



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

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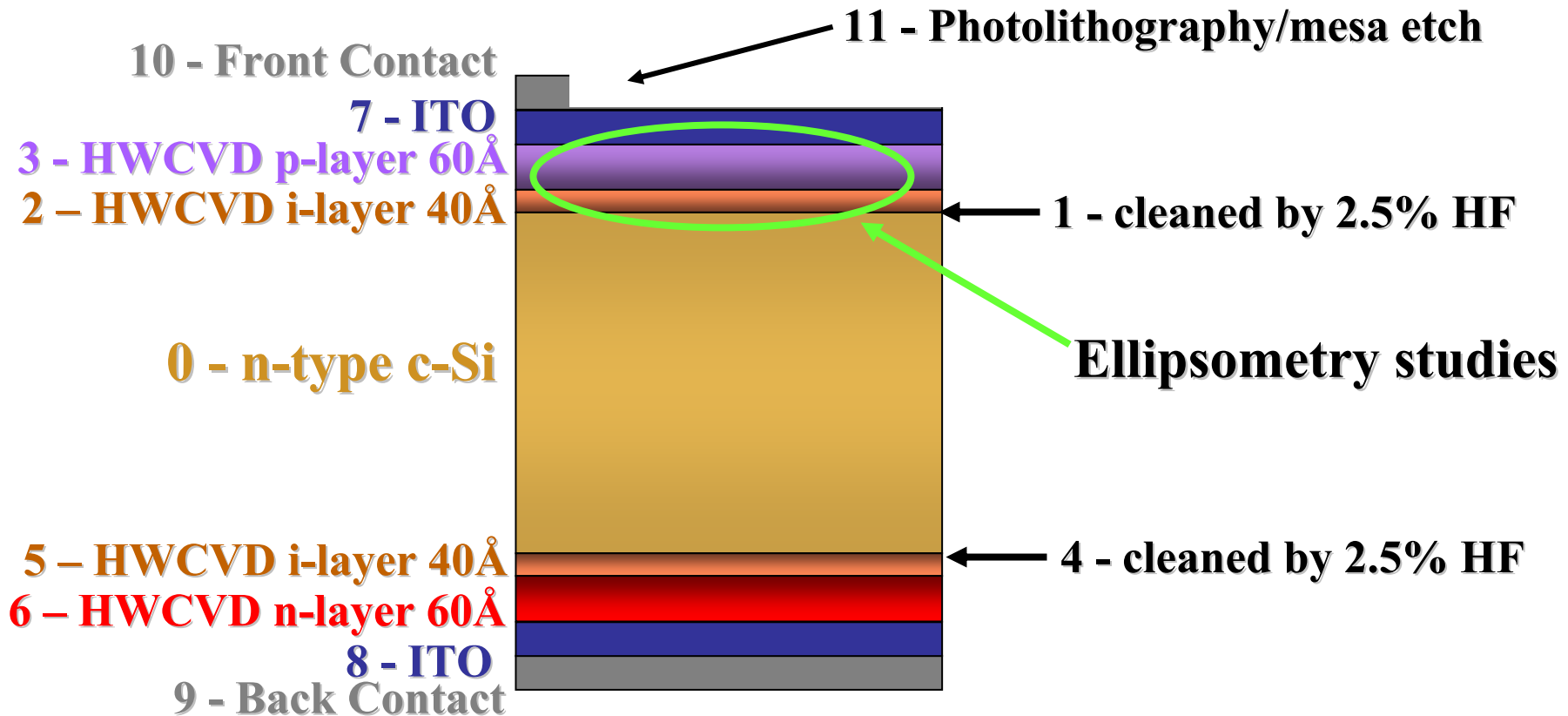
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SHJ Solar Cell Fabrication

