UNIFORM GROWTH OF LARGE AREA a-Si / μc-Si TANDEM JUNCTION THIN FILM SOLAR CELLS BY CAPACITIVE COUPLED PECVD

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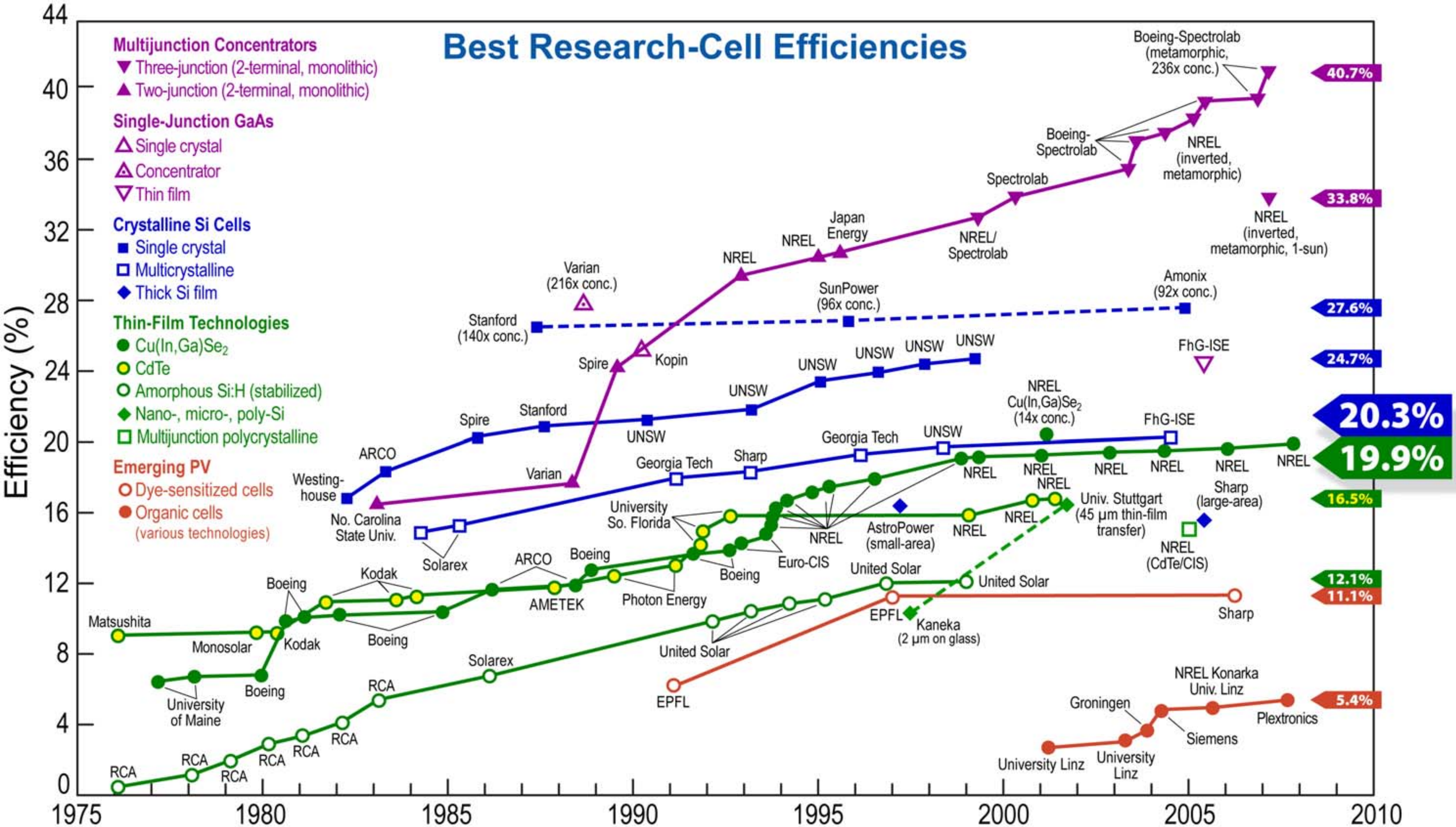
think it. apply it.

