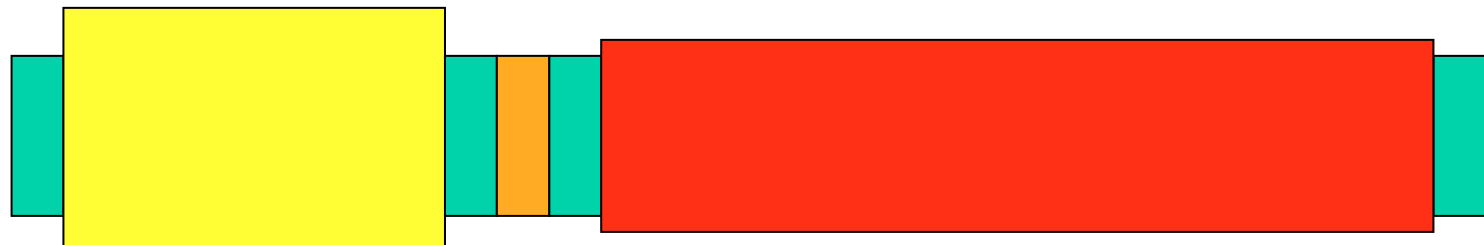
Anomalous Dark SR Tandem Solar Cells

- The SR measured under dark conditions (dark SR) normally matches at each wavelength the lowest of the two cells (top and bottom) SR under bias light.
- In some tandem structures a departure of this typical triangular shape have been observed indicating the presence of an apparent leakage.
- The dark SR shows response from one of the sub cells and the open circuit voltage (V_{oc}) of the tandem cell decreases.
- This anomalous behavior has been reported in nip micromorph tandem silicon solar cells where the absorber layer was deposited with HWCVD by Stolk et al..at UU.

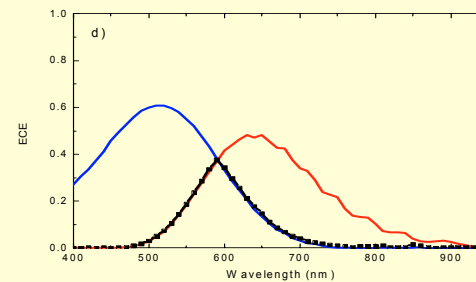
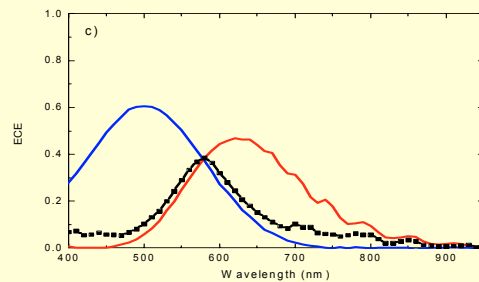
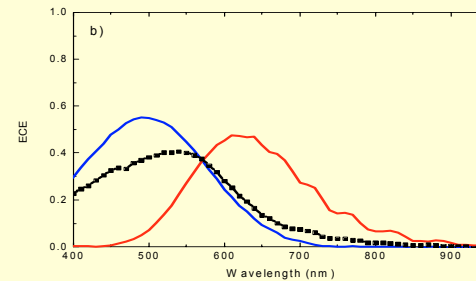
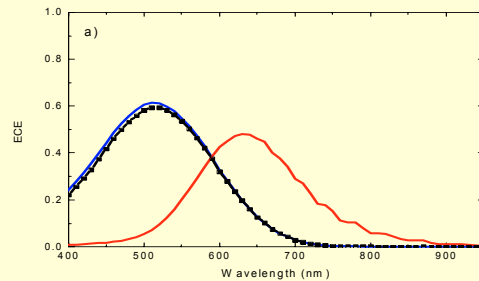
Experiments: Samples

a-Si/ μ c-Si micromorph nip configured solar cells .

- Substrate: Plain stainless steel (SS). No back textured.
- Intrinsic layers deposited with the HWCVD technique.
- Doped layers deposited by PECVD at 13.65MHz.
- Intrinsic a-Si and μ c-Si gaps: 1.8eV and 1.25eV respectively.
- p-layers thicknesses: 26nm.
- Bottom cell n-layer thickness: 77nm.
- Buffer layer of wide band gap i-a-Si at both p-i interfaces.
- Defect rich SiO_x interface layer at the (p) μ c-Si/(n) μ c-Si TRJ.



