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Silicon heterojunction solar cell characterization and optimization using *in situ* and *ex situ* spectroscopic ellipsometry

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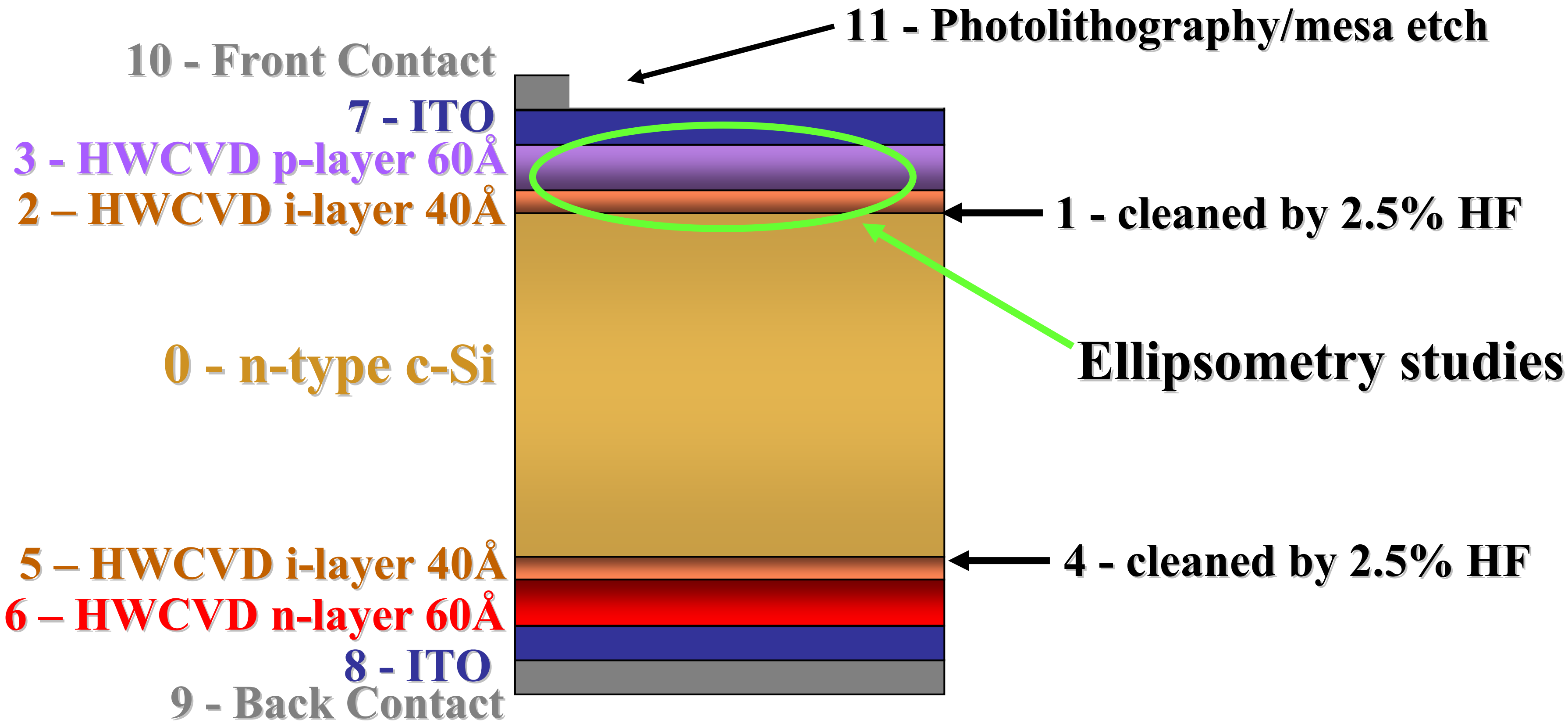
SHJ Solar Cell Fabrication

