



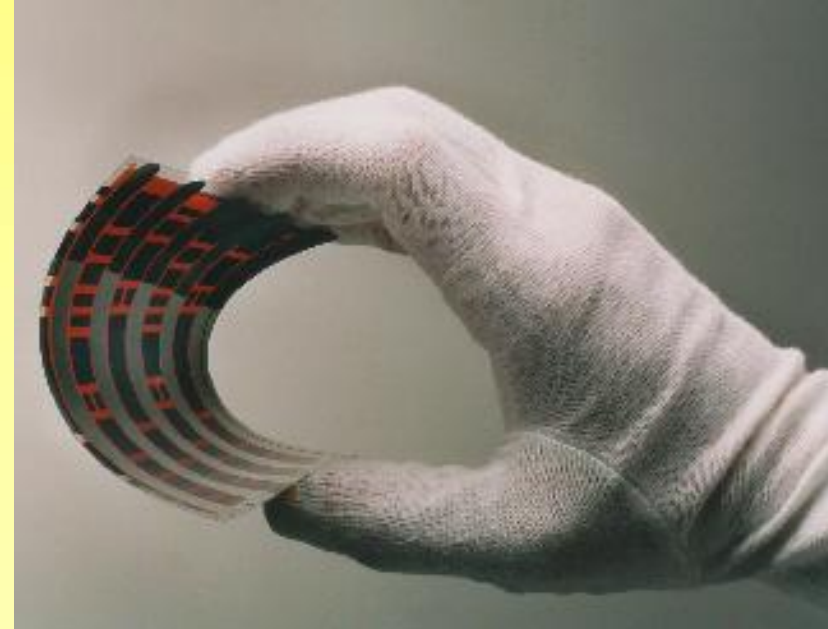
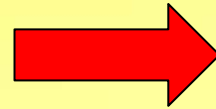
# **THIN FILM SILICON SOLAR CELLS FABRICATED BELOW 100°C ON FLEXIBLE LOW COST SUBSTRATES**

**P.C.P. Bronsveld, J.K. Rath, R.E.I. Schropp**

Utrecht University  
Debye Institute, SID-Physics of Devices  
Utrecht, The Netherlands