Experimental dark SR

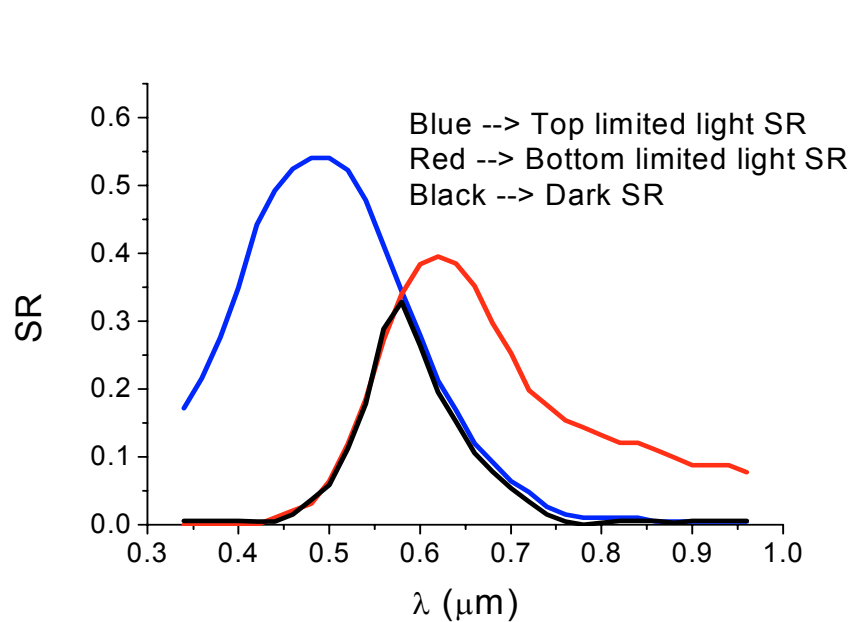


Sample	TRJ junction in the tandem structure: top/TRJ/bottom
1	n- μ c-Si(77nm)/SiOx/p- μ c-Si(26nm)
2	n- μ c-Si(31nm)/n-a-Si(2.5nm)/SiOx/p- μ c-Si(26nm)
3	n- μ c-Si(31nm)/n-a-Si(5nm)/SiOx/p- μ c-Si(26nm)
4	n- μ c-Si(33nm)/n-a-Si(5nm)/SiOx/p- μ c-Si(26nm) This n- μ c-Si layer was deposited at a higher plasma power