Types of Solar Cells

- Crystalline Silicon
  - Monocrystalline, Multicrystalline, Ribbon, etc.
- Thin Films
  - Amorphous and crystalline silicon
  - Cadmium Telluride (CdTe)
  - Copper Indium Selenide (CIS, CIGS)
- Concentration
  - Silicon, multi-junction III-V, thermophotovoltaic
- Emerging Technologies
  - Organic materials, Nanostructures, etc.

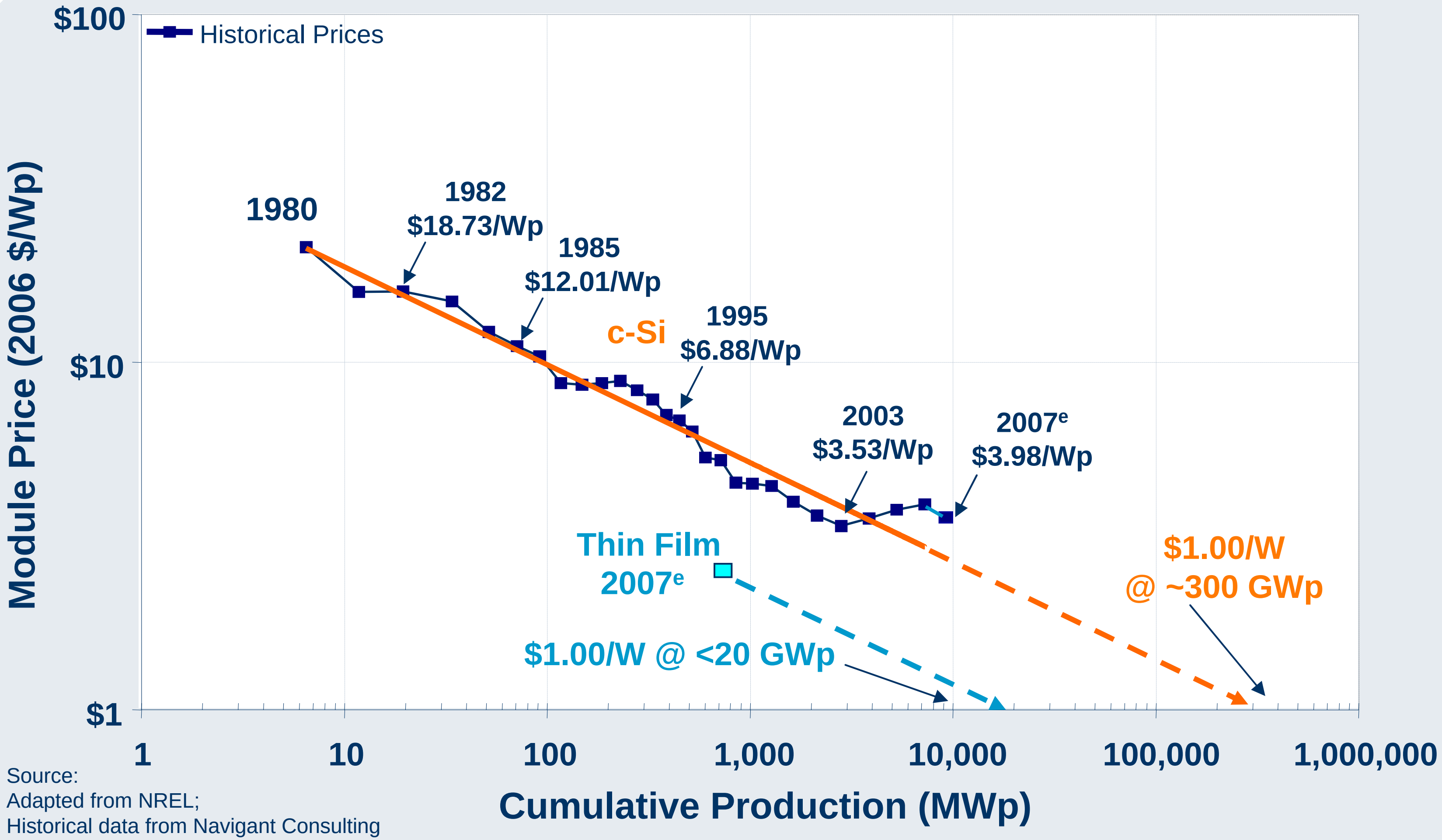
Crystalline Si and Thin Films dominate market today