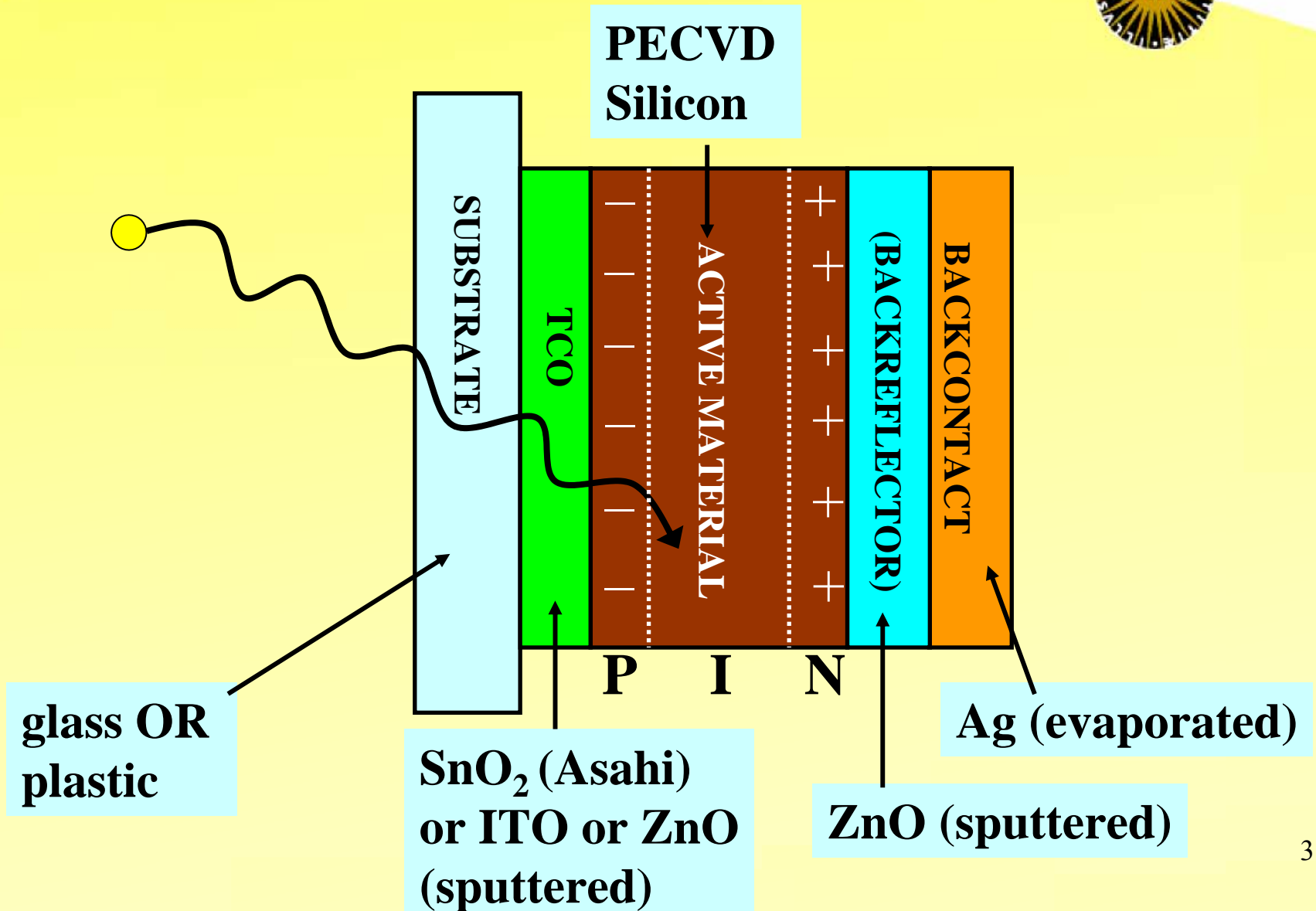
# TO FLEXIBLE MODULES



Energy source for flexible electronics and displays, clothing, price tags, labels etc. 2



# P-I-N SOLAR CELL



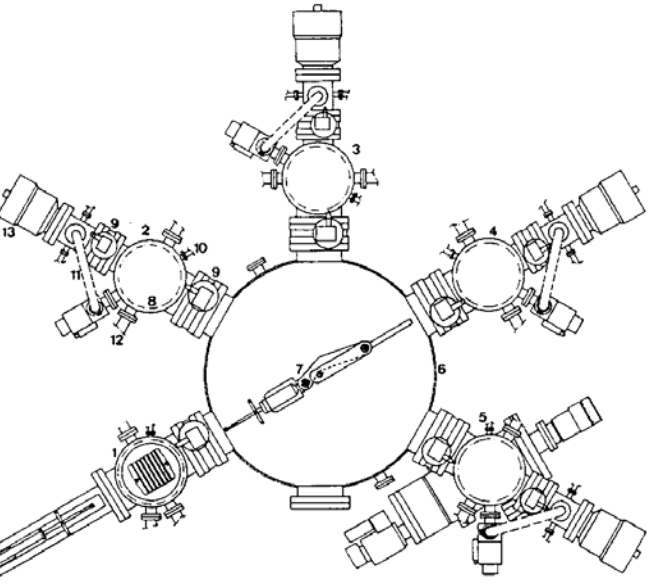


# APPROACHES

- **ADJUST SUBSTRATE**
  - T-resistant plastic ( $\sim 140\text{-}200^\circ\text{C}$ ), suitable for silicon
  - High T-resistant substrate (eg. Al) and transfer to LT plastic afterwards (Helianthos project)
- **ADJUST PROCESS**
  - Organic materials
  - Inorganic materials  $\leq 100^\circ\text{C}$  (eg. Low T silicon)
  - (Post deposition treatment)

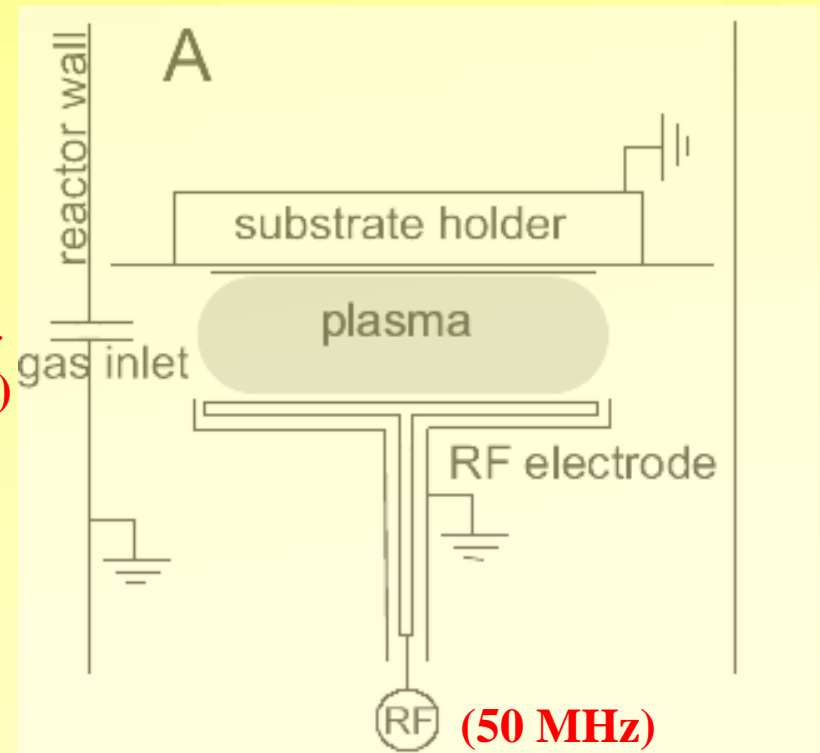


# ASTER DEPOSITION SYSTEM



Very High Frequency  
Plasma Enhanced  
Chemical Vapor Deposition  
(VHF-PECVD)

$\text{SiH}_4 \rightarrow$   
(Silane)