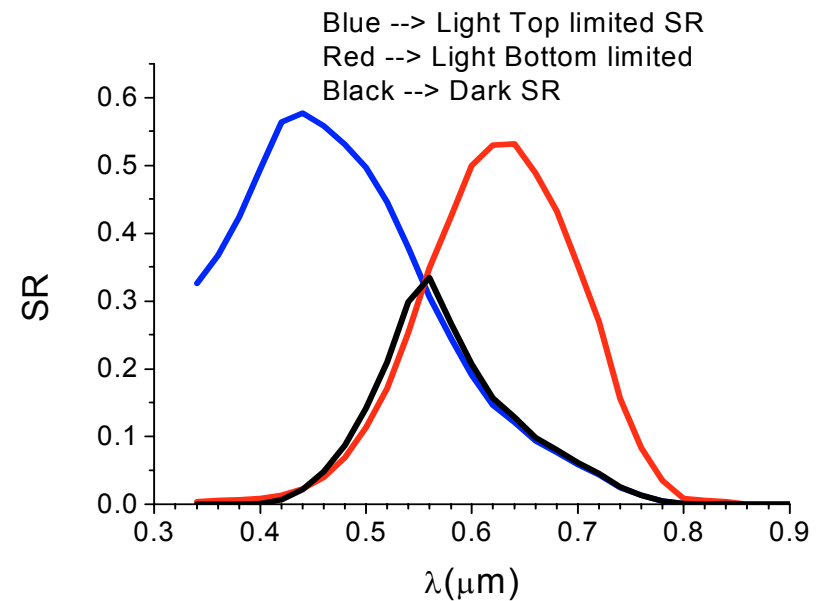
More experimental results

- Top cell initial n-layer thickness of 77 nm:
 - Dark SR matched the top cell SR under bias light.
 - Voc resulted lower than expected ($\sim 1.31\text{V}$).
- Thinner n- $\mu\text{c-Si}$ layers and insertion of a-Si layer between TRJ doped $\mu\text{c-Si}$ layers.
 - The expected dark SR is obtained and Voc increases by $\sim 0.1\text{V}$.
- Best results obtained for these two TRJ configurations:
 - (a) n- $\mu\text{c-Si}(33\text{nm})/\text{n-a-Si}(5\text{nm})/\text{SiO}_x/\text{p-}\mu\text{c-Si}(26\text{nm})$.
 - (b) n- $\mu\text{c-Si}(33\text{nm})/\text{SiO}_x/\text{n-a-Si}(5\text{nm})/\text{SiO}_x/\text{p-}\mu\text{c-Si}(26\text{nm})$.
- Deposition time of n- $\mu\text{c-Si}$ layer decreased by reducing its thickness and by using a higher plasma power.
- Similar results found in a-Si/a-Si and a-Si/poly-Si tandems.

Computer predicted dark SR



a-Si/μc-Si light and dark SR
at short circuit conditions



a-Si/aSi light and dark SR
at short circuit conditions

General statements Computer predictions

- The dark SR practically coincides with the lowest values of the light SR regardless the intrinsic layer thicknesses.
- Same result for a-Si/a-Si and $\mu\text{c-Si}/\mu\text{c-Si}$ tandem solar cells.
- The triangular shape of the dark SR is a common signature of tandem solar cells.
- Agreement between computer predictions and experimental observation.

Motivations

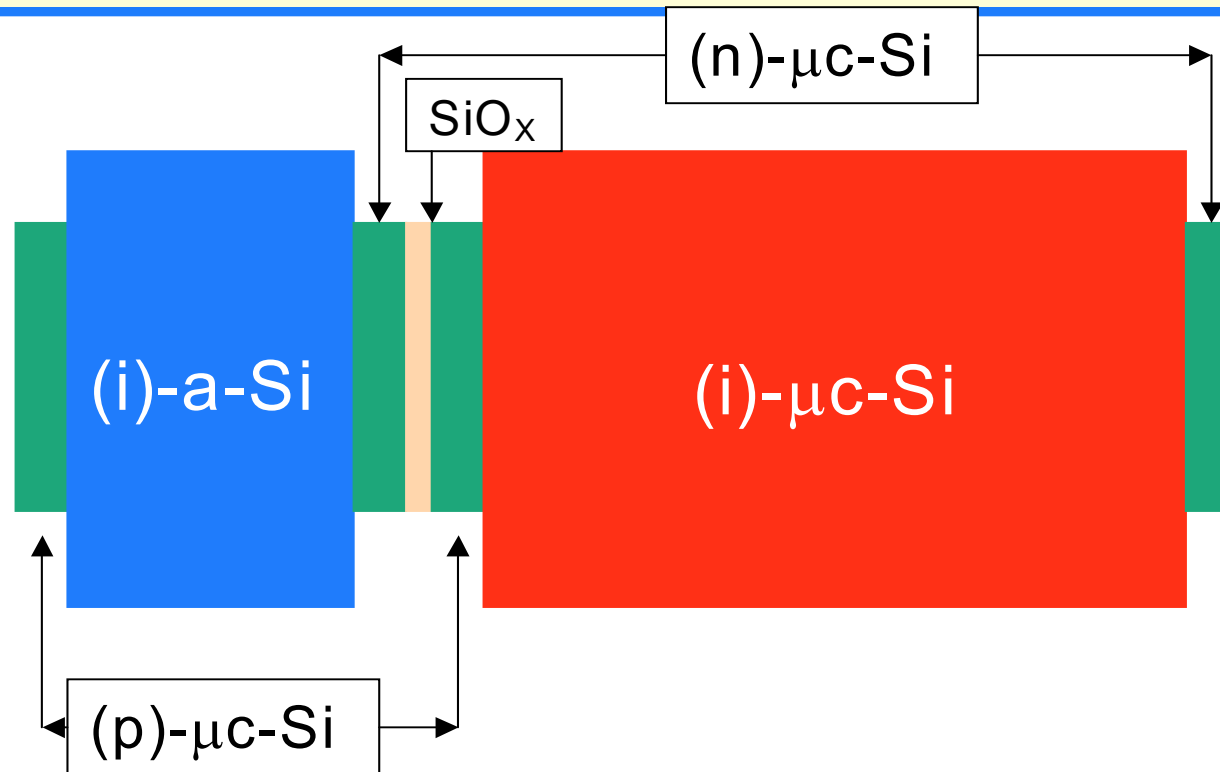
- • *To explore with computer modeling the causes behind the departure of the typical triangular shape of dark SR observed in tandem solar cells.*
- • *The recovering of the regular triangular shape in dark SR curves could be an useful tool to remove leakages and to optimize tunnel recombination junctions (TRJ) in tandem solar cells.*