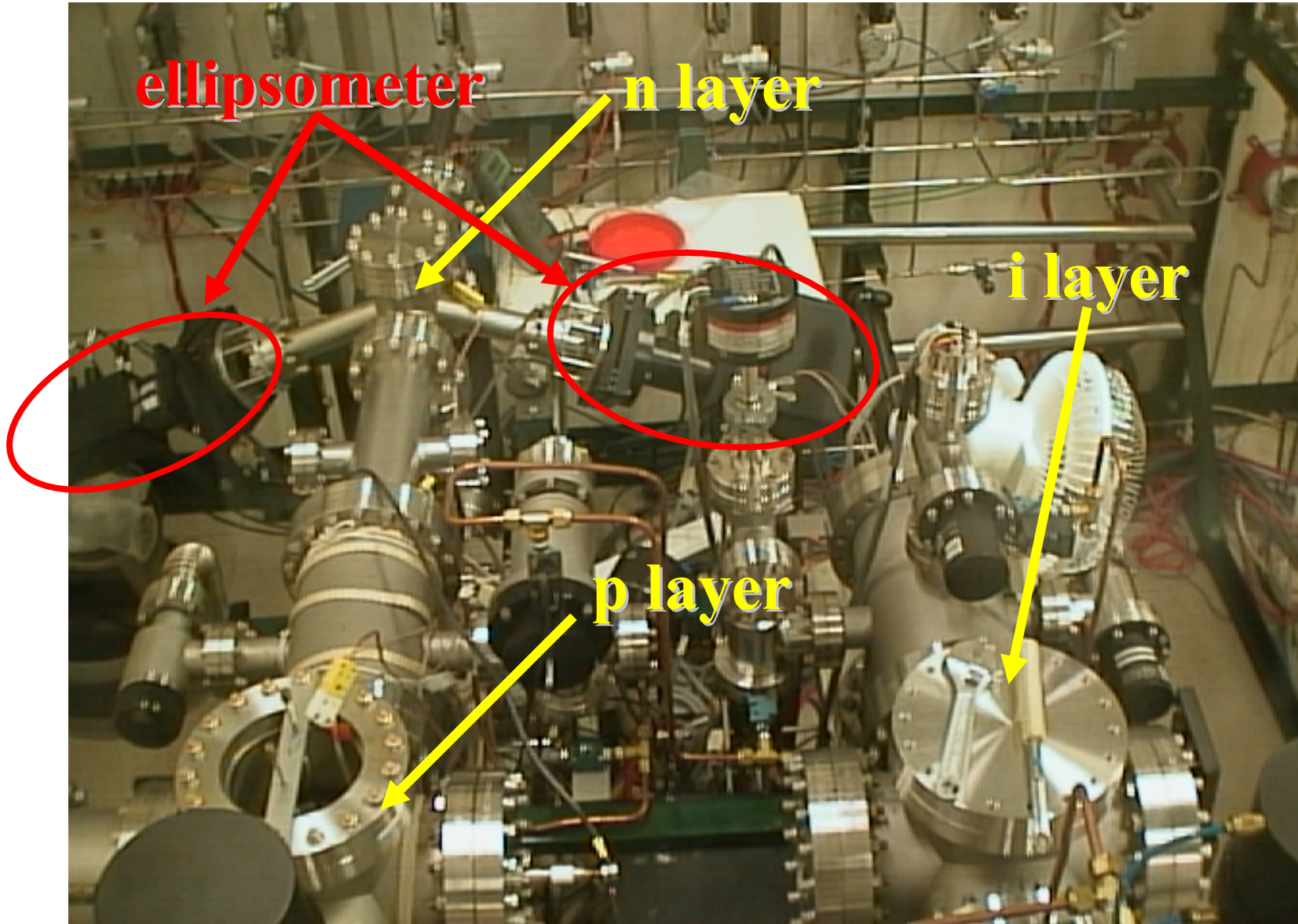


Flat wafers $\eta = 16.9\%$

Textured wafers $\eta = 17.8\%$

HWCVD deposition system:

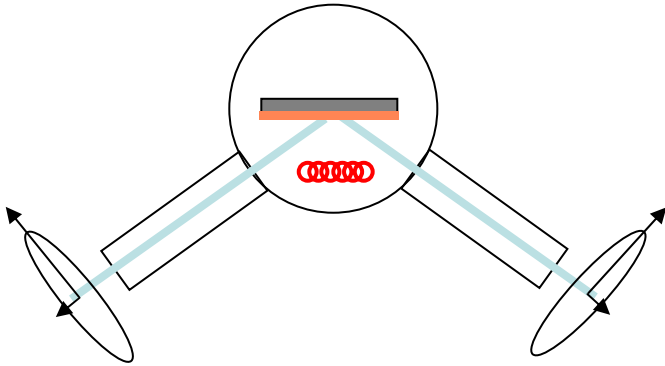
i, n, and p layers are deposited in separate chambers



Fabrication and characterization sequence

- *in situ* RTSE

- Measures individual layers during deposition

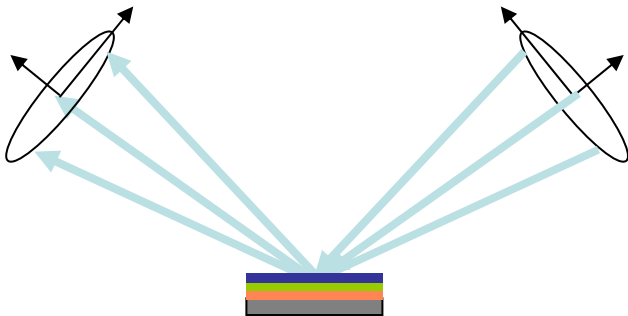


- layer thickness
- growth rate
- surface roughness
- optical properties
- crystallinity

RTSE

- *ex situ* VASE

- Measures all layers at once in completed device



On actual devices

- layer thickness
- optical properties
- integrated optical response
- enables optical device modeling