# PECVD AT LOW TEMPERATURE

Without sufficient substrate heating, the contribution of surface reactions (diffusion, abstraction, adhesion) to the growth process is reduced

- Columnar growth a-Si
- Electronic defects (dangling bonds)
- Inhomogeneity in growth direction

**LOWER MATERIAL  
QUALITY**



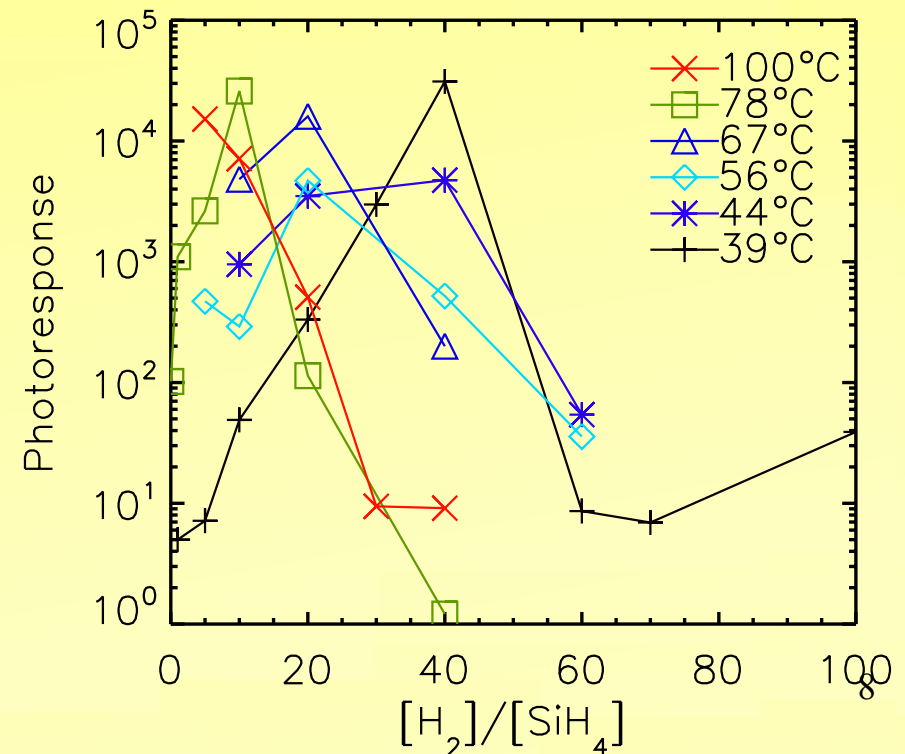
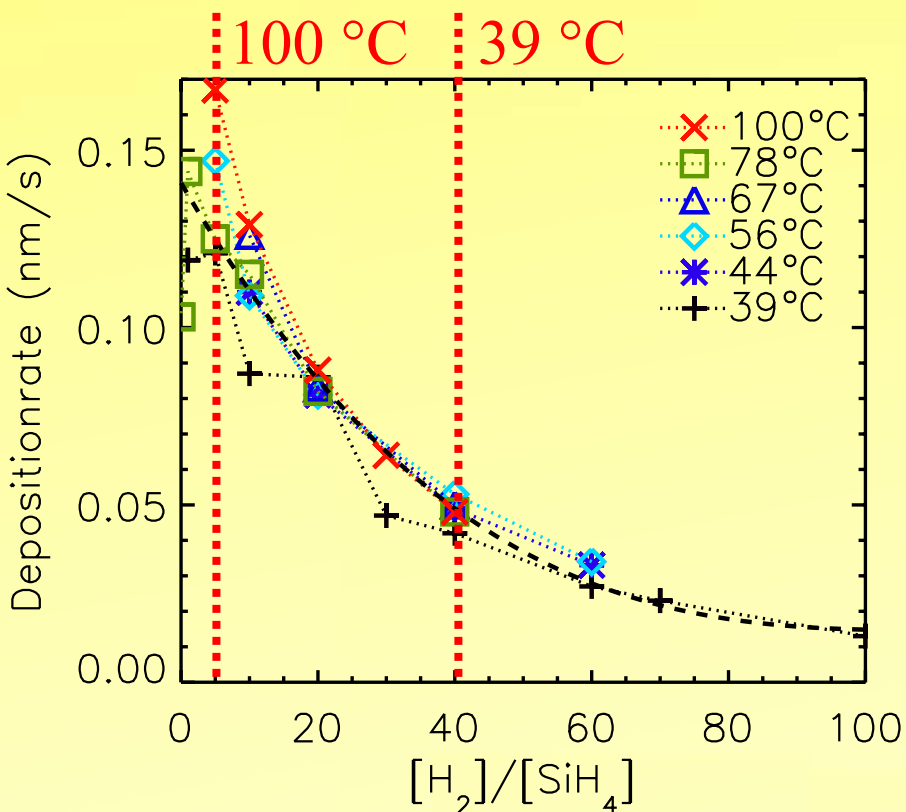
# POSSIBLE SOLUTIONS

- Etching of weak Si-Si bonds by dilution of silane with  $H_2$ , He or Ar
- Increase kinetic energy of approaching ions (adjust external bias, pressure, flow rate, power)
- Post deposition treatment (eg. laser annealing)
- Alternative deposition methods like HWCVD



# HYDROGEN DILUTION SERIES

Exploring temperature range 39°C to 100°C :  
photoresponse, crystallinity, hydrogen content, defect density...