Simulations: D-AMPS

Assumptions

- Neutral boundary (Flat-band) conditions.
- Offsets half-half between conduction and valence bands.
- Amphoteric mid-gap states.
- Light scattering at rough surfaces.
- Field dependent N_C and N_V at the TRJ.
- Density of states described by two tails and three Gaussians: D^- , D^0 , and D^+ .
- Electrical and optical parameters selected from data and from fittings performed on single a-Si and $\mu\text{c-Si}$ p-i-n and on a-Si/a-Si tandems.

What was it studied?



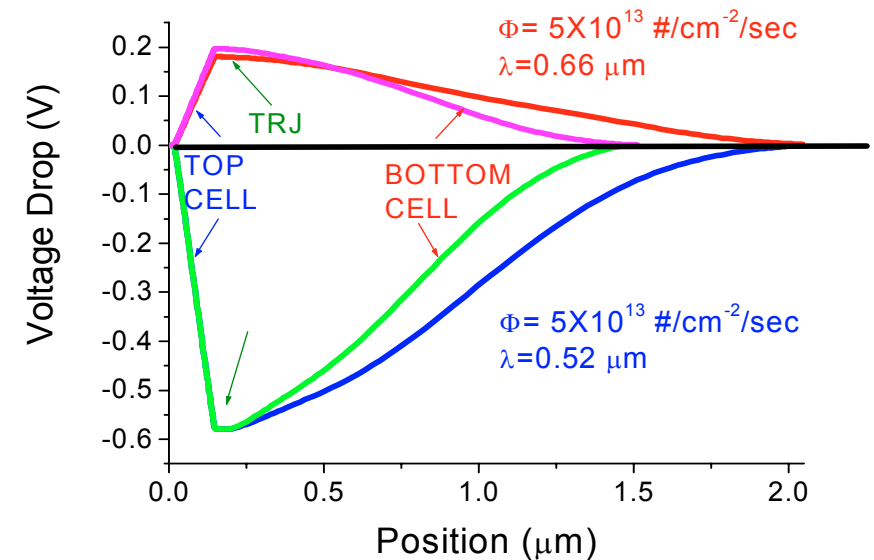
Sensitivity of the dark SR to the density of traps and location of defective layers (DL) inserted in the intrinsic layers of top and bottom sub cells.

• Internal voltage introduced in the tandem cell by free carriers -generated by the monochromatic beam used in dark SR measurements•

Possible causes leading to the appearance of anomalous dark SR in a-Si/μc-Si and in other tandem solar cells.

Voltage drop in a-Si/ μ c-Si tandems - Dark SR

- Top cell limits $J \rightarrow$ more photo-generated holes than electrons reach TRJ \rightarrow piling-up of holes that forward (reverse) bias the bottom (top) cell.
- Bottom cell limits $J \rightarrow$ more photo-generated electrons than holes reach TRJ \rightarrow piling-up of electrons forward (reverse) bias the top (bottom) cell.
- The monochromatic beam intensity used in dark SR measurements is strong enough to alter the electric field.
- For wavelengths $\lambda < \lambda_c$ the bottom limits $J \rightarrow$ top (bottom) cell is forward (reverse) biased
- For wavelengths $\lambda > \lambda_c$ the top cell limits $J \rightarrow$ top (bottom) cell is reverse (forward) biased