NREL Cell Efficiency Map



Thin Film Efficiencies Rapidly Advancing

PV Module Price Reduction



Source:
Adapted from NREL;
Historical data from Navigant Consulting

Module price decreases 20% for every 2x production increase

Thin-film Advantages and Disadvantages

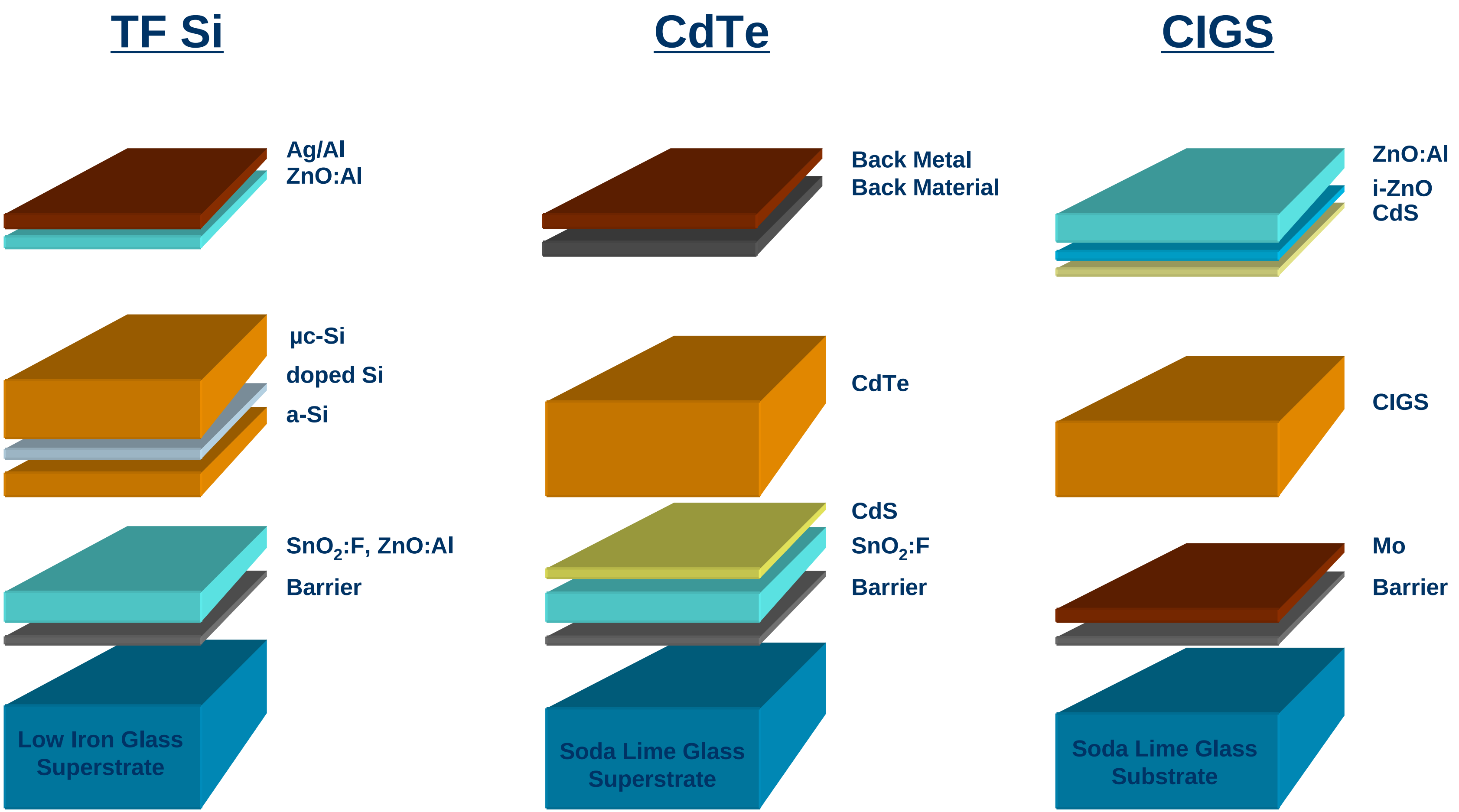
Advantages

- CIS
  - Highest thin-film efficiencies
  - Good cell stability
  - Good product appearance
- CdTe
  - High deposition rate
  - Proven large-volume mftg
  - Current low cost leader
- Si
  - Well-known Si-based PV science
  - Multi-junctions for high efficiency
  - Large-area, large-volume mftg

Disadvantages

- CIS
  - Mftg yield and volume
  - Indium price / availability
  - Field durability
- CdTe
  - Mftg and product restrictions (Cd)
  - High-temperature process
  - Absorber thickness ; Te availability
- Si
  - Single-junction efficiency
  - Deposition rate
  - Multi-junction mftg control