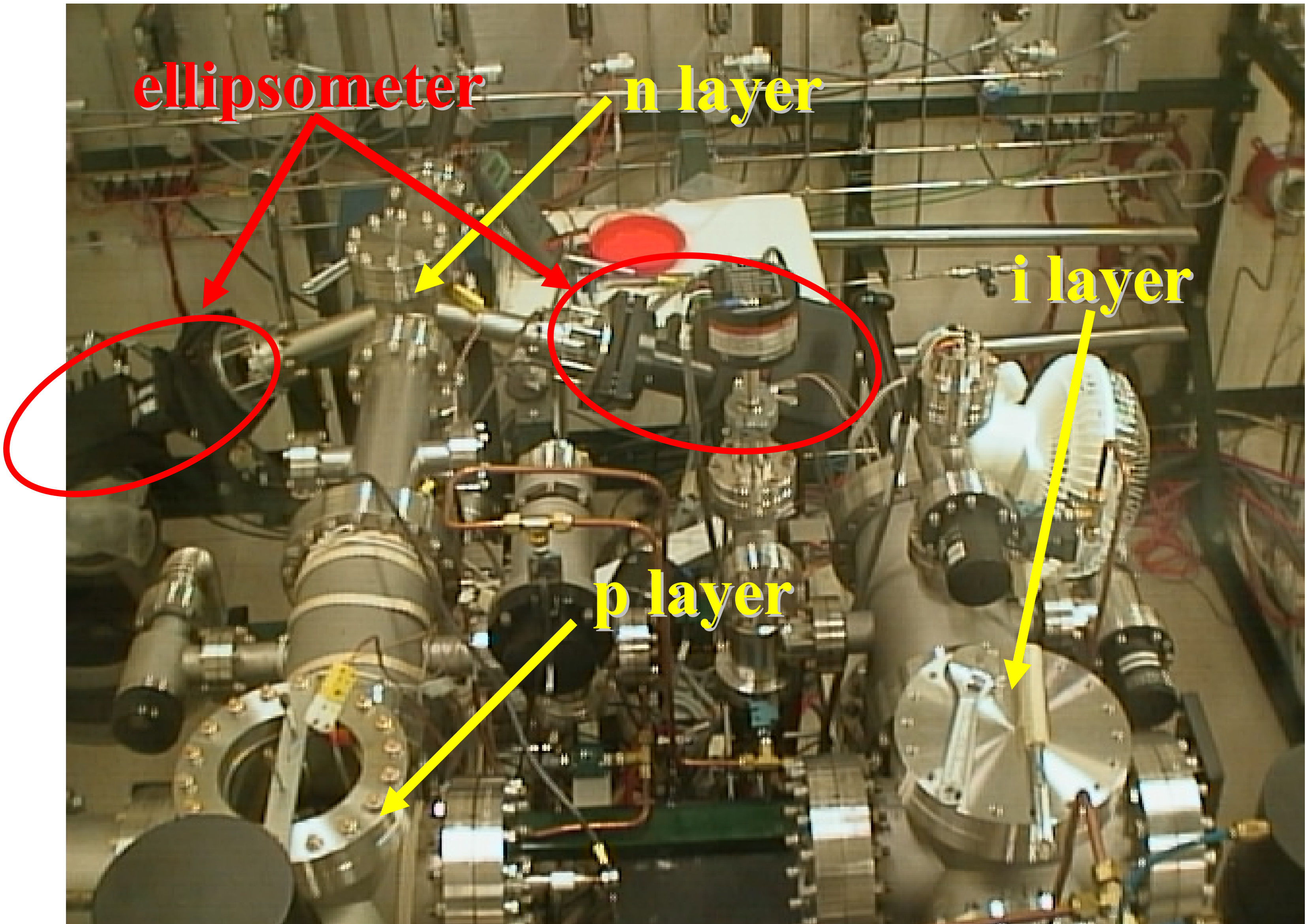


Flat wafers $\eta = 16.9\%$

Textured wafers $\eta = 17.8\%$

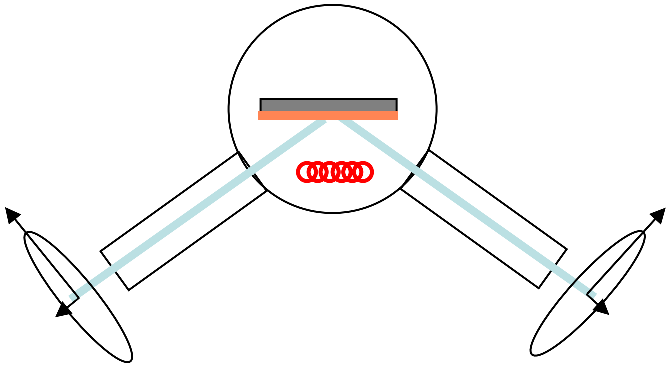
HWCVD deposition system:

i, n, and p layers are deposited in separate chambers



Fabrication and characterization sequence

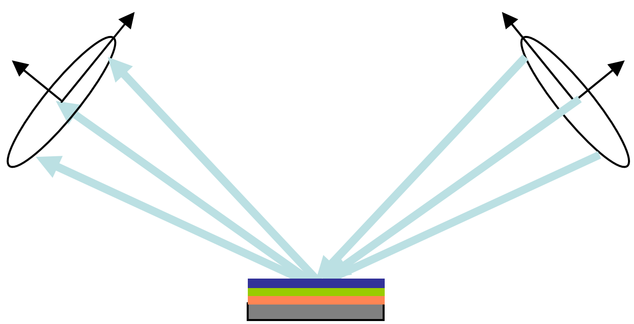
- ***in situ* RTSE**
  - Measures individual layers during deposition



RTSE

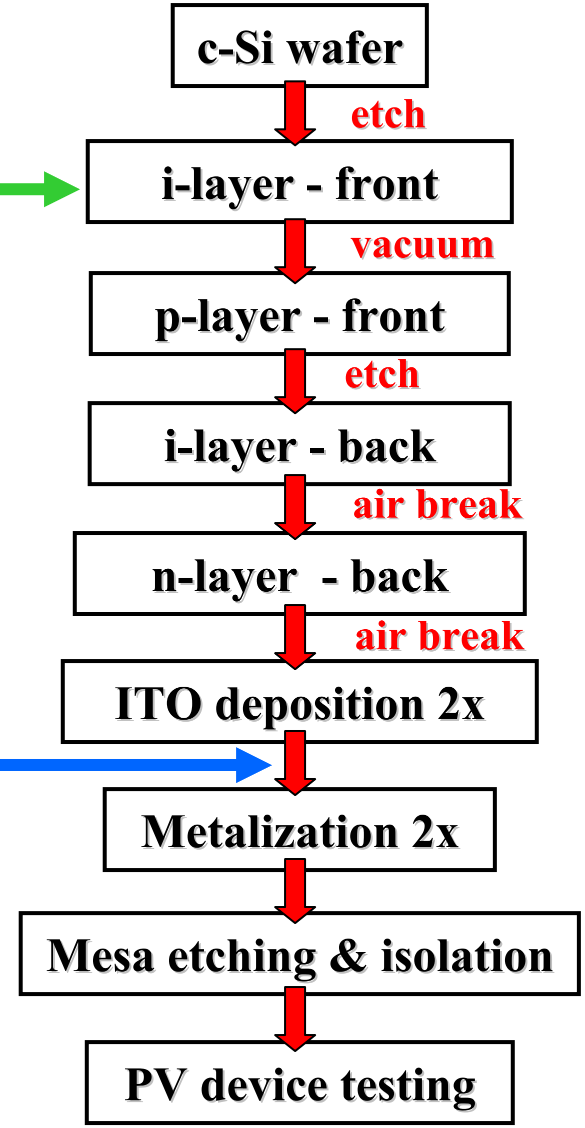
- layer thickness
- growth rate
- surface roughness
- optical properties
- crystallinity

- ***ex situ* VASE**
  - Measures all layers at once in completed device



VASE

<u>On actual devices</u>
- layer thickness
- optical properties
- integrated optical response
- enables optical device modeling



in situ ellipsometry of a-Si:H growth

- ► Surface roughness indicates growth dynamics
- ► Optical properties reveal structural and electronic properties

Evolution of surface roughness: R_s

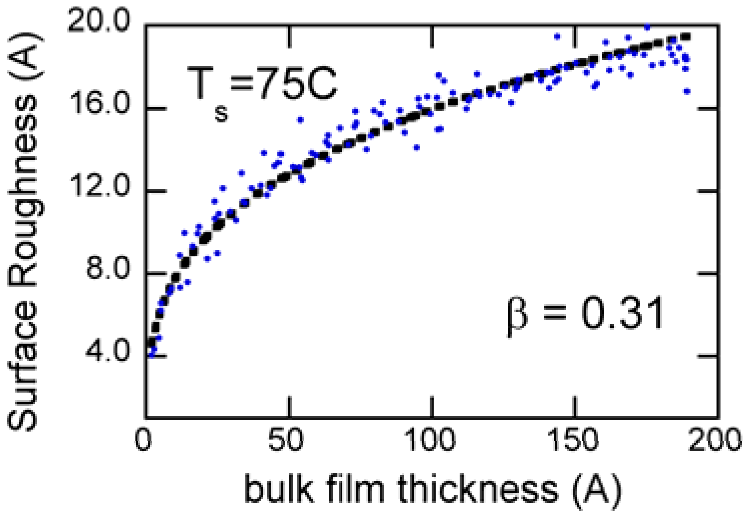
- **The evolution of R_s with bulk film thickness d_b provides insight into the film growth process.**
- **R_s can be represented as a function of d_b**