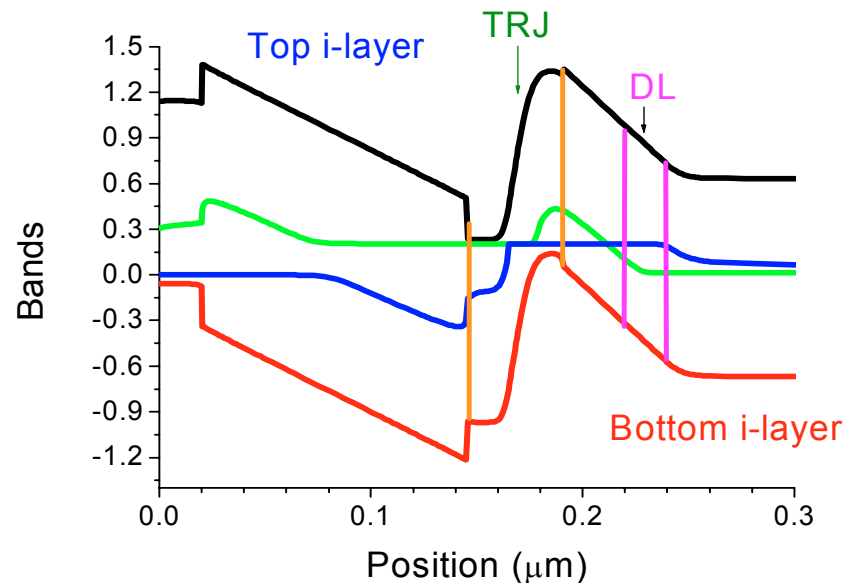
Voltage drop under short circuit on a 125-1900nm (top limited under AM1.5 light) and on a 125-1300nm (bottom limited under AM1.5 light) a-Si/ μ c-Si tandem

Defective Layers (DL)

* The voltage bias introduced by the monochromatic beam reverse bias zones where e-h pairs would be thermally generated.

* These zones are formed more easily in the bottom cell.

* Thin DL present in these zones could generate enough e-h pairs that can change the shape of the dark SR.



Band diagram of an a-Si/μc-Si tandem solar cell under dark and under short circuit conditions.

The monochromatic light beam has an intensity of 5×10^{13} #/cm²/sec and its wavelength is of 0.52 μm.

DL inserted in the top cell (i)-layer → Effect on the dark SR

$W(\text{DL}) = 20\text{nm}$. The DB density is $5 \times 10^{18}\text{ cm}^{-3}$ if nothing is said.

DL with 10^{19} cm^{-3} DB at the p/i interface → top limited dark SR

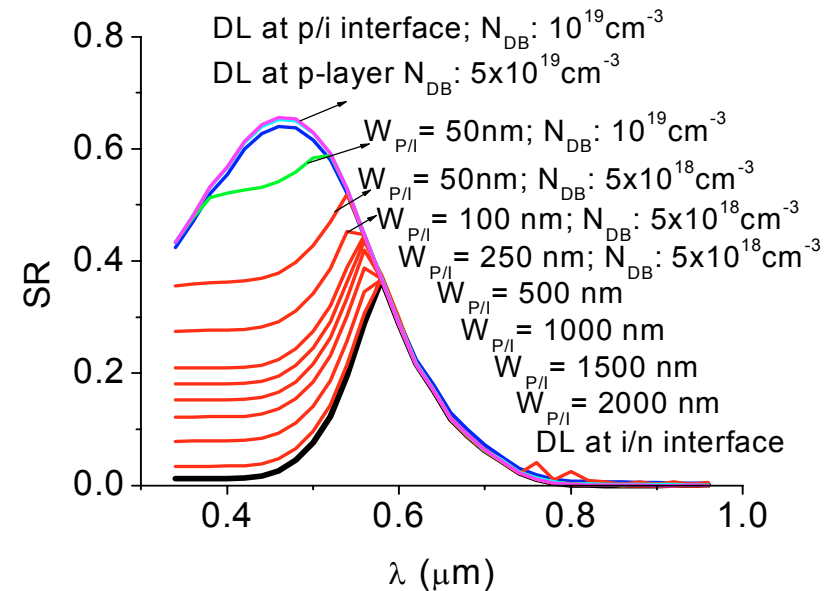
The same effect is obtained using a DL in the (p) $\mu\text{c-Si}$ layer using a DB density of $5 \times 10^{19}\text{ cm}^{-3}$ >

$N_A = 8.2 \times 10^{18}\text{ cm}^{-3}$. Unlikely!

DL moved farther from the p/i interface → dark SR decreases.

DL at the i/n interface → triangular shape of the dark SR is recovered.

