Thin Film PV Transparent Conductive Oxide History, Functions, and Developments

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Introduction

- Thin-film modules often require a front Transparent Conductive Oxide (TCO)
- High growth thin-film PV industry requires rapidly growing material supply.
- Textured tin oxide can be produced on a float production line with large volumes and good economies of scale.

History

- Early TCO's were produced off-line
- On-line textured SnO_2:F TCO for a-Si first produced in late 1993.
- Sizes up to 130" x 204" (3.3 x 5.2m)
- 10 miles per day in length
- Enough for 4.2 MW per day at 8% efficiency
- About 410 tons per day of front glass

Fluorine Doped Tin Oxide

- Mechanically durable
- Easily produced and processed
- Heat resistant
- Chemically stable
- Moisture resistant
- Controllable morphology
- Lower cost than other TCOs such as ITO
- Can resist sodium damage

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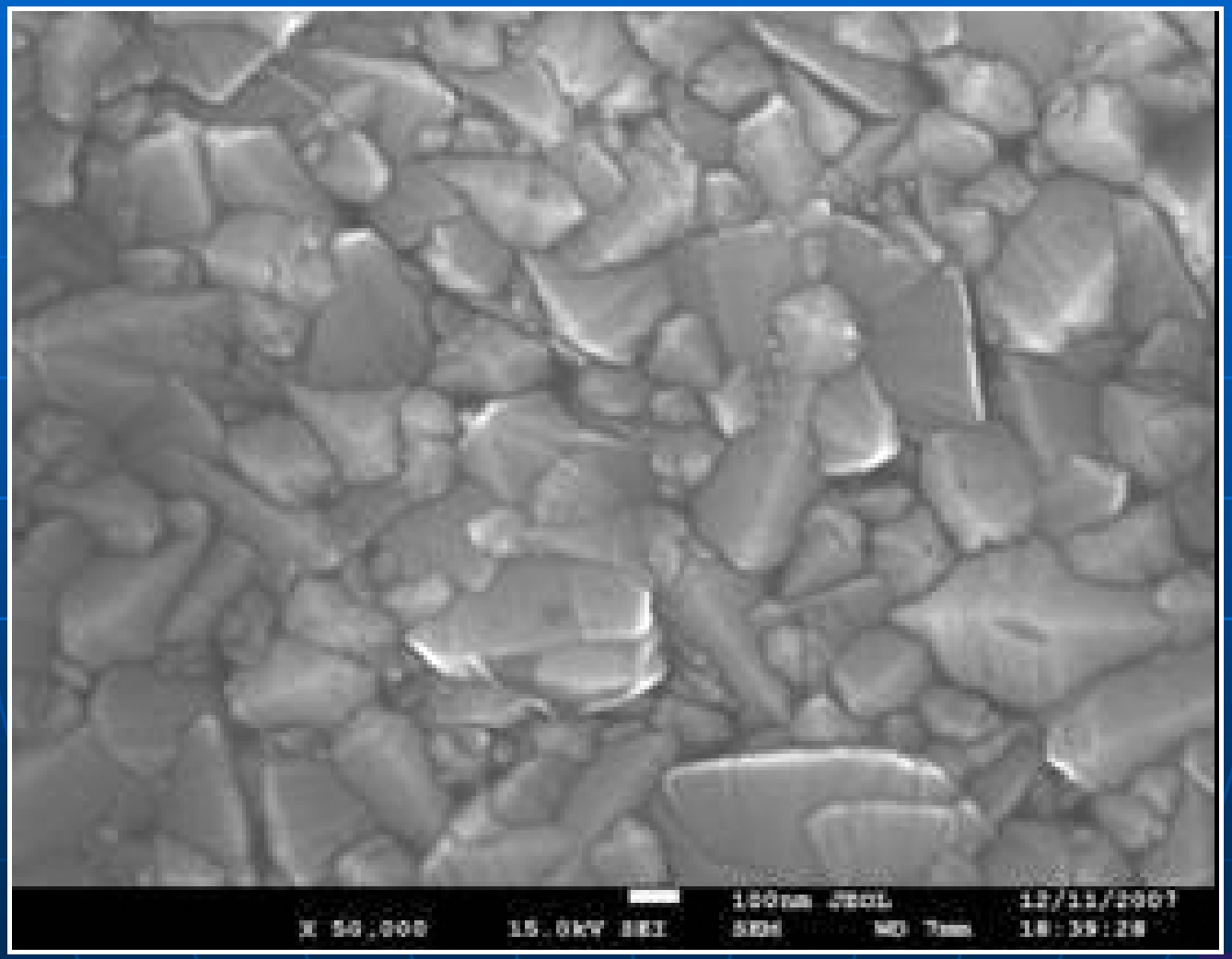
Properties and Functions