VASE

c-Si wafer

etch

i-layer - front

vacuum

p-layer - front

etch

i-layer - back

air break

n-layer - back

air break

ITO deposition 2x

Metalization 2x

Mesa etching & isolation

PV device testing

***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.

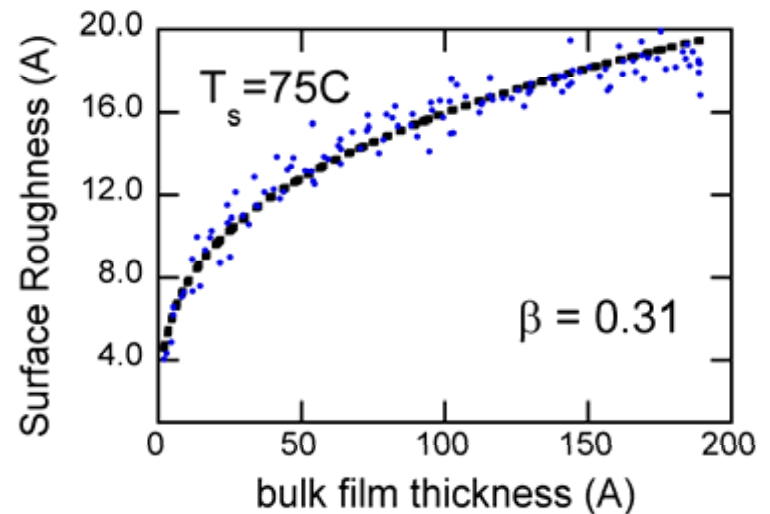
Growth exponent β

- R_s can be represented as a function of d_b

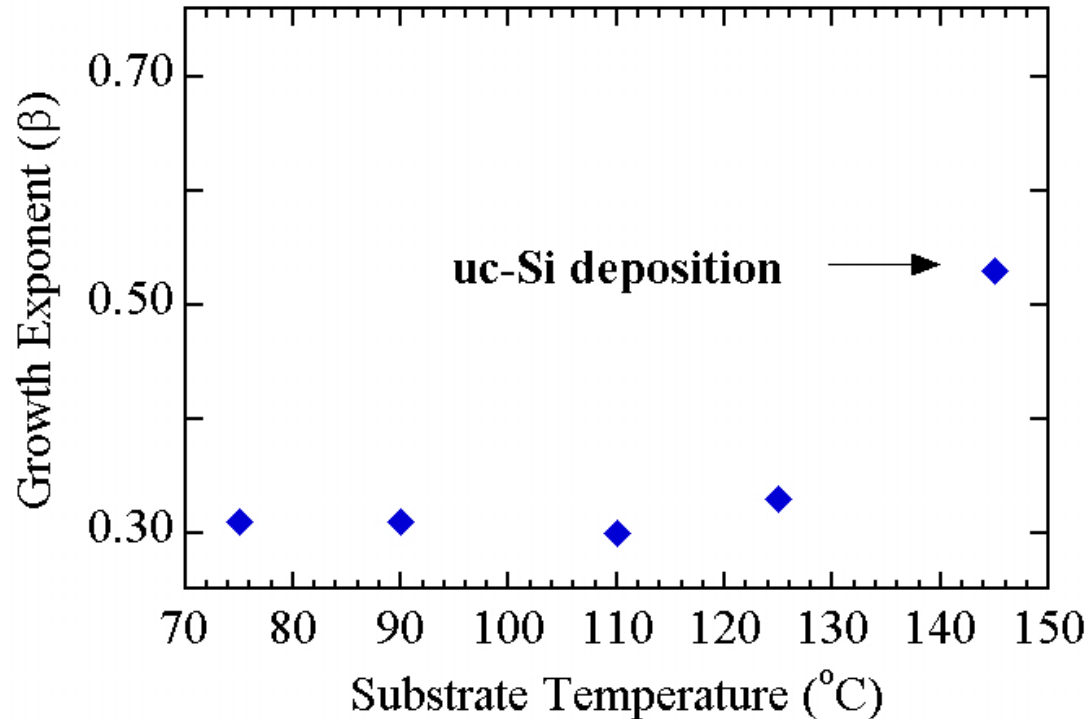
$$R_s \propto d_b^\beta$$

Universality classes

$\beta = 0.5$ random deposition
 $\beta = 0.25$ RD w/diffusion
 $\beta = 0$ RD w/relaxation



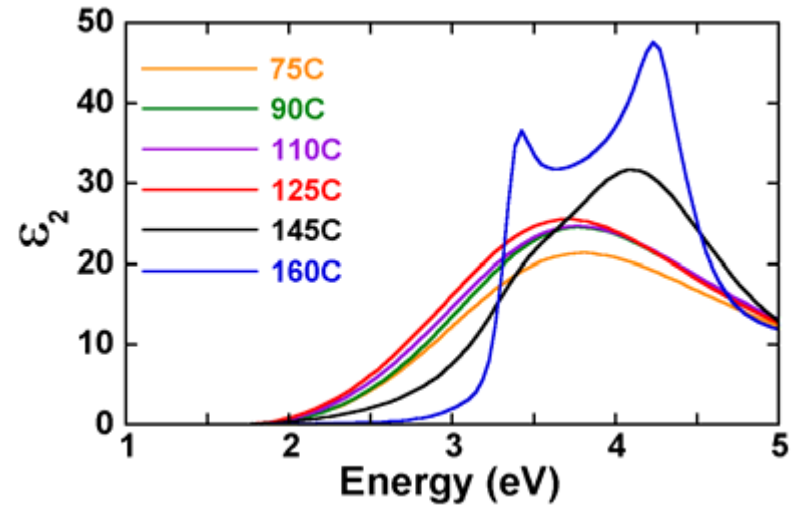
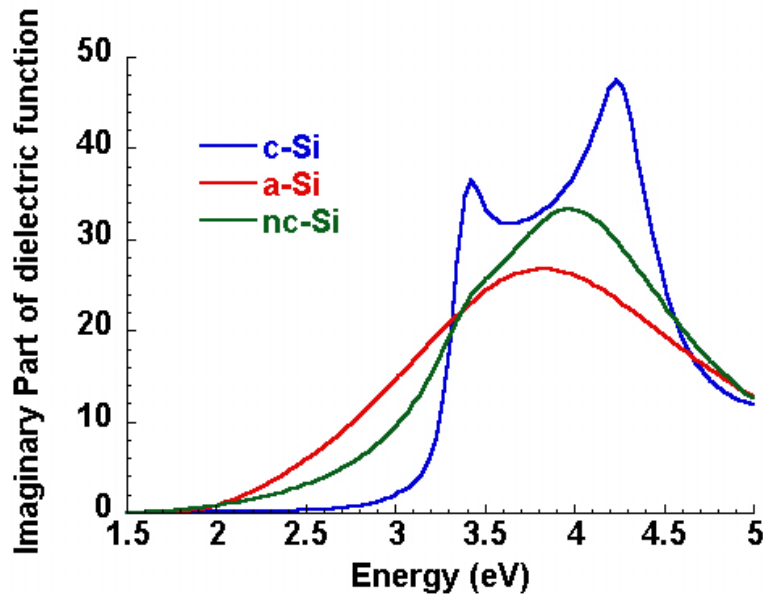
Growth exponent for i-layer growth