Growth exponent β

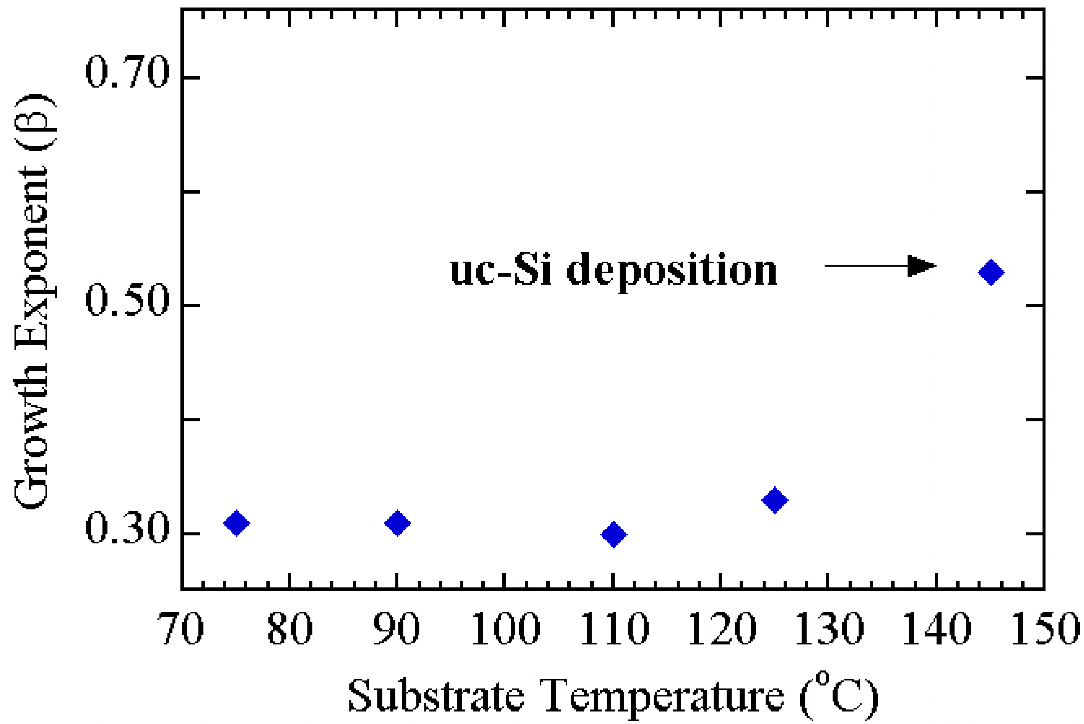
$$R_s \propto d^{\beta}$$

Universality classes

β = 0.5	random deposition
β = 0.25	RD w/diffusion
β = 0	RD w/relaxation



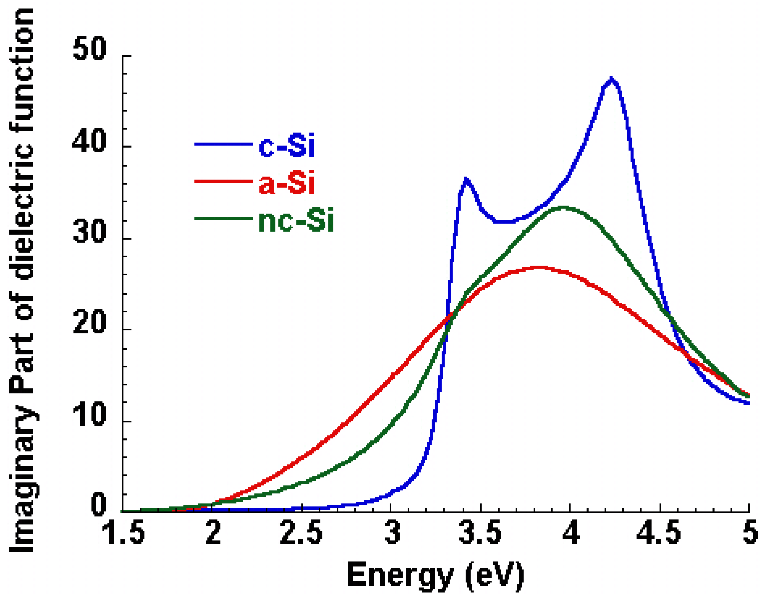
Growth exponent for i-layer growth

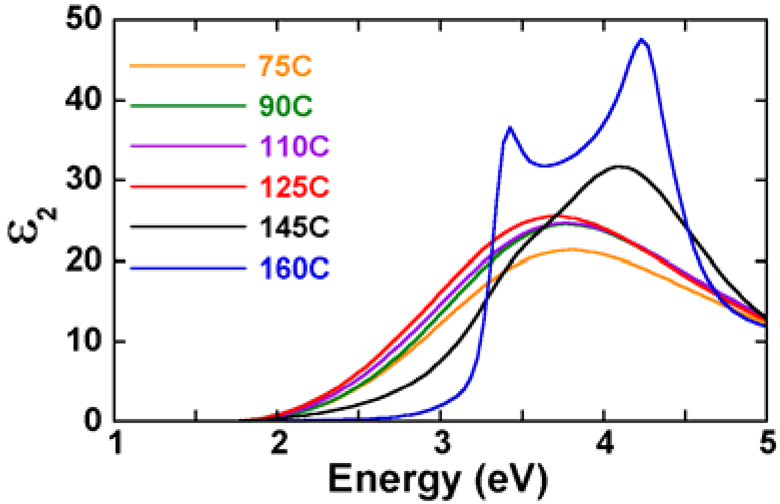


- β is nearly constant for $T_s < 145^oC$