Leading Thin Film PV Technologies

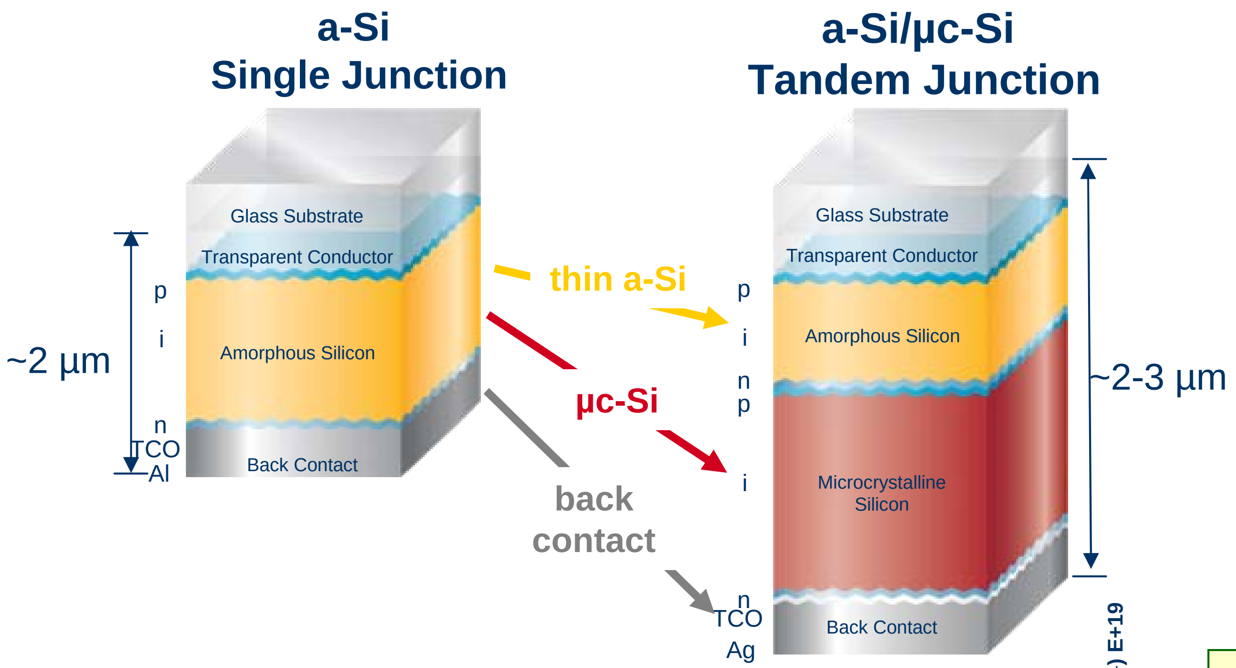


Thin Film Technology Comparison

	CIGS	CdTe	TJ a-Si/uc-Si
Module Size (m^2)	$\leqslant$ 0.72 m^2	$\leqslant$ 0.72 m^2	1.43m^2, 2.86m^2, 5.72m^2
Stabilized Module Efficiency Today	8-12%	10%	8%
Stabilized Module Efficiency Roadmap to 2010	15%	12%	10%
Best Laboratory Cell Efficiency	19.5%	17%	13.5%
Temperature Coefficient, Power	-0.36 % / °C	- 0.25 % / °C	- 0.2 % / °C
Raw Materials for PV	3 – 5 GW annual (limited Indium increases cost)	3 – 5 GW annual (limited Telluride increases cost)	Unlimited Si supply
Volume Production Ramp Readiness	Material, uniformity, t-put, equipment maturity, etc.	In volume production	In volume production
Module Reliability	Limited field data impacts financiability	Limited but growing field data	a-Si >20 years
Production Cost / Wp in 2010	No volume production cost data	<$1.00 /Wp	<$1.00 /Wp