- β is nearly constant for $T_s < 145^{\circ}\text{C}$
- Abrupt increase in β above 145°C indicates change in growth mode – uc-Si deposition

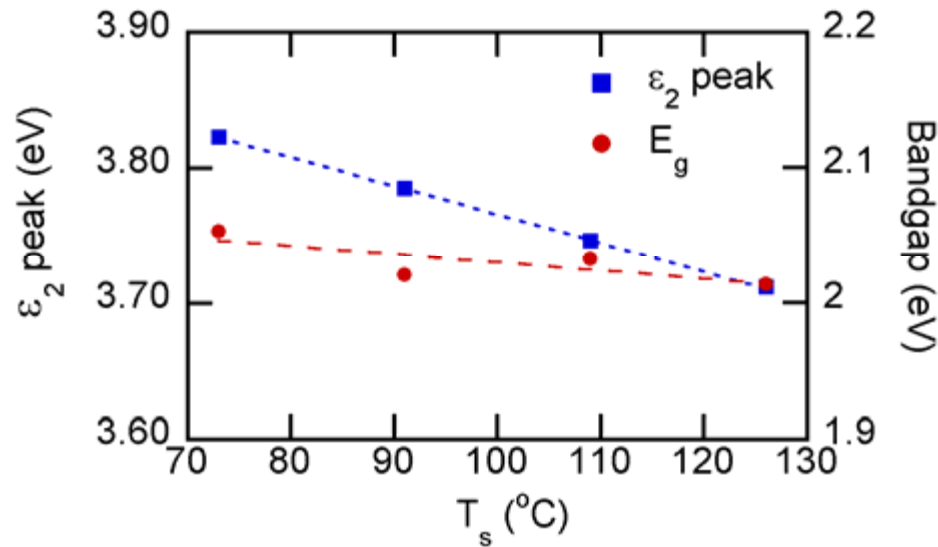
Optical properties vs T_s

- **i layers** are deposited on oxide-free $\langle 100 \rangle$ 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