No changes in the dark SR when the DL is included at the (n) $\mu\text{c-Si}$ /(p) $\mu\text{c-Si}$ interface or inside the (n) $\mu\text{c-Si}$ layer

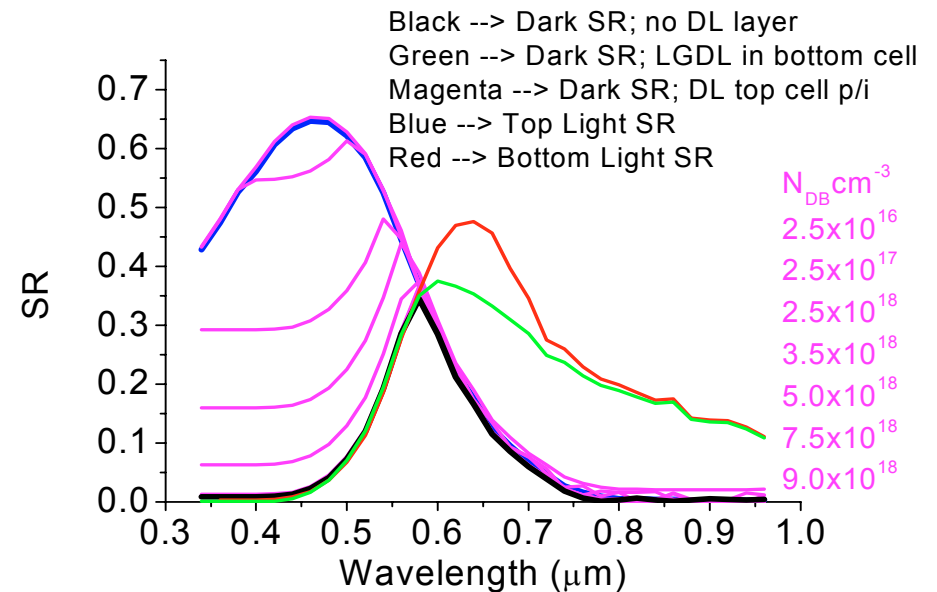


Dark SR and top cell light SR of an a-Si/ $\mu\text{c-Si}$ tandem under short circuit conditions.

Impact of inserting a DL in the bottom cell. $W_{\text{P/I}}$: distance of the DL from the p/i interface.