Applications	Rooftop, BIPV	Solar Farms, Rooftop, BIPV	Solar Farms, Rooftop, BIPV

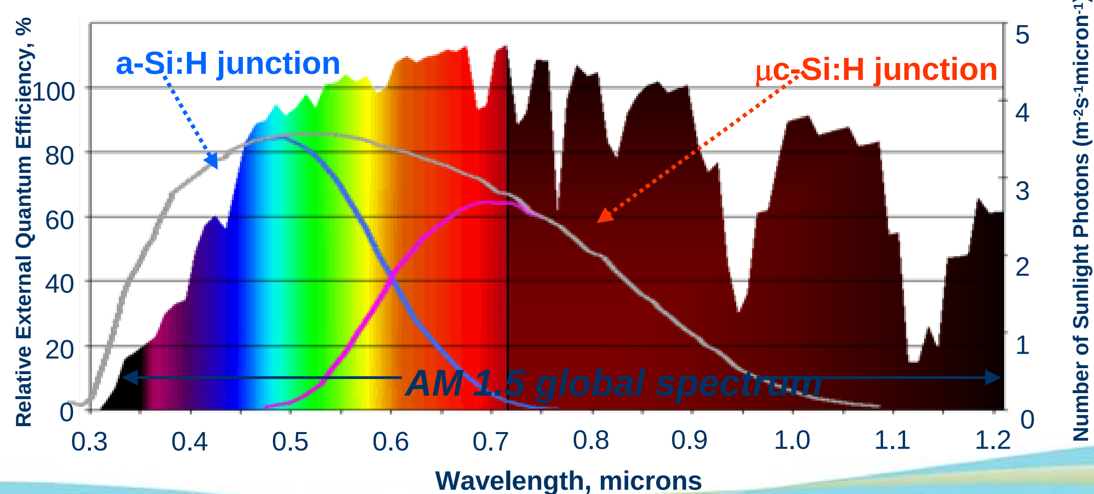
*Sources: NREL, Deutsche Bank, USGS, Photon International

Thin Film Si PV Cell - Single Juction & Tandem Junction



a-Si:H/µc-Si:H advantages

- Low-cost
- Better temperature stability
- Better diffuse light efficiency
- Paths to higher CE



a-Si:H/µc-Si:H challenges

- Large area film uniformity
- High equipment cost
- Low dep rate
- Low CE

Applied's Tool Box

Silicon Systems

Advancing Technology
Innovating Productivity

Display Business

Delivering New
Technology and Scale

Energy & Environmental Solutions

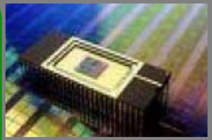
Changing the
Energy Equation

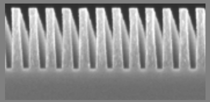
Thin Film

Crystalline

Fab Solutions

Driving Fab Productivity





Our demonstrated capability in large area TFT-LCD tools

AKT PECVD Size Evolution

4 up
10.4”

6 up
12.1”