- Haze (texture)
- Light transmission
- Conductivity

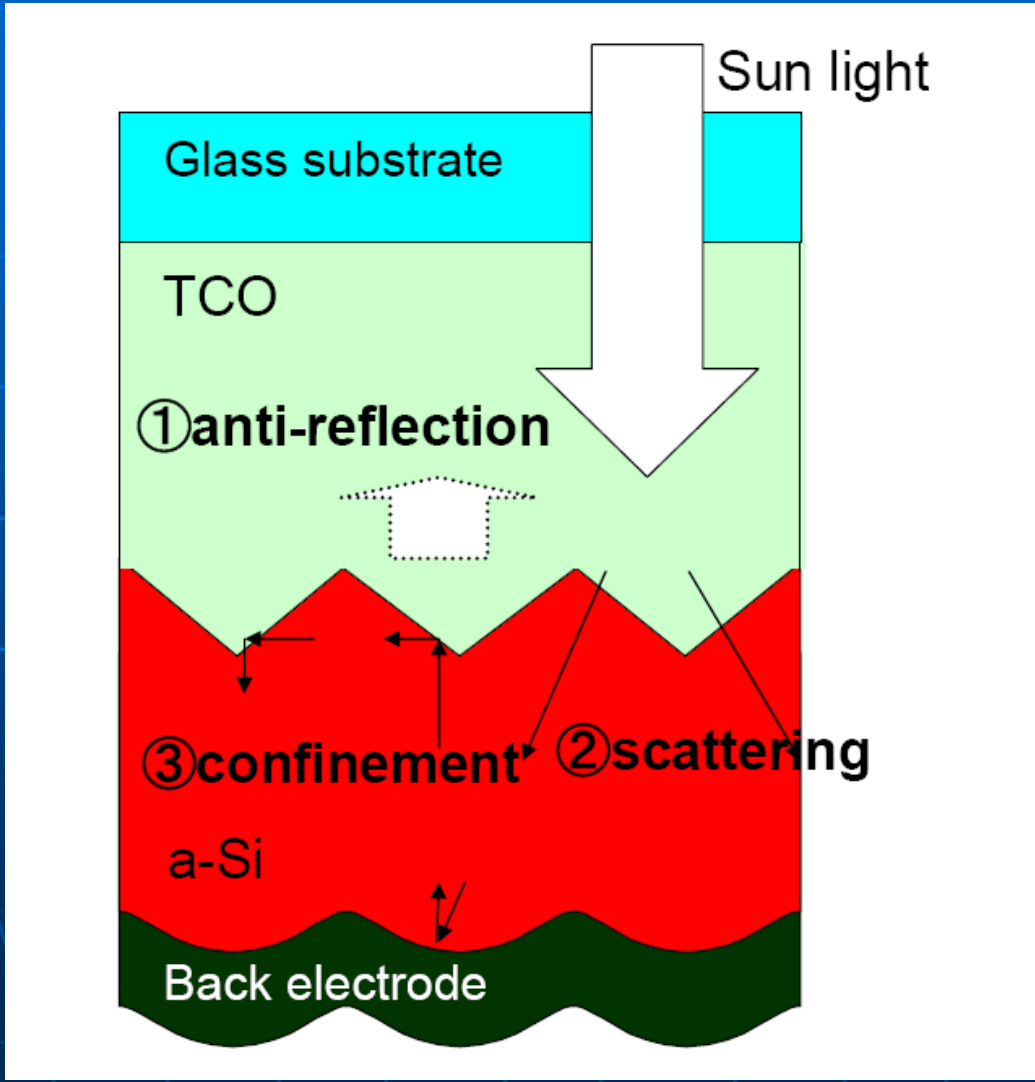
Haze

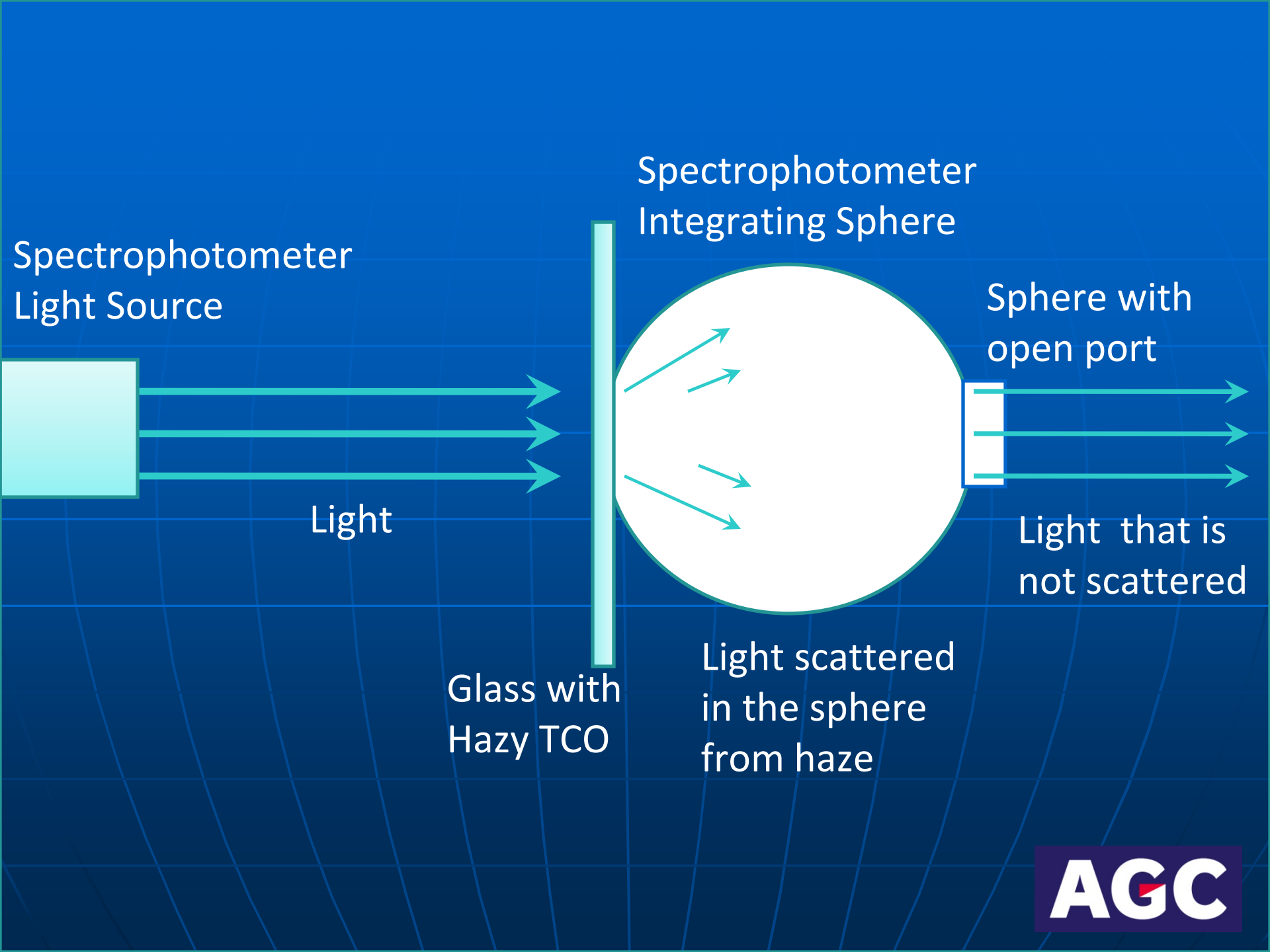


Haze

- Scatters light into the silicon layers
- Creates a gradient index of refraction between the tin oxide and silicon.
- Imposes texture to the back contact for light scattering.
- Increases surface area for electron transport
- Increases active area of silicon
- Increases surface area for silicon adhesion

Haze


Sun light
Glass substrate
TCO
①anti-reflection
③confinement
②scattering
a-Si
Back electrode


Spectrophotometer
Integrating Sphere
Spectrophotometer
Light Source
Sphere with
open port
Light
Light that is
not scattered
Glass with
Hazy TCO
Light scattered
in the sphere
from haze
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Light Transmission

- Desire a low absorption coefficient
- Low carrier concentration
- High electron mobility
- Good morphology required
- Can be more accurately measured by reducing haze error by covering with methylene iodide (CH_2I_2) and a quartz plate
- Low iron glass

Conductivity

- Measured by a four-point probe
- Carrier concentration
- Electron mobility
- Film thickness
- Crystal shape, size, orientation
- Can be fixed conductivity or mobility shifting

TCO Adhesion

- TCOs can be subject to peeling due to sodium in the glass if the TCO is not properly designed
- The best published test is by Energy Photovoltaics (EPV):
- K. W. Jansen, Dr. A. E. Delahoy “A Laboratory Technique for the Evaluation of Electrochemical Transparent Conductive Oxide Delamination from Glass Substrates,” Thin Solid Films 423 153 – 160 (2003), Elsevier Science B.V. (2002)