# 39°C: TRANSITION MATERIALS

Slow, tunable transition to microcrystalline material  
→ interesting to study crystal growth in silicon

X-TEM of 1:40 dilution (scalebar 200 nm, also best electronic layer !)

AFM study

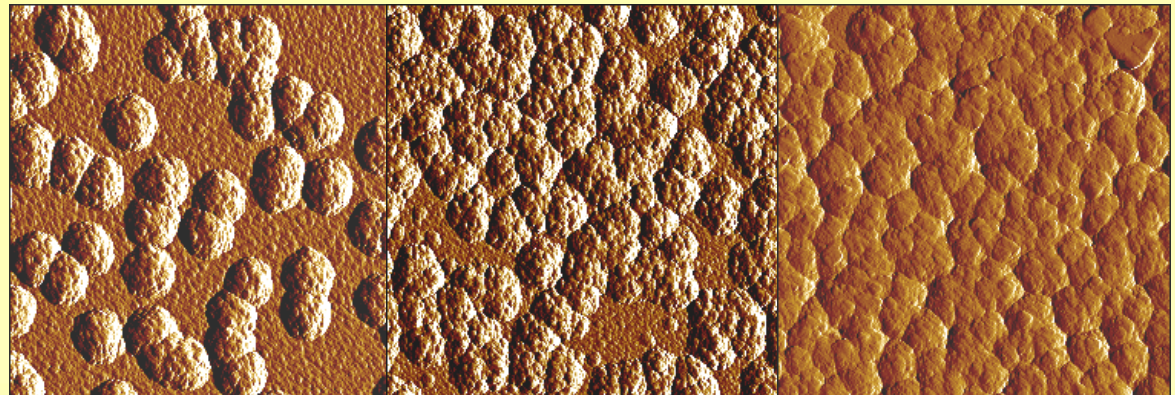
Prague

(5 x 5  $\mu\text{m}$  scans, increasing H<sub>2</sub>-dilution from left to right)

35

36

38

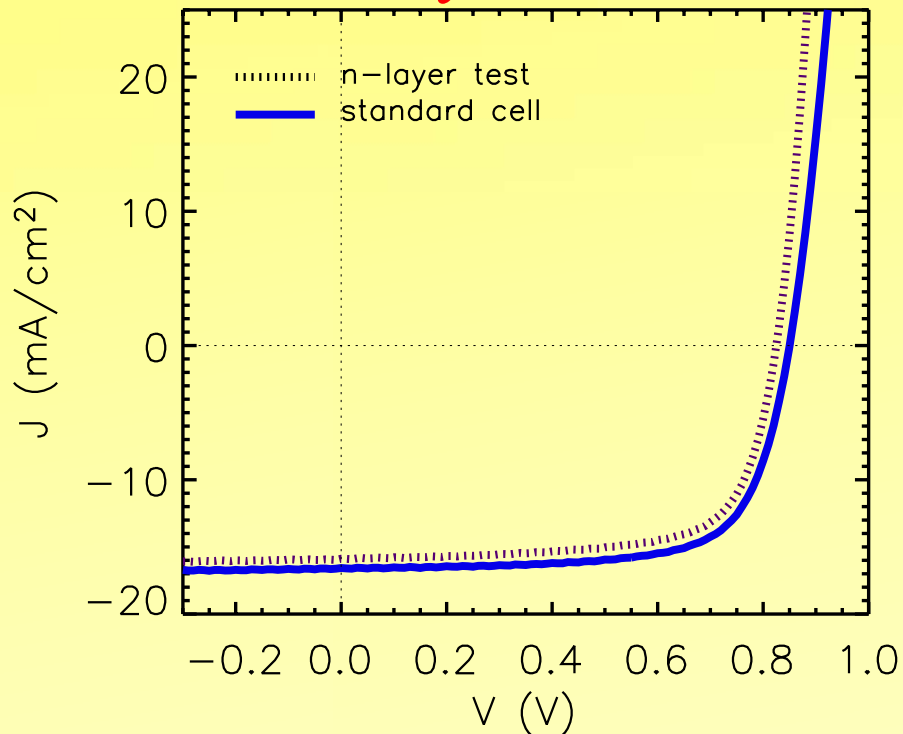




# 39°C: DOPED LAYERS

Quick approach: recipe of layer with best electrical properties (transition layer) used. Dopant gas flow varied.