- Abrupt increase in β above 145^oC indicates change in growth mode – uc-Si deposition

Optical properties vs T_s

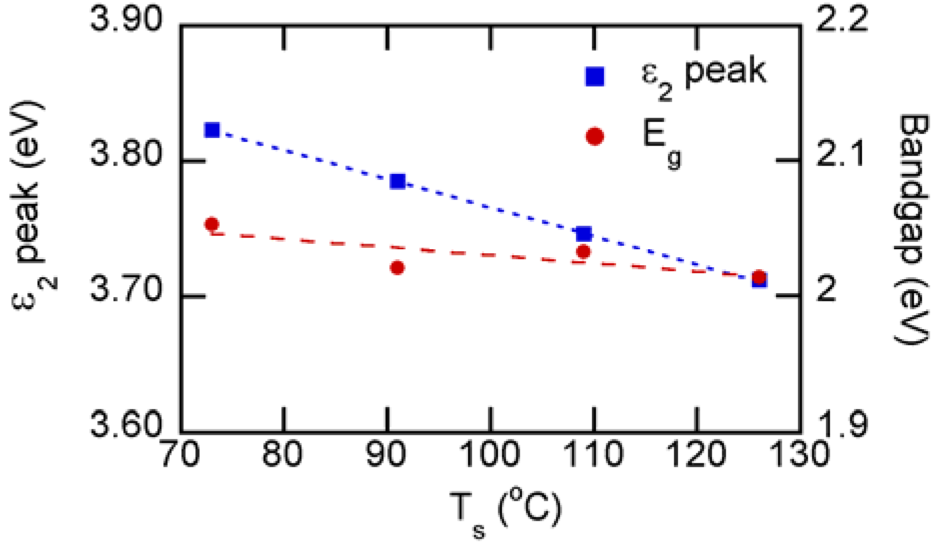
- **i layers are deposited on oxide-free <100> c-Si etched in 5% HF**





- **73C – 126C layers all a-Si:H**
- **144C layer is mixed a-Si:H uc-Si:H**
- **162C layer is epitaxial c-Si**