$$d\epsilon_2/dT_s = -210 \text{ meV}/100^{\circ}\text{C}$$

$$dE_g/dT_s = -60 \text{ meV}/100^{\circ}\text{C}$$

$$\Delta(d\epsilon_2/dT_s) = 17 \text{ meV} / 1 \text{ at.}\% \text{ C(H)}^*$$

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**

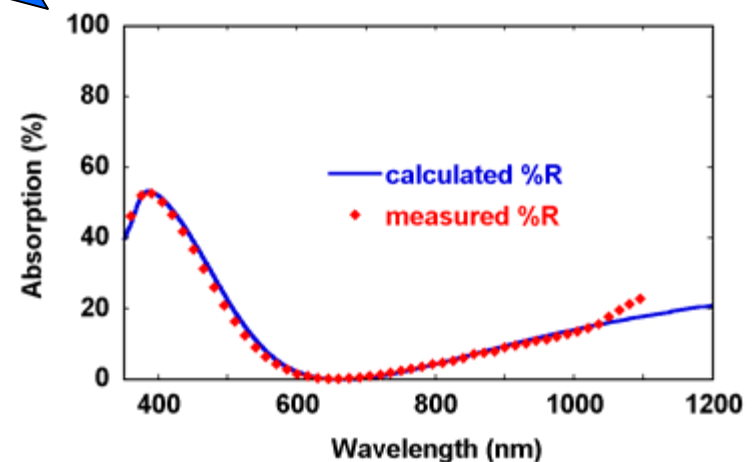
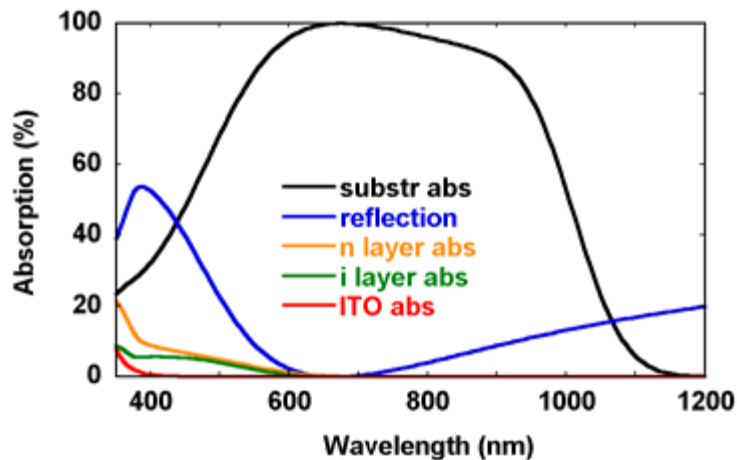
ex situ SE on finished devices

Example: single-sided n-i-p SHJ

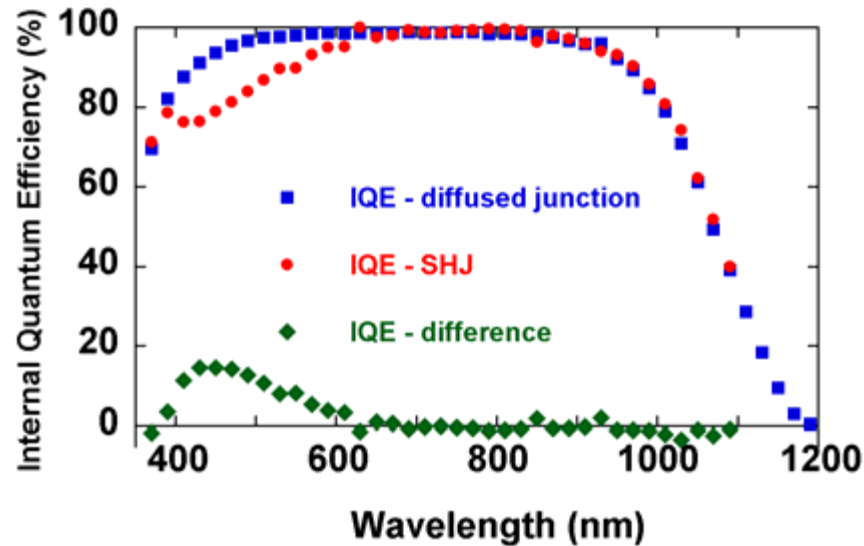
SE measures the amplitude ratio Ψ and the phase change Δ as a function of wavelength at multiple angles