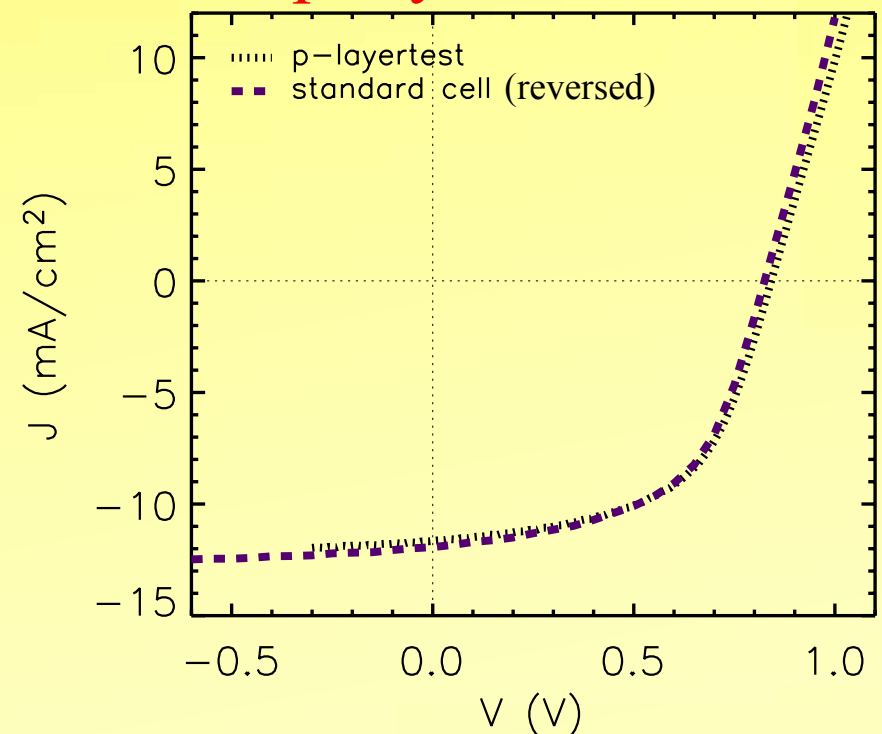
## n-layer test



$$\sigma_d = 4.74 \times 10^{-6} \Omega^{-1}\text{cm}^{-1}$$

$$E_a = 0.42 \text{ eV}$$

## p-layer test

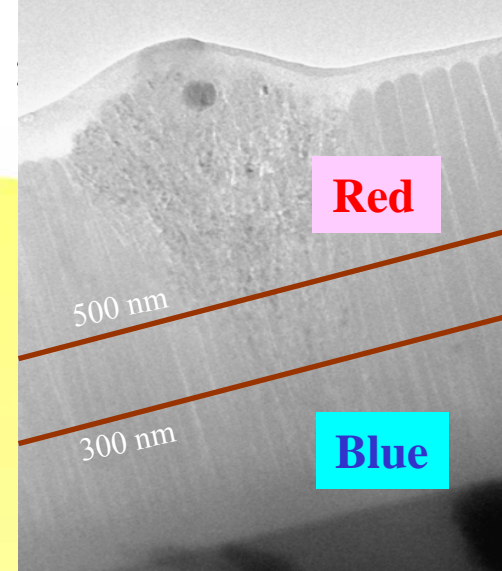


$$\sigma_d = 5.85 \times 10^{-8} \Omega^{-1}\text{cm}^{-1}$$

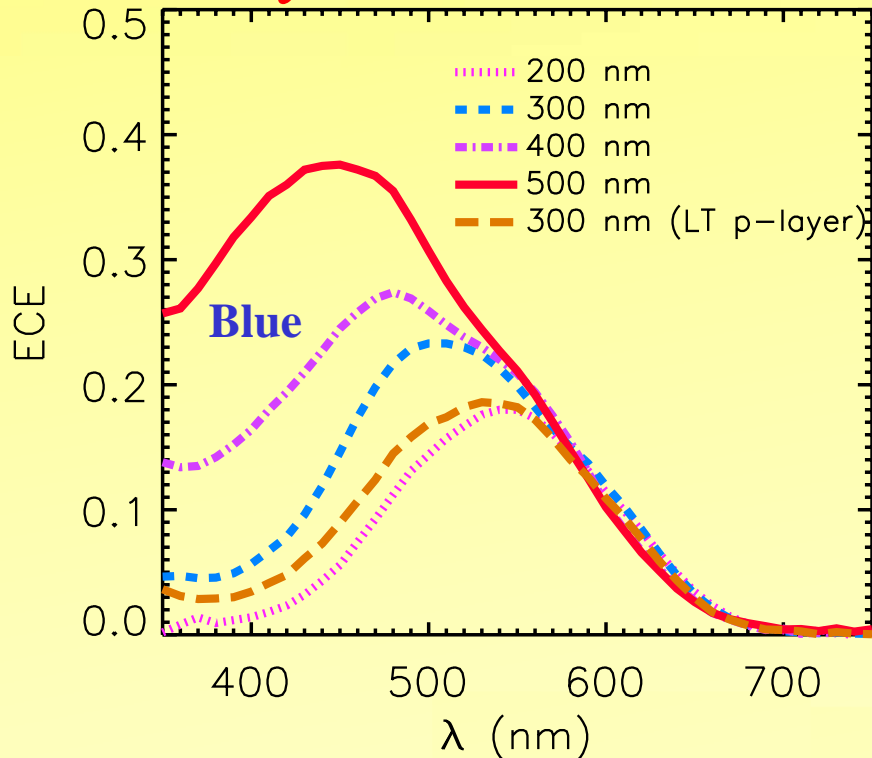
$$E_a = 0.55 \text{ eV}$$