Analysis of i-layer ε_2 T_s dependence



$d\varepsilon_2/dT_s$ = -210 mev/100°C

dE_g/dT_s = -60 meV/100°C

$\Delta(d\varepsilon_2/dT_s)$ = 17 meV / 1 at.% C(H)*

12% drop in C(H) w/100°C increase in T_s

*** G.F. Feng, et al., Phys. Rev. B 45, 9103 (1992)**

ex situ ellipsometry of finished devices

- Ellipsometry measurement and analysis
- optical model to calculate R,T,A for each layer
- Compare calculations with device performance
  - SHJ compared w/diffused junction
  - 2 SHJ devices w/different p-doping

ex situ SE on finished devices

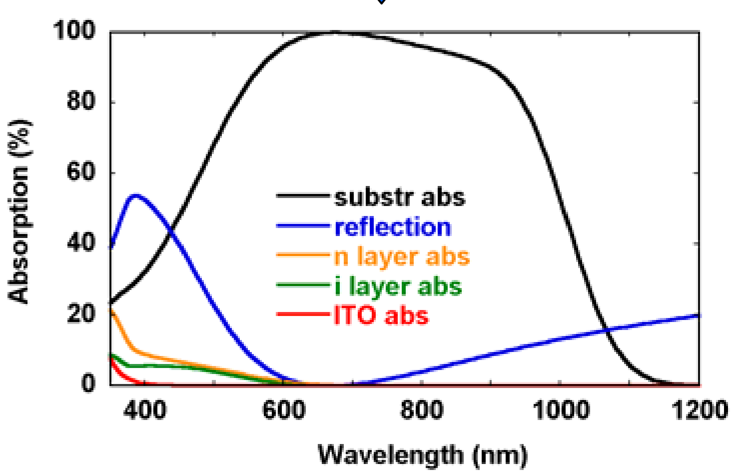
Example: single-sided n-i-p SHJ

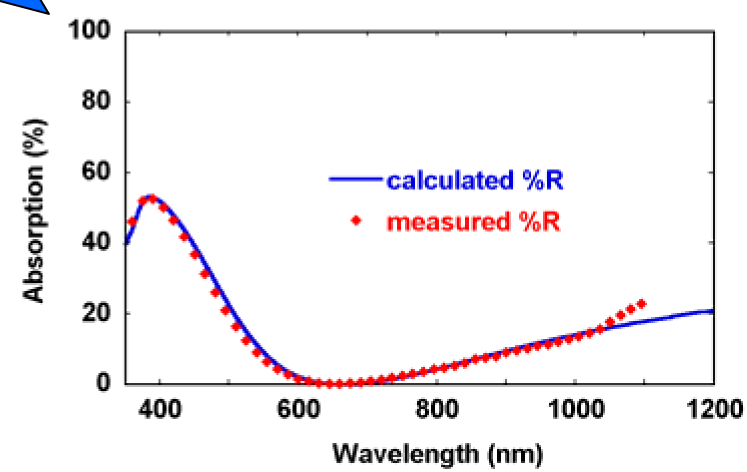
SE measures the amplitude ratio Ψ and the phase change Δ as a function of wavelength at multiple angles

Surface roughness	65 Å
ITO	835 Å
n layer	57 Å
i layer (100°C)	40 Å
c-Si (p-type)	200 μm

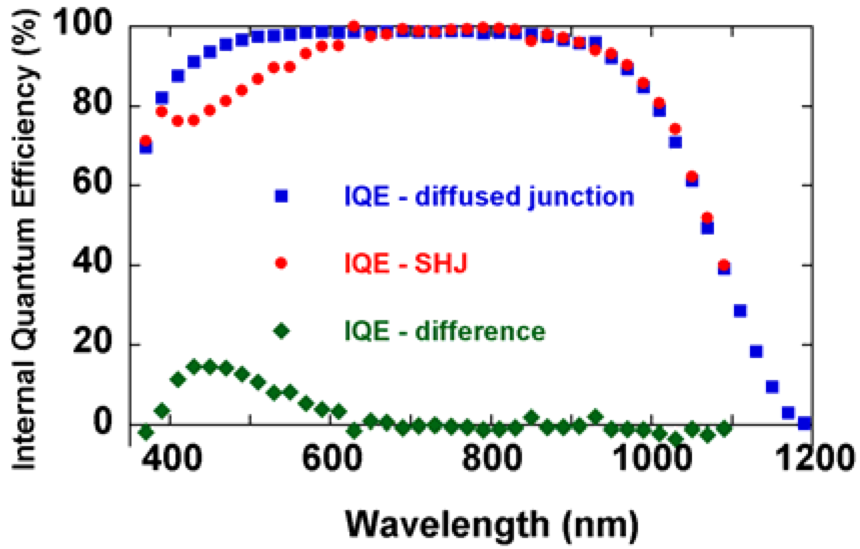
least squares

$$\Psi(\lambda), \Delta(\lambda) = \mathbf{f}[\, n_i(\lambda)\,,\, k_i(\lambda), d_i \,]$$