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

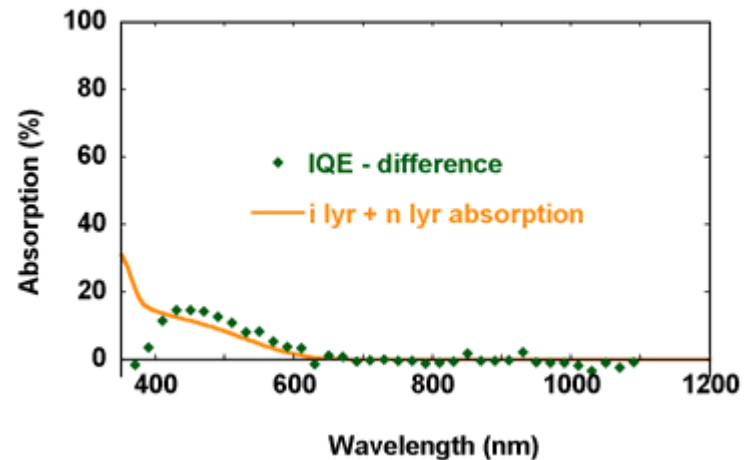
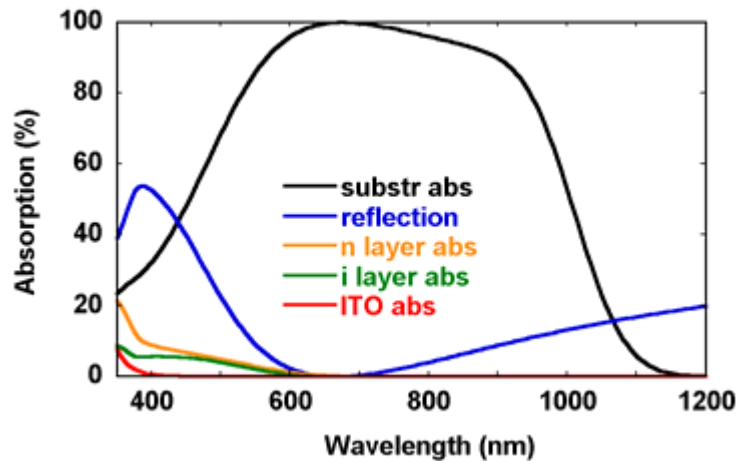
least squares $\Psi(\lambda), \Delta(\lambda) = \mathbf{f}[n_i(\lambda), k_i(\lambda), d_i]$



Comparison of SHJ w/diffused junction cell

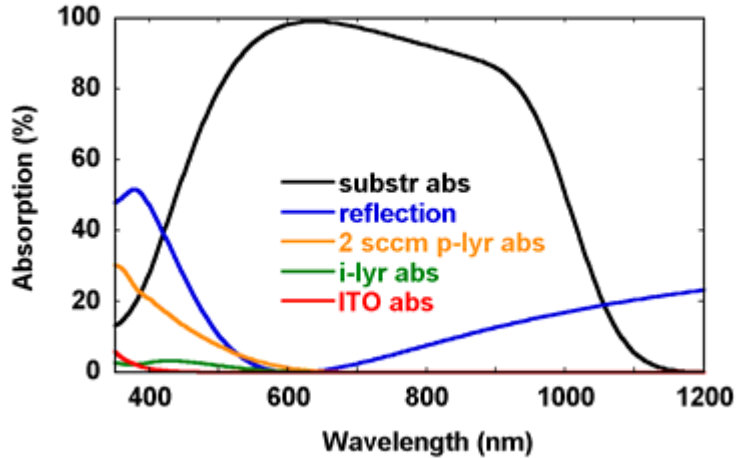


- Two devices are identical except for front junction (both use Al-BSF contact)