# 39°C: SOLAR CELLS

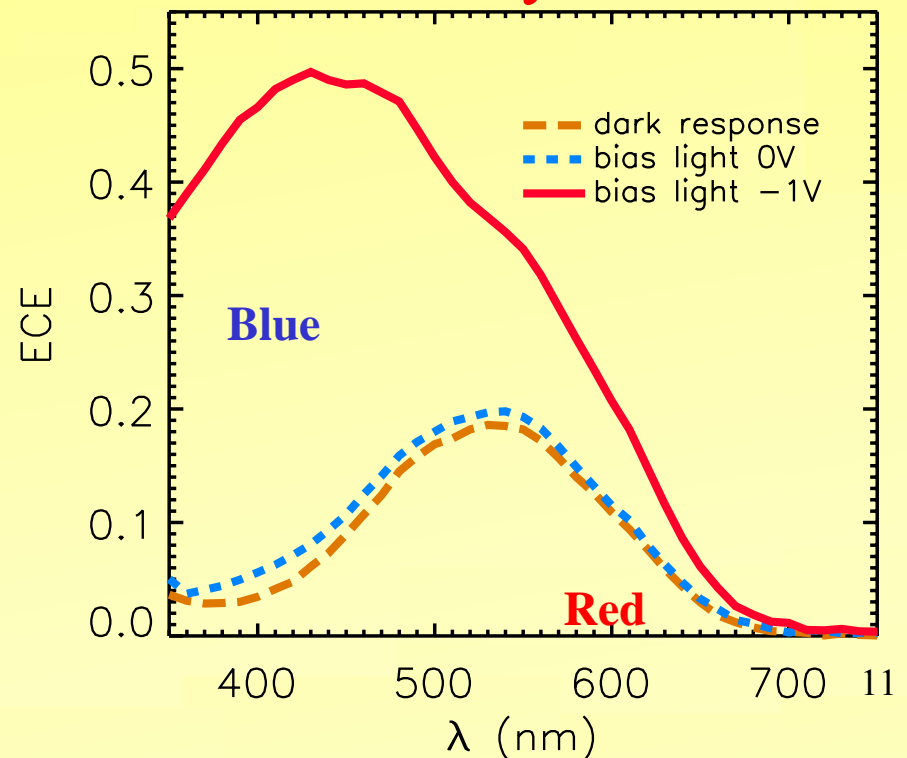
- Influence of crystal growth on cell properties (mixed phase is best)
- Possible application on paper or very T-sensitive plastic (best efficiency 1.4%)



## i-layer thicknesses



## 300 nm i-layer

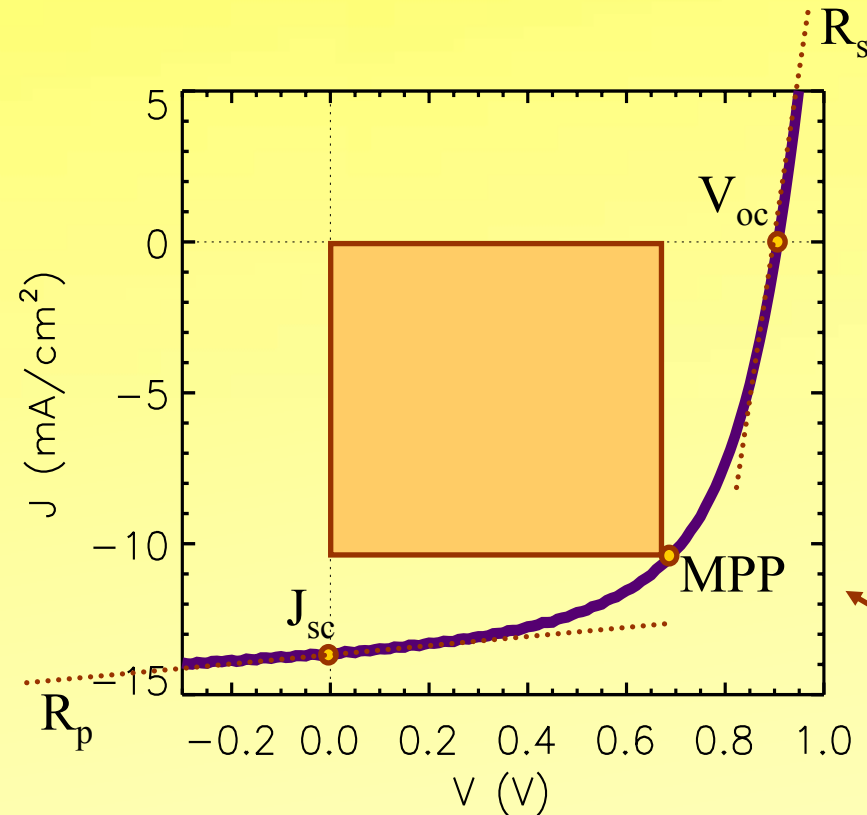


# 100°C: SOLAR CELL GLASS



On Glass excellent quality !