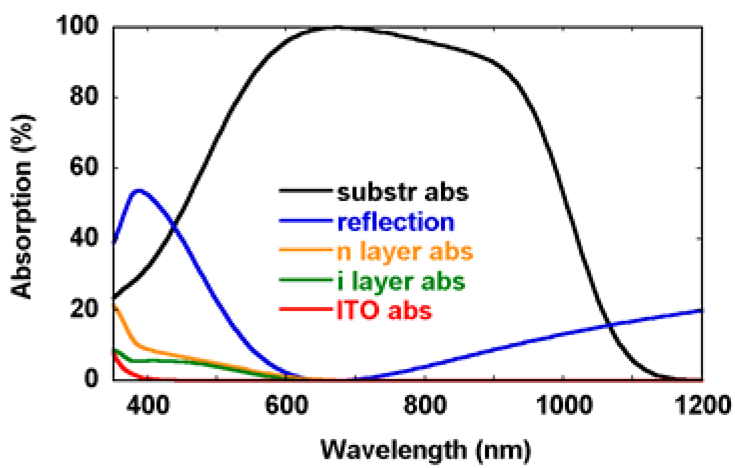


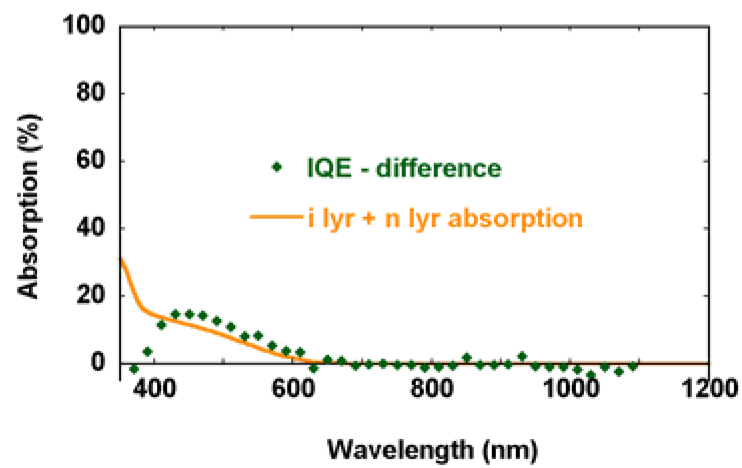


Comparison of SHJ w/diffused junction cell



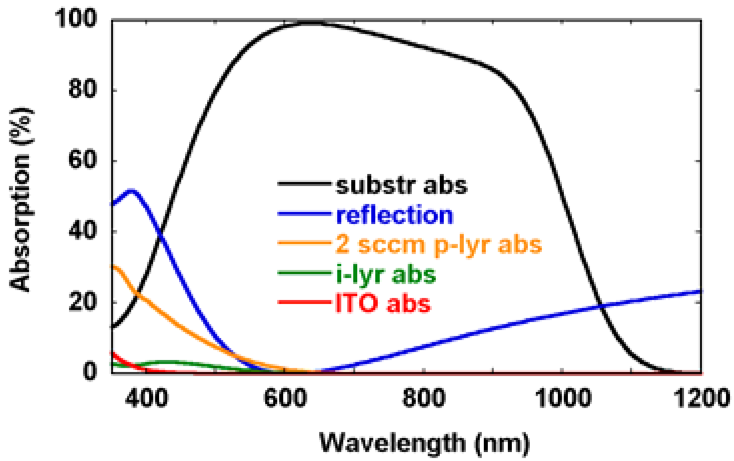
- **Two devices are identical except for front junction (both use Al-BSF contact)**