DL in the top and bottom cell (i)-layers → Effect on the dark SR

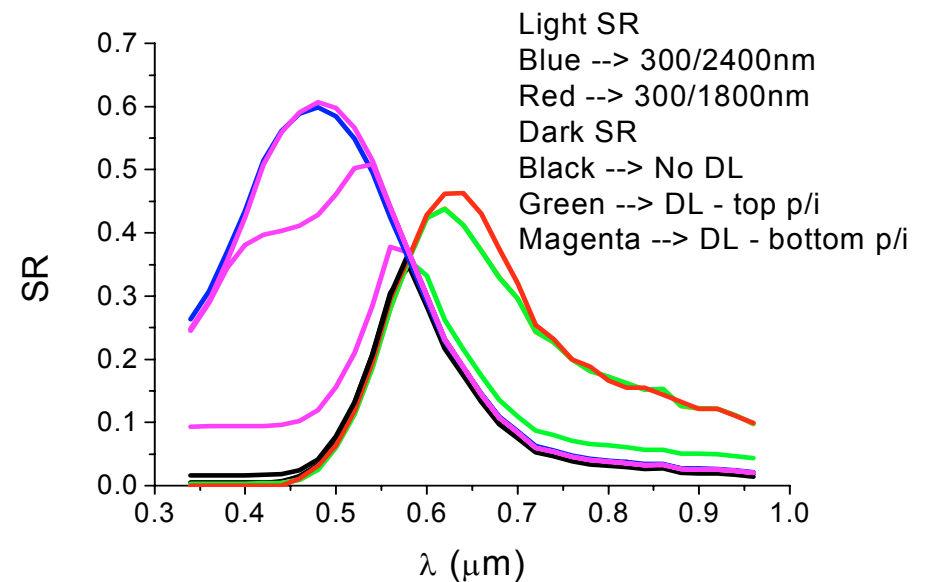
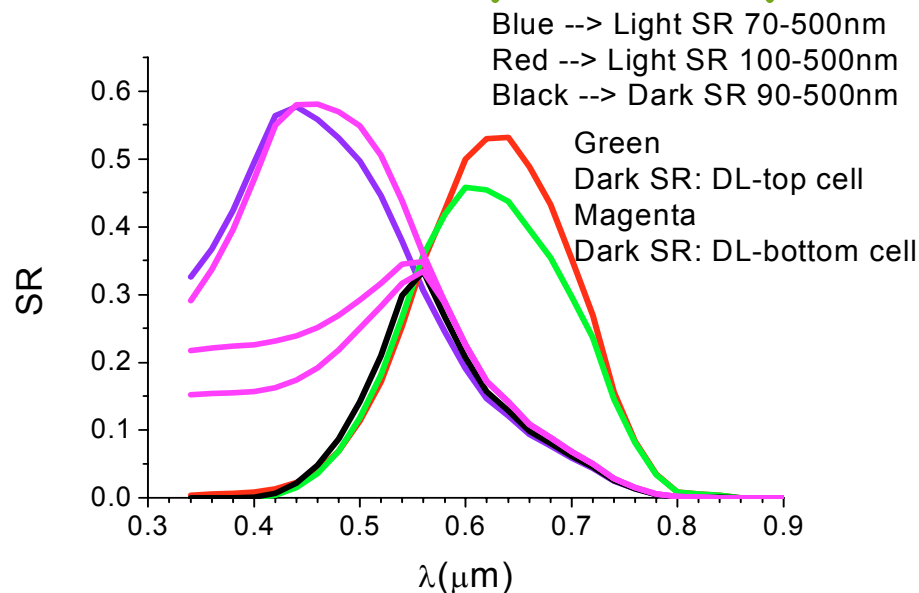
- Less defects in the DL layer → SR looks more triangular.
- Insertion of a DL in top cell → not easily lead to bottom limited SR
- Higher band-gap of the top cell → lower thermal gen. of e-h pairs
- Low band gap DL layer (LGDL) (20nm thick) near the p/i interface of the top cell ($E_G = 1.2\text{eV}$) → important effects on the dark SR are observed
- LGDL layer at the i/n interface → no changes in the dark SR.



Dark SR, top and bottom light SR of an a-Si/ $\mu\text{c-Si}$ tandem under short circuit conditions.

Impact in the dark SR of inserting DL with different DB densities at the bottom cell p/i interface and of a LGDL at 25nm from the top cell p/i interface.

Dark and light SR in a-Si/a-Si and $\mu\text{c-Si}/\mu\text{c-Si}$ tandems



Dark and Light SR in a-Si/a-Si tandems

- Departure of the dark SR triangular shape for highly defective layers ($5 \times 10^{19} \text{ cm}^{-3}$ DB) or LGDL layers.

Effects are observed when DL layers are inserted near the p/i interface.

Dark and light SR in $\mu\text{c-Si}/\mu\text{c-Si}$ tandem.

- DL are more effective in altering the triangular shape of the dark SR when they are placed near the p/i interface.
- Very high density of DB ($>10^{19} \text{ cm}^{-3}$) or gap lowering in the DL are not needed.

Dependence of Voc and FF with respect to the DB density present in the DL

- DL inserted at the p/i interface of the a-Si/ μ c-Si tandem.
- Computer trends in agreement with experimental observations.

DB density ($\text{cm}^{-3} \text{eV}^{-1}$)	Voc (V)	FF
5×10^{15}	1.396	0.746
5×10^{16}	1.396	0.746
5×10^{17}	1.383	0.748
10^{18}	1.343	0.739
2×10^{18}	1.308	0.725
2.5×10^{18}	1.296	0.721
5×10^{18}	1.259	0.714
7.5×10^{18}	1.241	0.710
9×10^{18}	1.232	0.707
2.5×10^{19}	1.185	0.679

Dark SR in Tandems

Conclusions

- Thin defective regions (DL) perpendicular to the charge transport direction inside the intrinsic layers, near the p/i interface can give rise to dark SR curves coinciding with the light SR.
- DL also decrease the Voc of the tandem cell.
- The dark SR is more sensitive to the presence of defects in the front region of the intrinsic layer of the bottom sub cell of tandem structures.
- The effect is non observed when the defective region is present at the other end of this sub cell, i.e., at i/n interface.
- Similar trends are obtained in other tandem cells: a-Si/a-Si and $\mu\text{c-Si}/\mu\text{c-Si}$ cells.