Tempering/Heat Strengthening

Modulus of Rupture (M.O.R.) in Flexure 60 Second Duration:

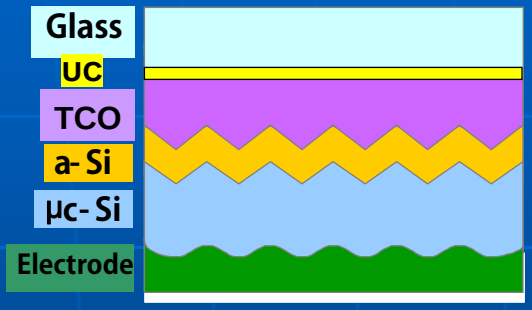
- Mean M.O.R. (Probability of breakage 50%)
  - 6,000 psi (41 MPa) Annealed
  - 12,000 psi (82 Mpa) Heat Strengthened
  - 24,000 psi (165 Mpa) Tempered
  -

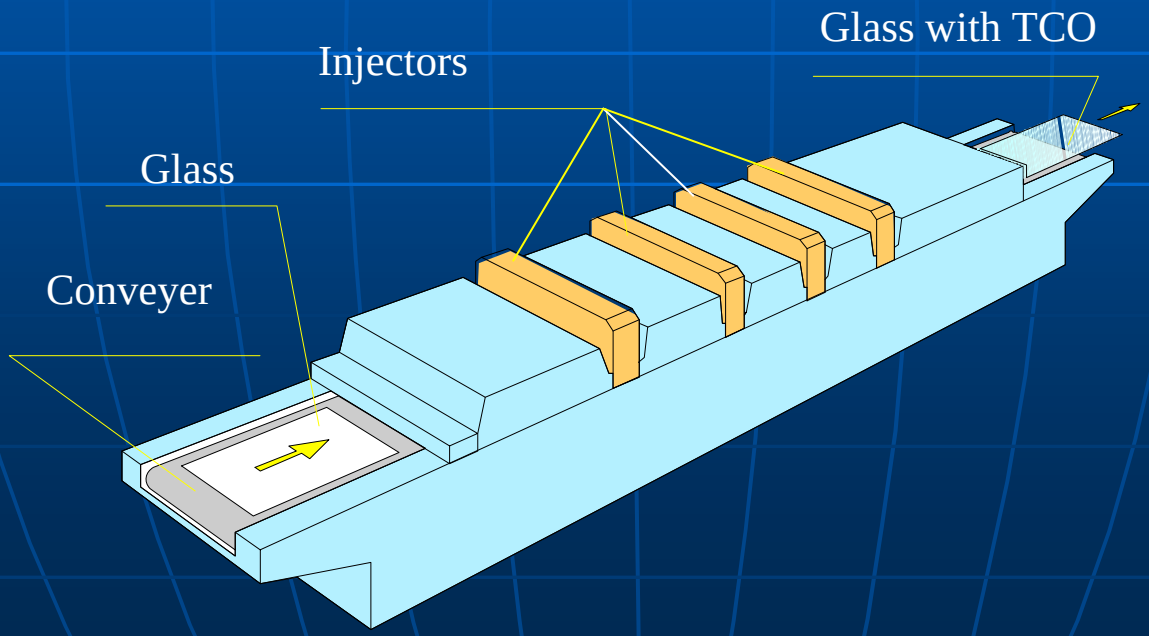
Typical Design M.O.R. (Probability of breakage 0.8%)

- 2,800 psi (19 Mpa) Annealed
- 5,600 psi (39 Mpa) Heat Strengthened
- 11,200 psi (77 Mpa) Tempered

Recent Advances in TCOs

Objective: Develop optimal TCO
For a-Si/μc-Si tandem solar cell





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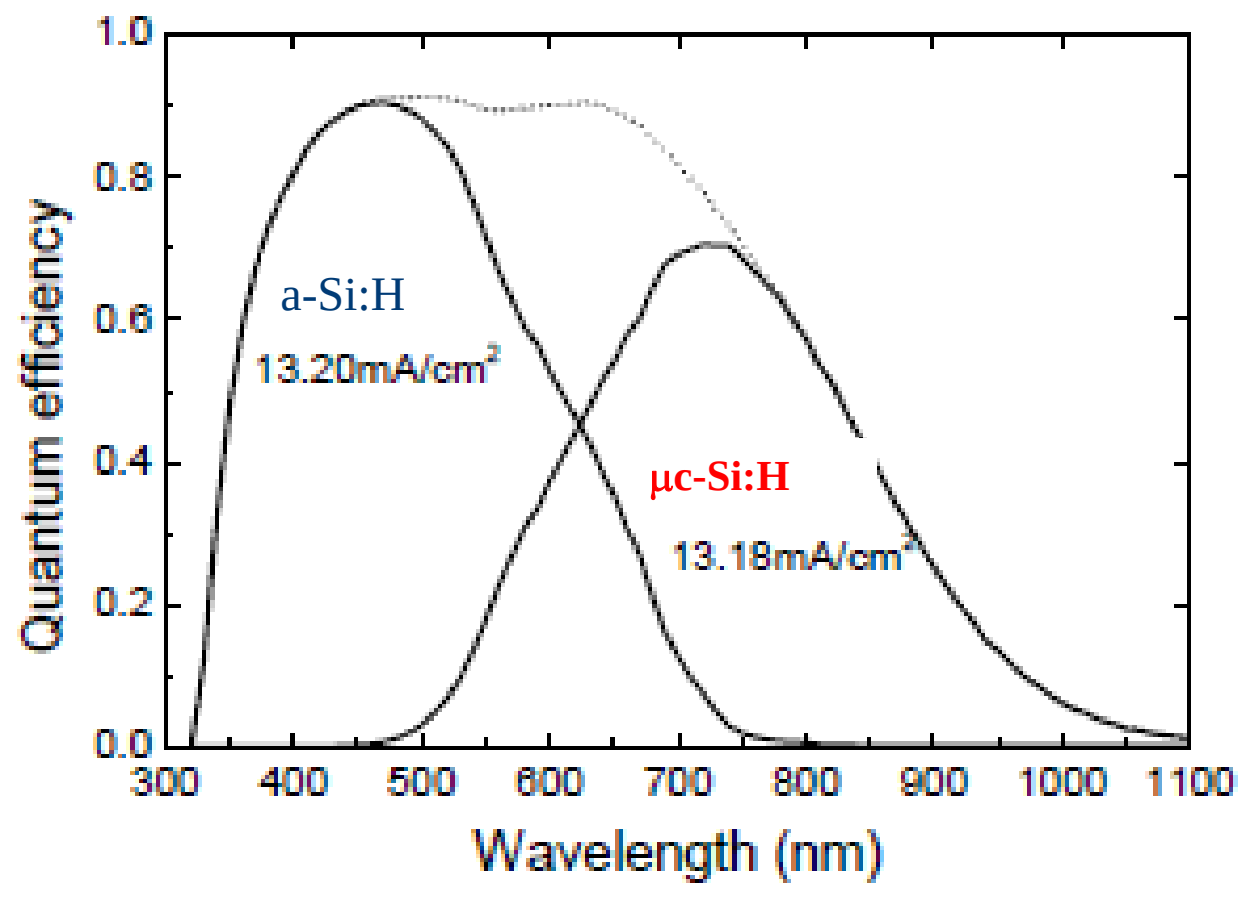
QE by Wavelength