	T (°C)	Substrate	Dep. Rate	$\eta$ (%)
U.Stuttgart	110	Glass	~0.2	6
	75	Glass	~0.2	3.8
	110	PET		5
<b>UU</b>	<b>100</b>	Glass	0.17	<b>7.3</b>

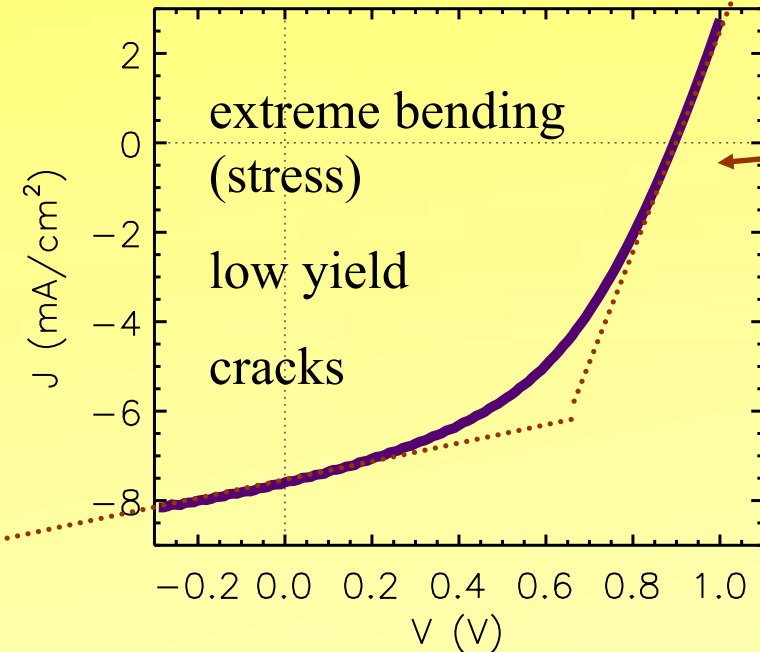


IV-curve of solar cell on textured SnO<sub>2</sub>:F (Asahi) with ZnO:Al/Ag backreflector

$\eta = 7.26\%$   
 $J_{sc} = 13.8 \text{ mA/cm}^2$   
 $V_{oc} = 0.91 \text{ V}$   
 $FF = 0.58$   
 $R_s = 10 \text{ } \Omega \text{ cm}^2$   
 $R_p = 764 \text{ } \Omega \text{ cm}^2$



# 100°C: SOLAR CELL PET



$$\eta = 3.00\%$$

$$J_{sc} = 7.6 \text{ mA/cm}^2$$

$$V_{oc} = 0.89 \text{ V}$$

$$FF = 0.43$$

$$R_s = 45 \text{ } \Omega \text{ cm}^2$$

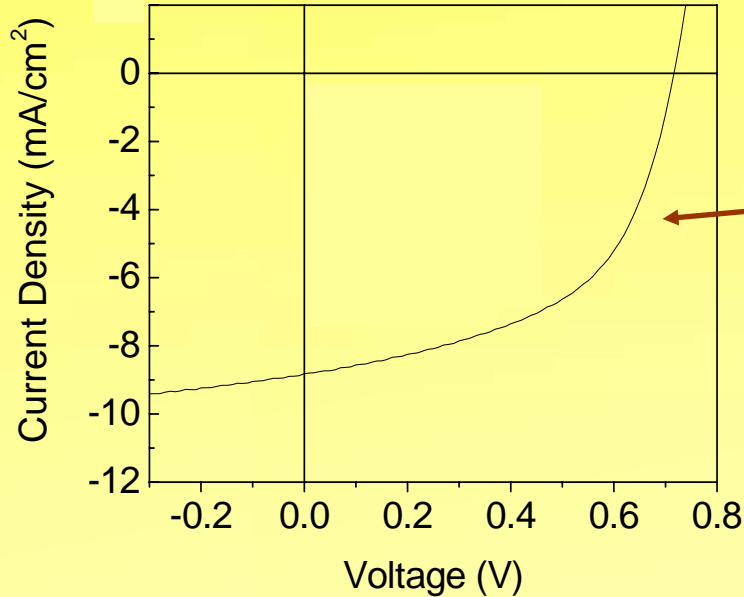
$$R_p = 422 \text{ } \Omega \text{ cm}^2$$

IV-curve of solar cell on  
flat ITO on PET  
no backreflector

New foil substrate holder → no bending (stress), no cracks, 100% yield, good reproducibility but cell needs to be re-optimized (electrode distance changed)

High yield → development of series connection

# 100°C: HWCVD SOLAR CELL



$$\eta = 3.38\%$$

$$J_{sc} = 8.9 \text{ mA/cm}^2$$

$$V_{oc} = 0.72 \text{ V}$$

$$FF = 0.53$$

$$R_s = 12 \text{ } \Omega \text{ cm}^2$$

$$R_p = 426 \text{ } \Omega \text{ cm}^2$$

100 °C reached without active cooling!