ex situ SE: p-doping comparison

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

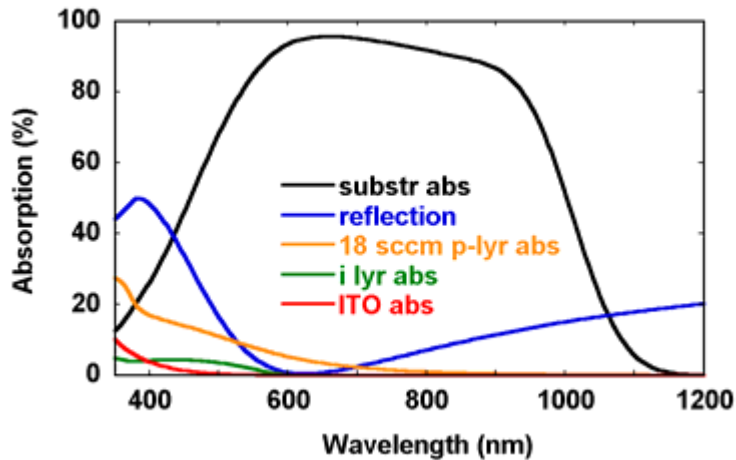


Surface roughness	56 Å
ITO	752 Å
p layer (2 sccm B_2H_6)	118 Å
i layer (100°C)	35 Å
c-Si	200 μm

Dep.
Time

50 sec

9 sec



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

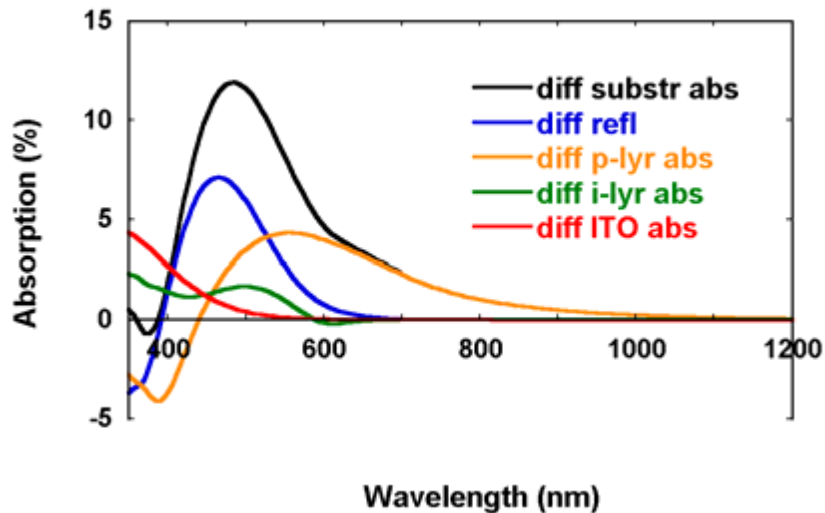
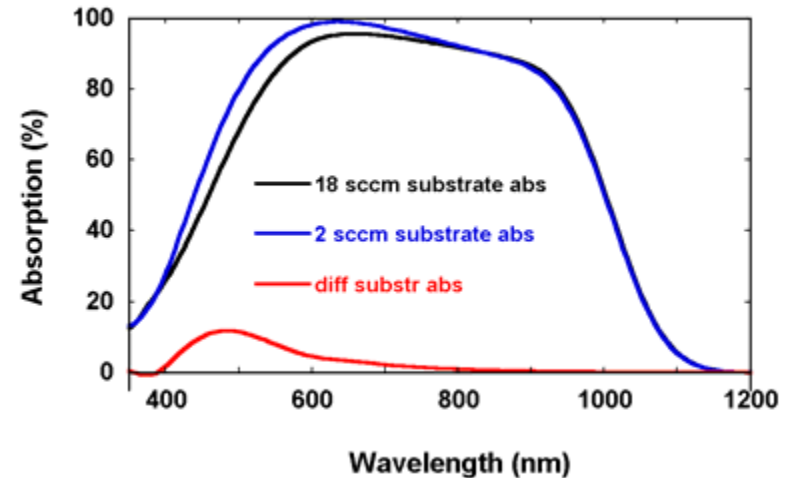
Dep.
Time

50 sec

9 sec

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.**



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