M.Vanecek, J.Springer et al.
Proceedings of WCPEC-3, p1527,(2003)

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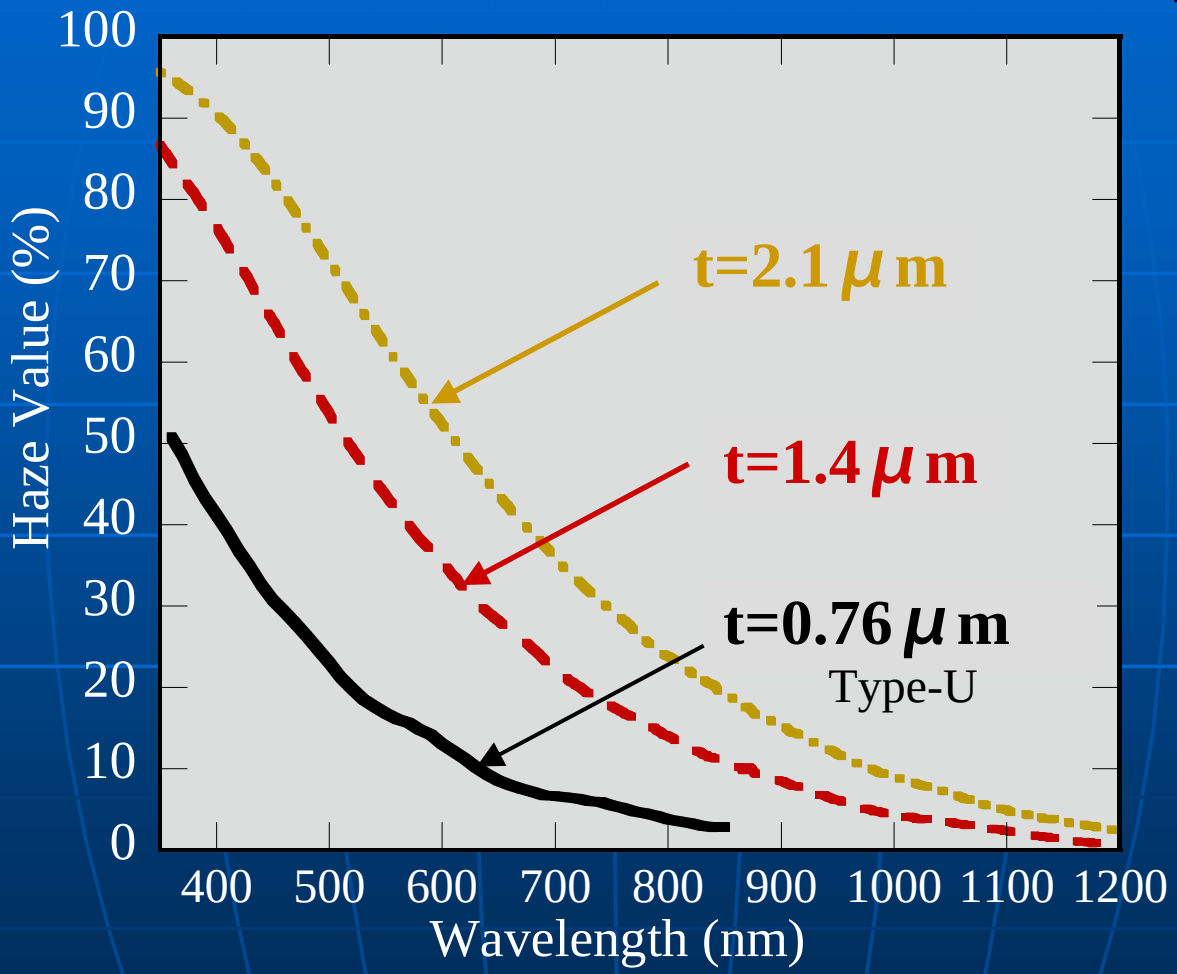
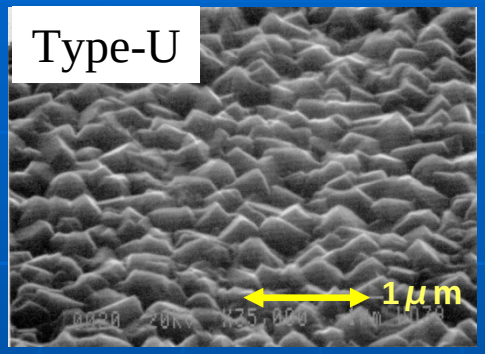
Haze vs λ Normal SnO_2:F

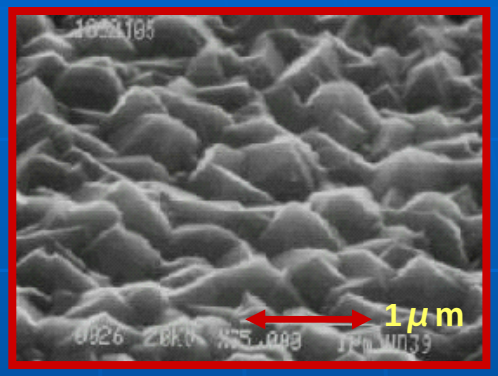


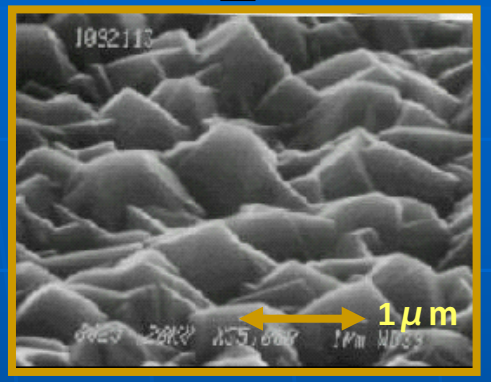
Haze decreases with increasing wavelength.