IV-curve of solar cell on  
textured SnO<sub>2</sub>:F (Asahi)  
without ZnO:Al/Ag  
backreflector

I-layer properties:

$$\sigma_{ph}/\sigma_d = 1.1 \times 10^5$$

$$\sigma_d = 2.5 \times 10^{-11}$$

$$E_a = 0.82 \text{ eV}$$



# SUMMARY

- $\leq 100^\circ\text{C}$  VHF-PECVD: quality is achieved, however at the cost of deposition rate
- $39^\circ\text{C}$ : a-Si  $\rightarrow$   $\mu\text{c-Si}$  transition and its effect on solar cell properties (doping shown to be possible at this T!)
- $100^\circ\text{C}$ :
  - record efficiency (7.3 %) by VHF-PECVD on glass
  - good cells on cheap PET, yield problem solved
  - HWCVD is an option
- Future: extrapolation of the transition-materials from  $39^\circ\text{C}$  to higher T, series connection

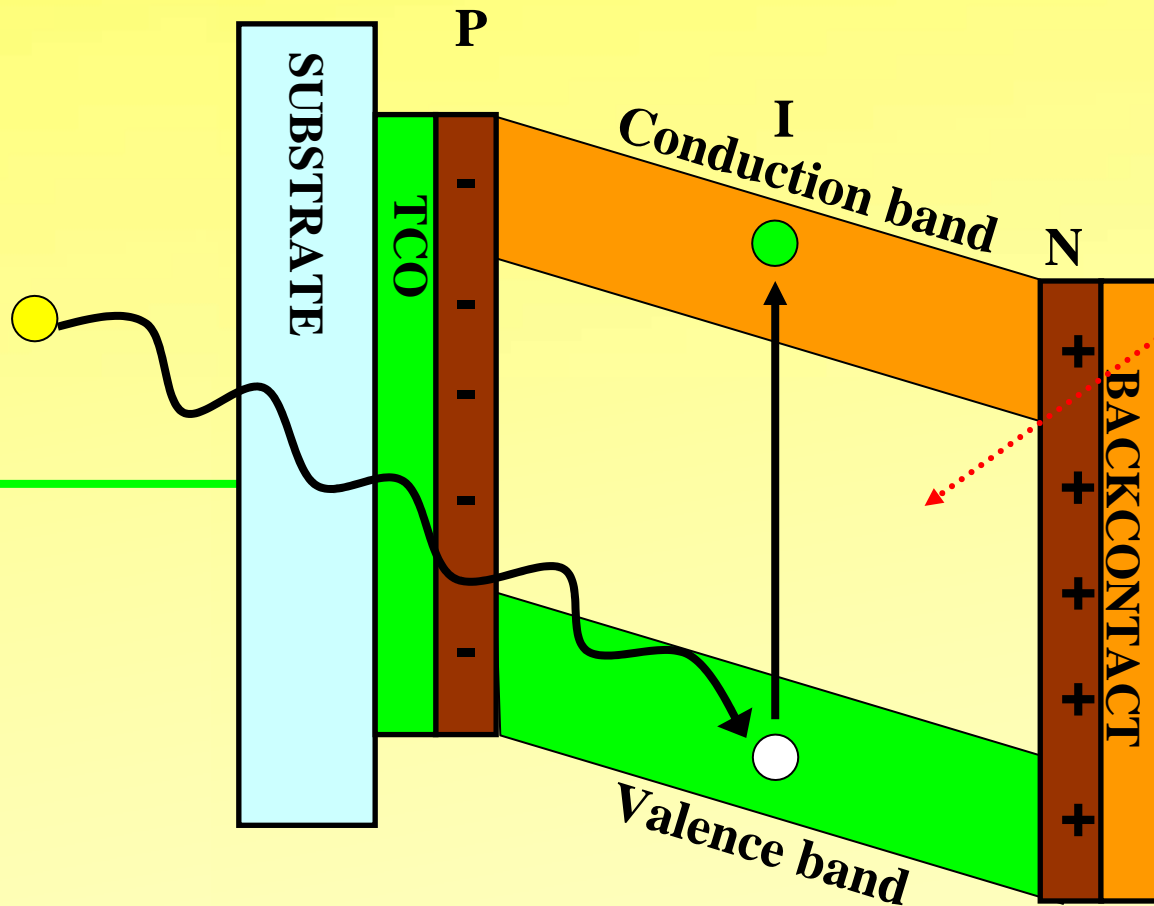
# THANKS!



- **AFM:** Tomáš Mates, Antonin Fejfar, Jan Kočka (Institute of Physics, Prague)
- **Depositions:** Jeroen Francke, Arjen Bink, Caspar van Bommel
- **Substrate holder:** Gerard van der Mark
- **ITO tests:** Eva Tois, Yanchao Liu
- **First tests on plastic:** Karine van der Werf
- **Characterization and discussions:** Ruurd Lof
- **X-TEM:** Aad Gordijn, Dirk Knoesen, Pim van Maurik, Hans Meeldijk



# P-I-N SOLAR CELL



ABSORBER  
SHOULD BE  
OF BEST  
ELECTRONIC  
QUALITY!