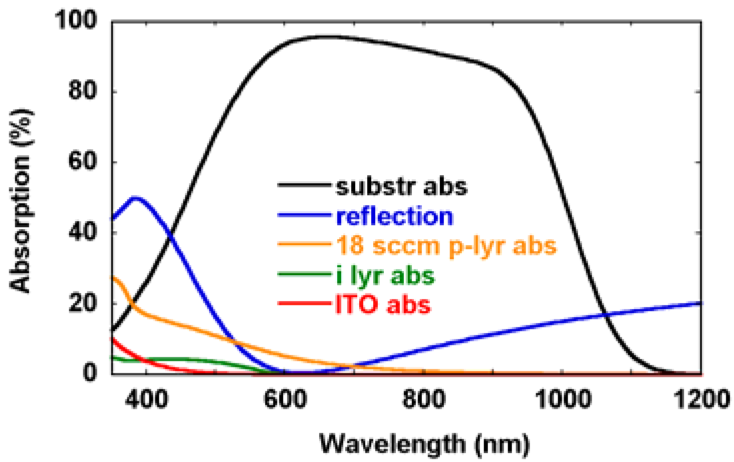


ex situ SE: p-doping comparison

- **2 nominally identical devices**
- **2 sccm vs 18 sccm B_2H_6**



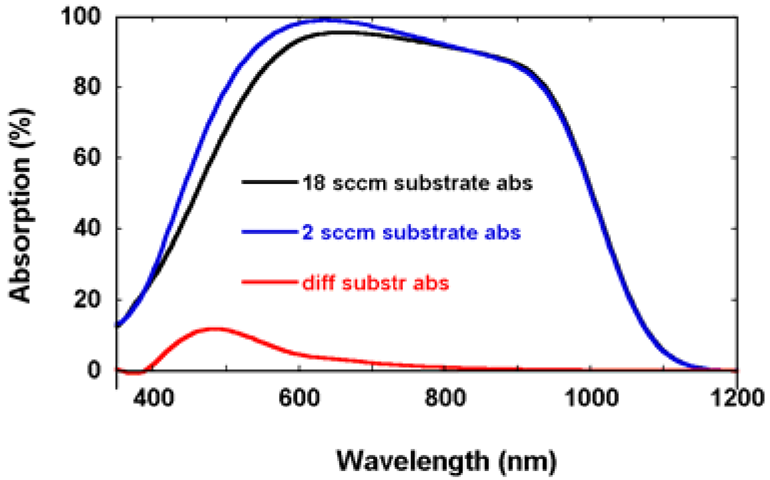
		Dep. Time
Surface roughness	56 Å	
ITO	752 Å	
p layer (2 sccm B_2H_6)	118 Å	50 sec
i layer (100°C)	35 Å	9 sec
c-Si	200 μm	

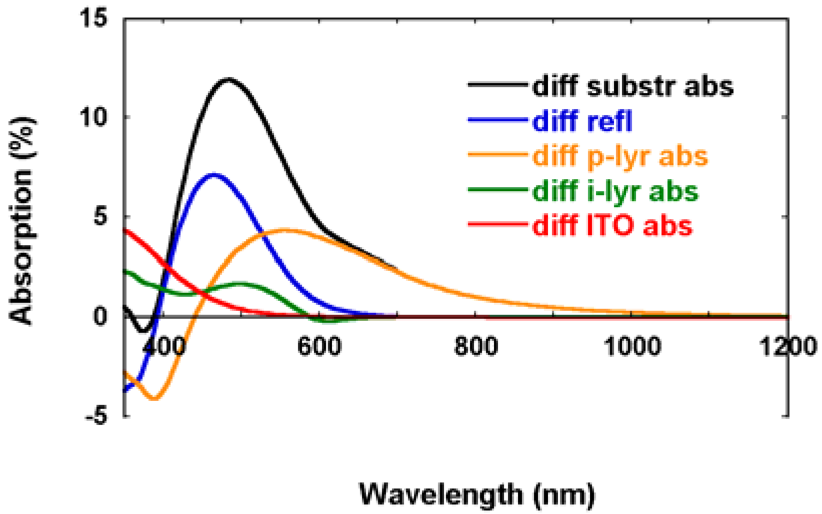


		Dep. Time
Surface roughness	142 Å	
ITO	766 Å	
p layer (18 sccm B_2H_6)	96 Å	50 sec
i layer (100°C)	35 Å	9 sec
c-Si	200 μm	

Device optical performance comparison

- Layer thicknesses and optical constants determined by *ex situ* SE
- Primary difference is p layer doping – flow rate of B_2H_6
- Optical model enables calculation of contribution of each layer





% spectral loss:
18 sccm vs. 2 sccm device = 4.4%

component	% contribution
p-layer abs	38
i-layer abs	14
reflection	34
ITO abs	14

Summary

- *in situ* **SE gives insight into growth mechanisms and accurate layer thickness**
- ***ex situ*** **SE measures completed device structures to determine integrated optical properties**

- **The combination of *in situ* and *ex situ* SE provides a powerful method for pinpointing the effects of processing changes in actual SHJ devices and guiding optimization.**

Acknowledgements

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