Properties of Normal SnO_2:F

SEM Images







Thickness	0.76μm	1.4μm	2.1μm
Haze Value (at 550nm)	16 %	42%	58%
Transparency (at 550nm)	88%	86%	85%
Sheet resistance	8 Ω/sq	5 Ω/sq	4 Ω/sq
RMS	45nm	62nm	80nm

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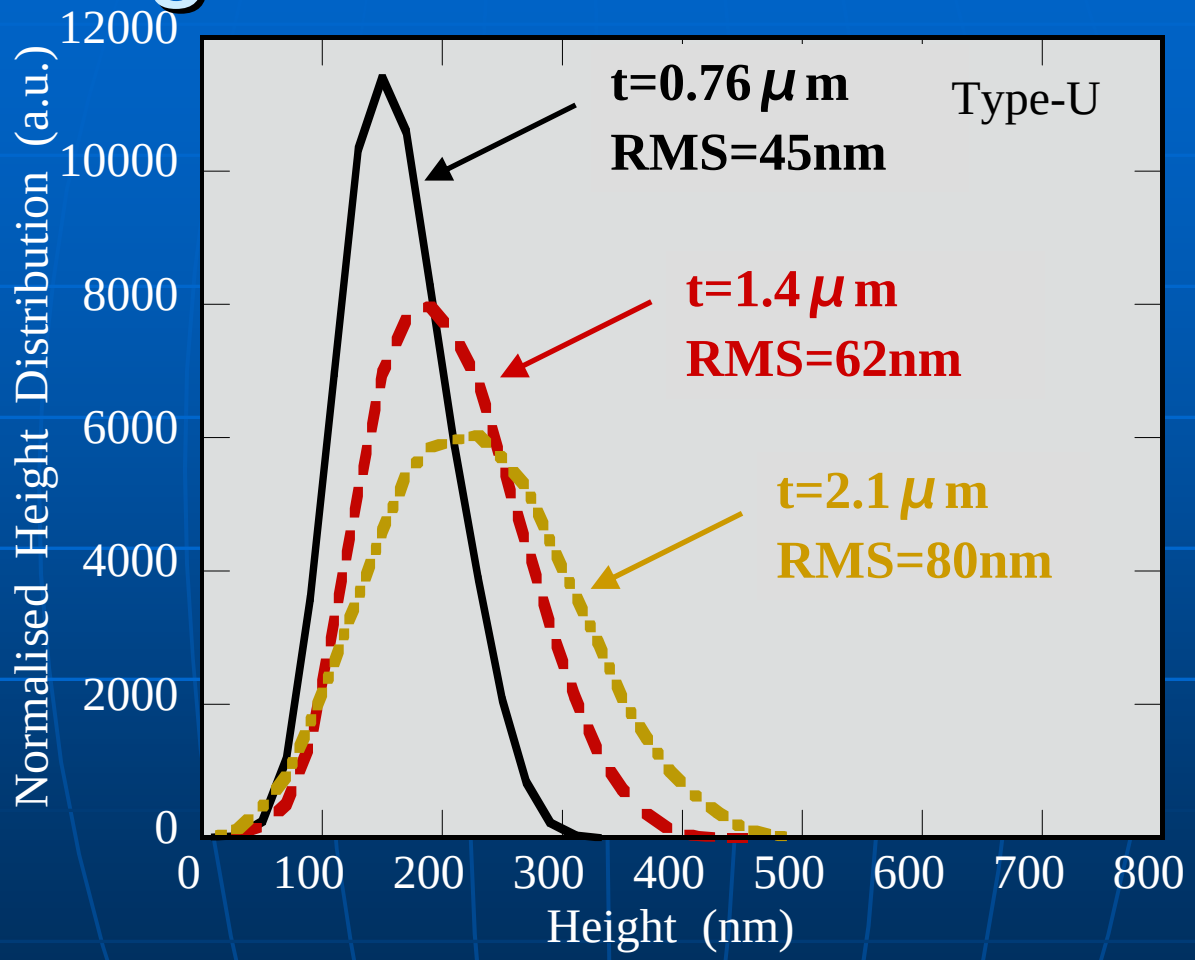
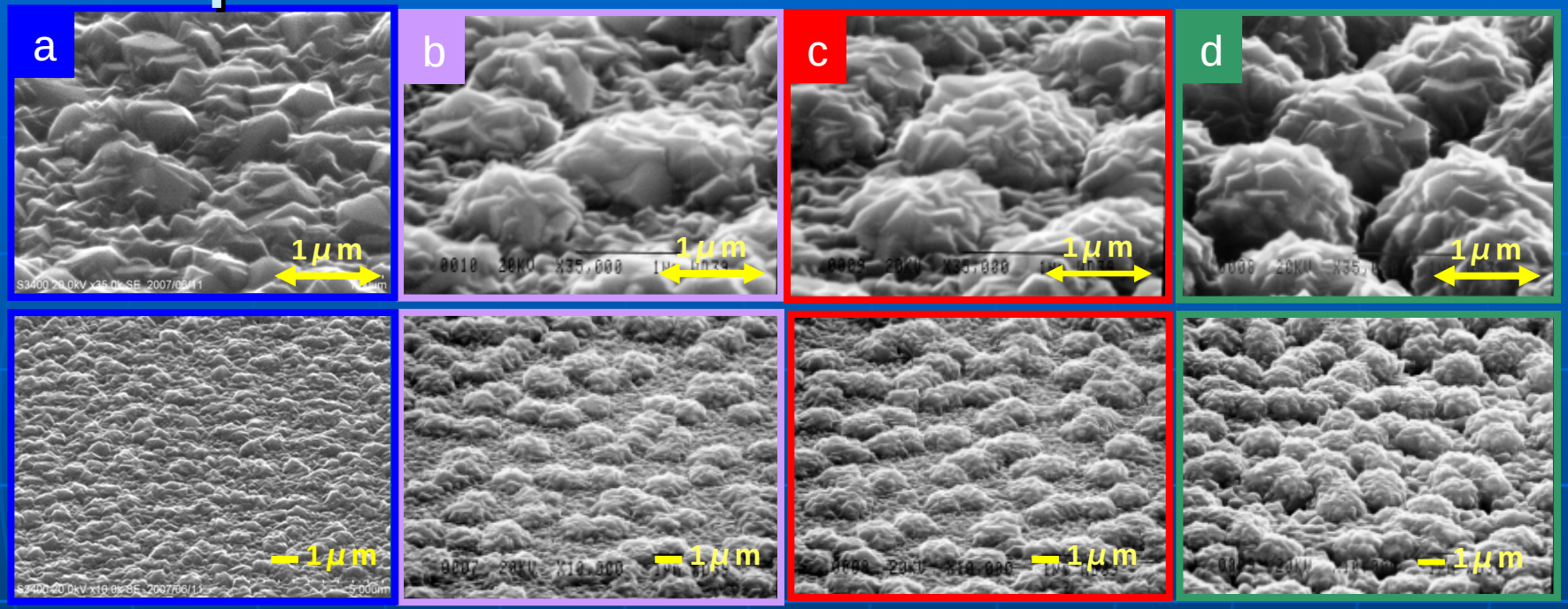
Height Distribution Curve



Thicker film has larger height distribution that results in large haze values, but no benefit at wavelengths over 500 nm.

Properties of W-Textured Films



Haze Value (at 550nm)

a	b	c	d
35 %	84%	95%	90%

Transparency (at 550nm/at800nm)

a	b	c	d
89%/88%	89%/88%	88%/88%	89%/88%
10Ω/sq	9 Ω/sq	8 Ω/sq	10 Ω/sq

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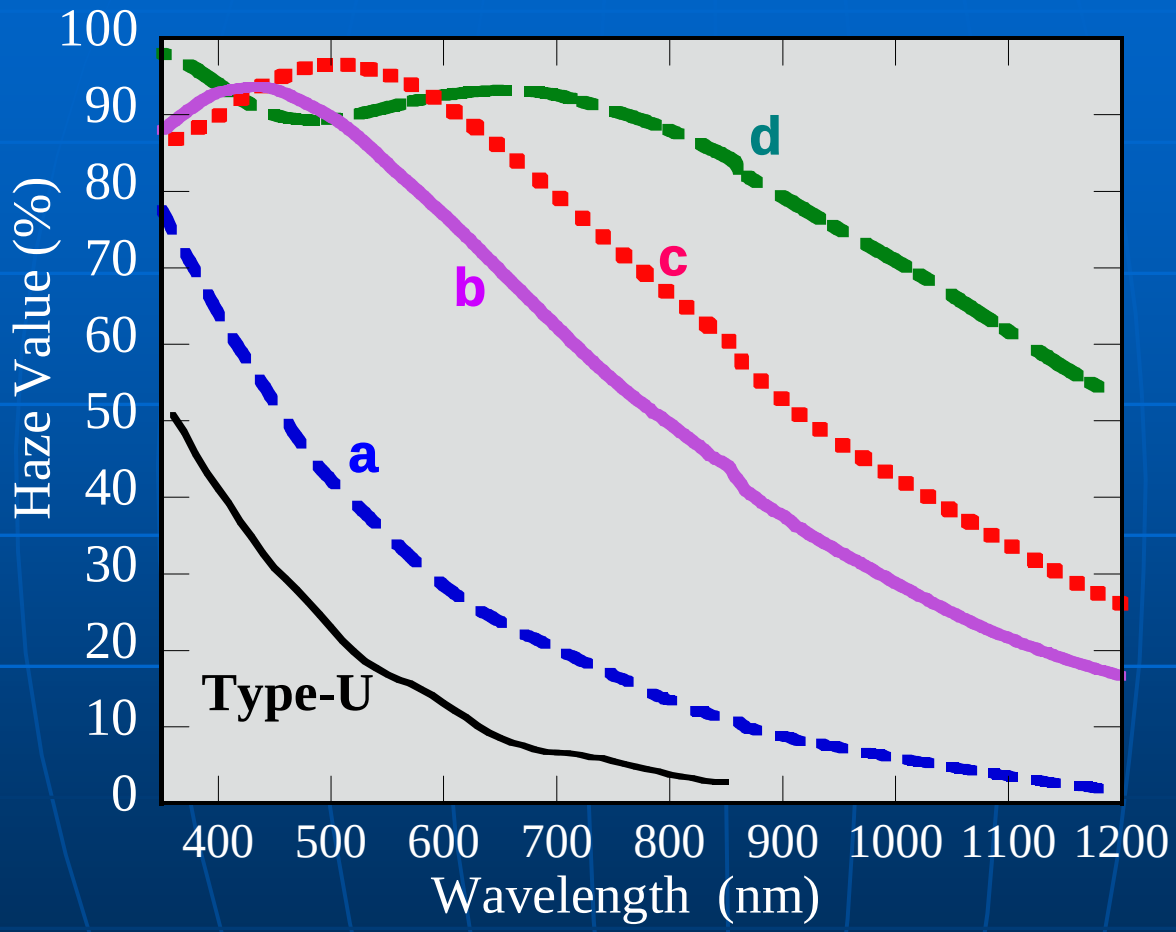
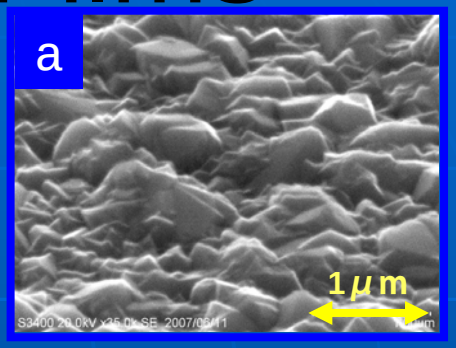
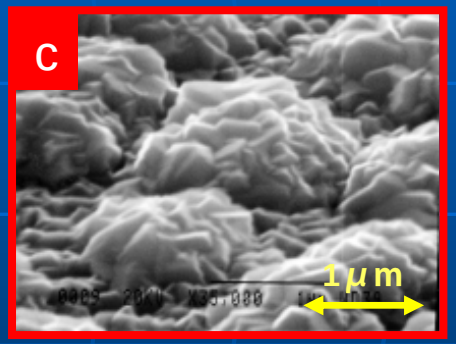
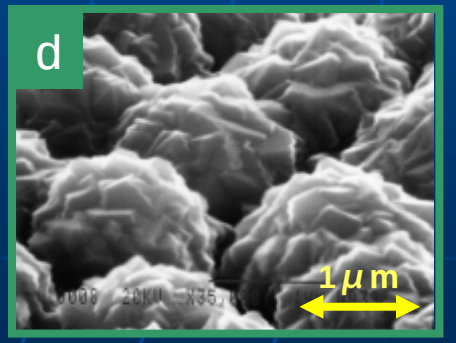
Haze for W-Textured Films









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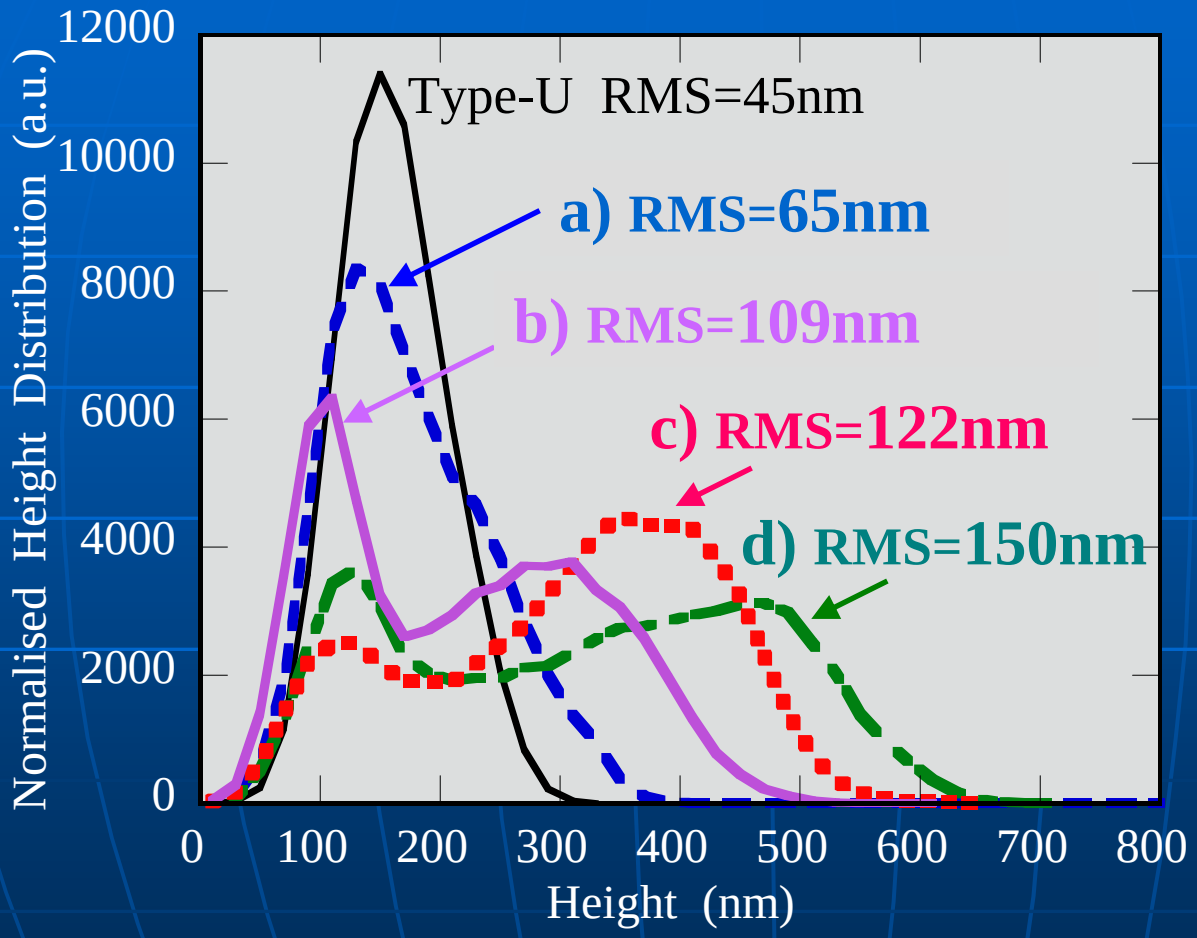
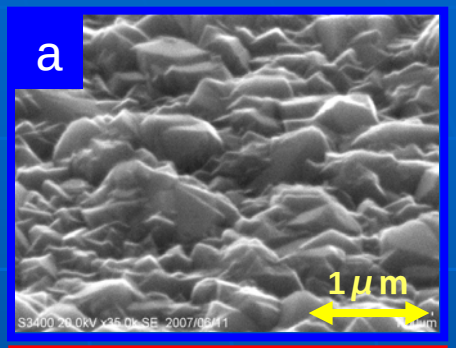
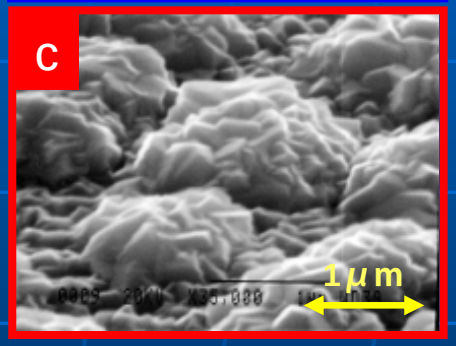
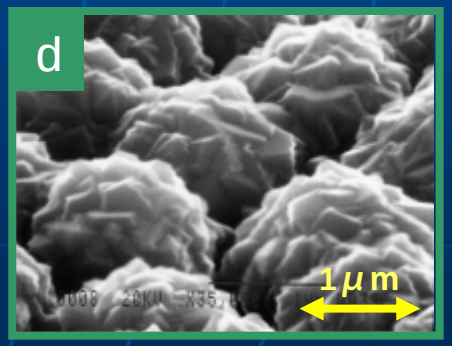
Surface Distribution of W-Texture









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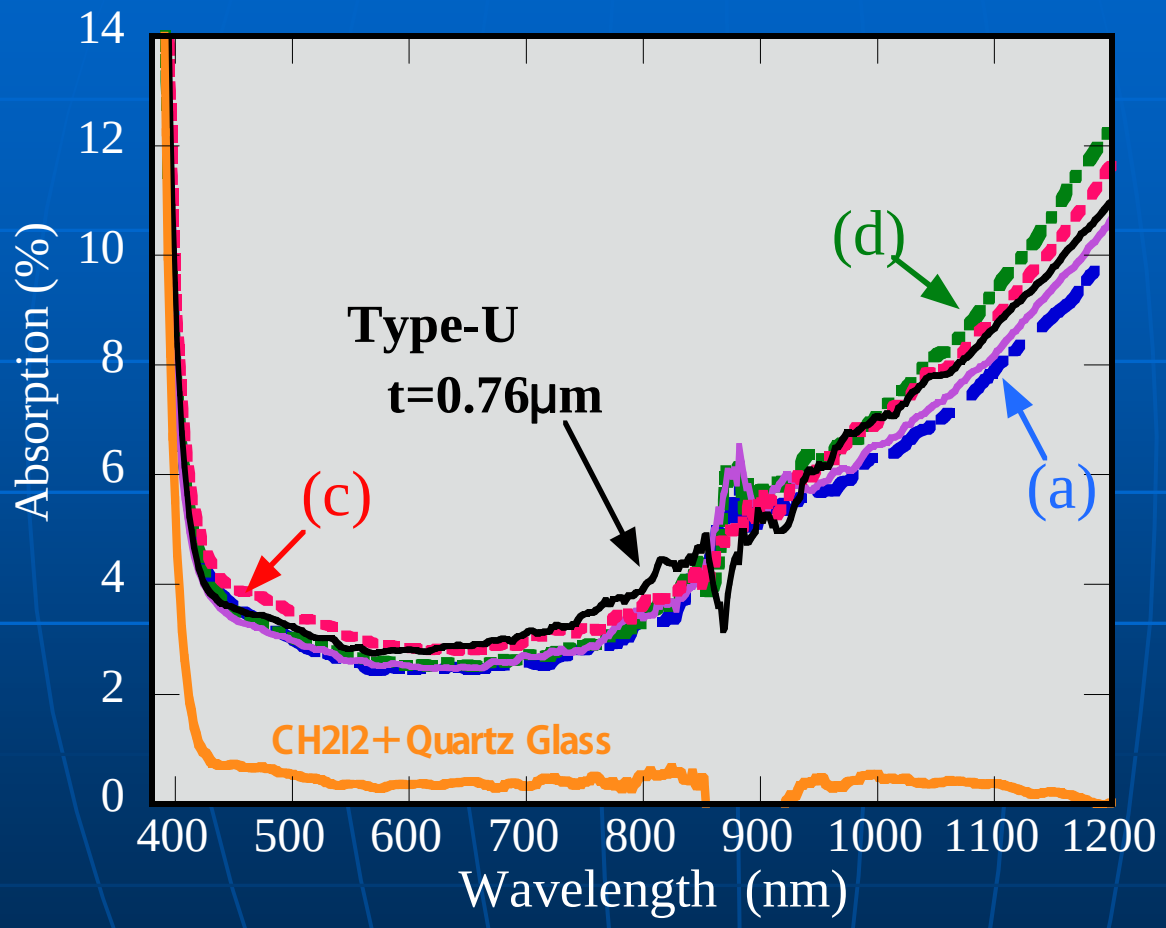
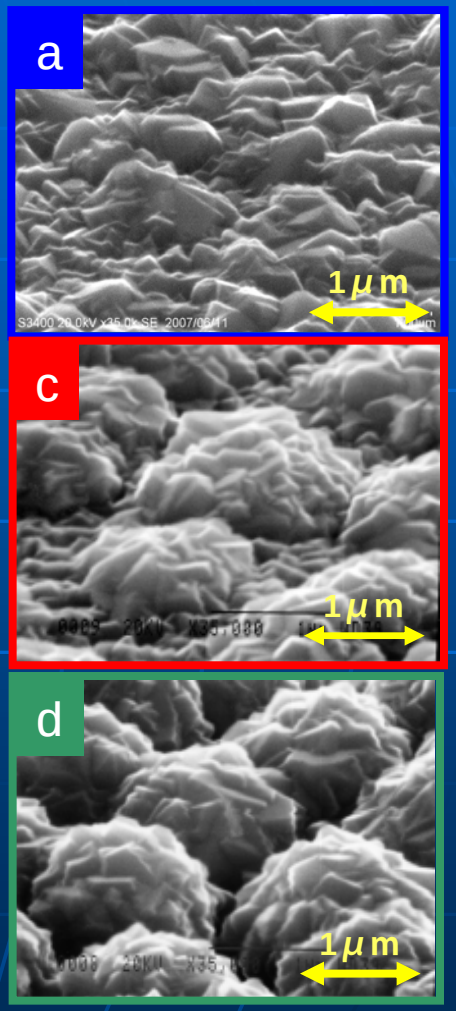
Absorption of W-Texture





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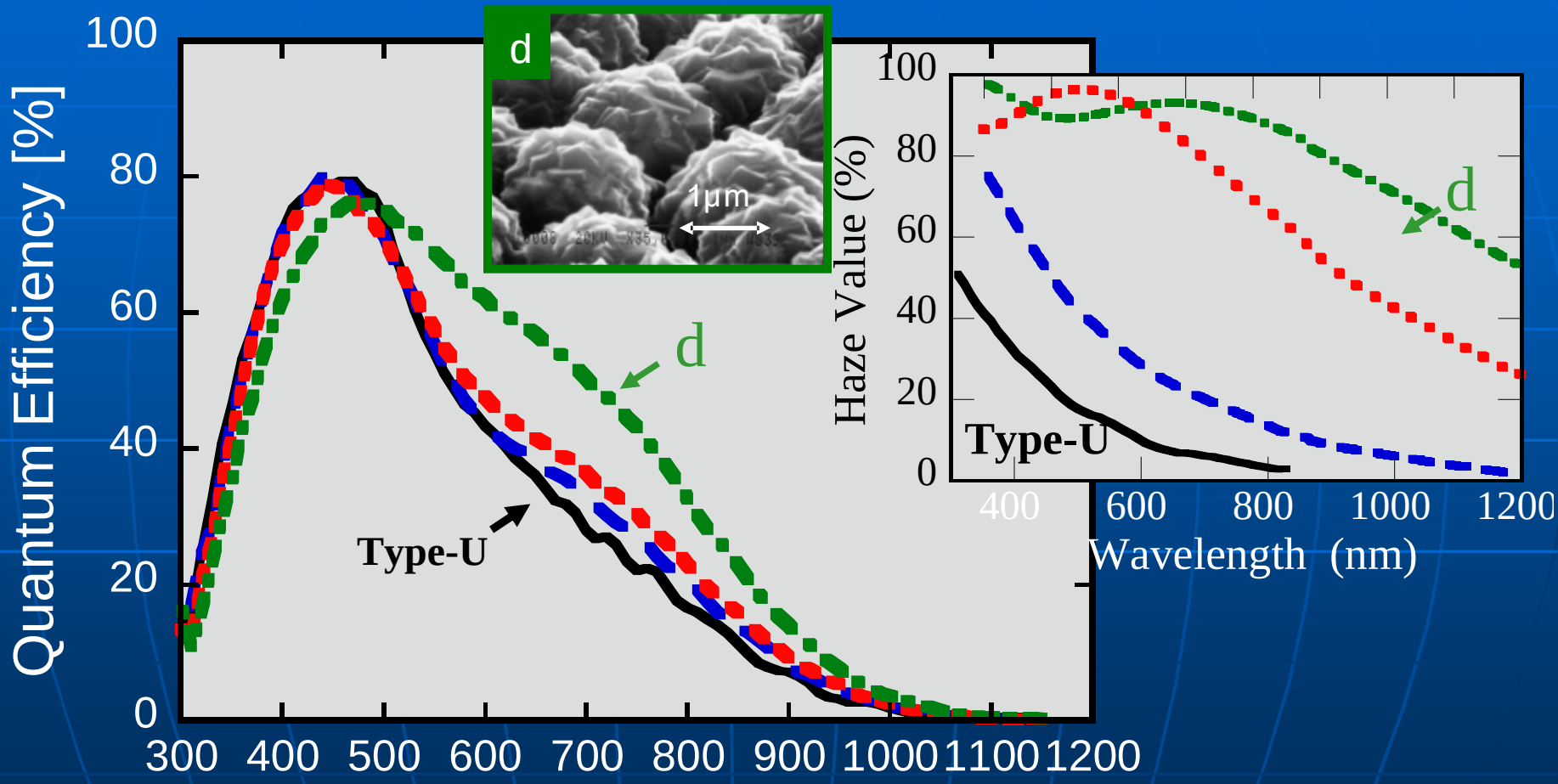
QE with W-Texture



Measured QE increases up to 35%!

Conclusions

- W-Texture is being developed in an off-line process.
- The cooperative efforts of thin-film PV manufacturers and the glass industry can result in economies of scale and a bright successful future.