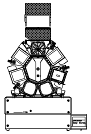
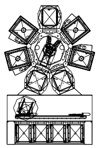
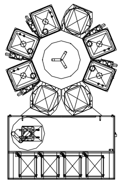
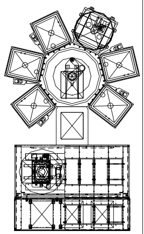
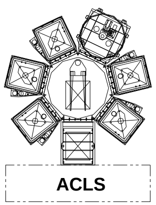
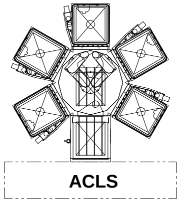
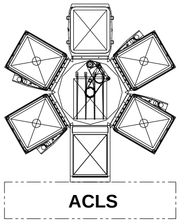
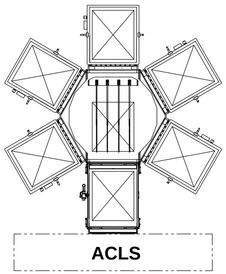
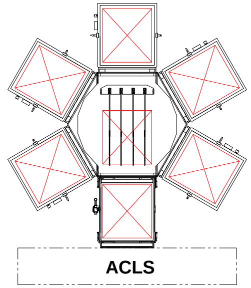
6 up
15.0” ~ 17.0”

6 up
19.0” ~ 24.0”

6 up
37.0” Wide panels

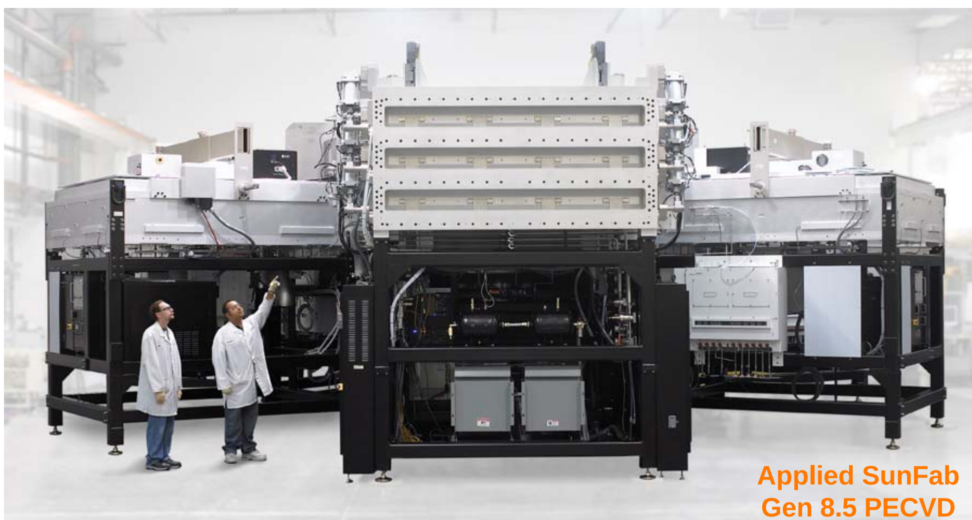
6 up
46.0” Wide panels

6 up
52.0” Wide panels

	Gen 2	Gen 3 / 3.5	Gen 4	Gen 5	Gen 5	Gen 5.5	Gen 6	Gen 7 / 7.5	Gen 8
1st Release	2/ '93~	4/ '95~	1/ '00~	8/ '01~	6/ '02~	8/ '04~	5/ '03~	7/ '04~	2006
System Layout									
Model Substrate Size (mm)	1600 370x470 400x500	3500 / 4300 / 4300A 550x650 600x720 620x750	5500/5500A 680x880 730x920	10K 1000x1200	15K / 15KA 1100x1250 1200x1300	20K 1300x1500	25K / 25KA 1500x1800 1500x1850	40K / 40KA 1870x2200 1950x2250	50K 2160x2460
Substrate Area	2,000 cm2 (1.00)	4,650 cm2 (2.33 from 1600)	6,716 cm2 (1.44 from 4300)	12,000 cm2 (1.79 from 5500)	15,600 cm2 (1.30 from 10K)	19,500 cm2 (1.25 from 15 K)	27,750 cm2 (1.78 from 15 K)	41,140 cm2 (1.52 from 25 K)	53,136 cm2 (1.21 from 40 KA)
Panel size Inch	10.4	12.1	15 ~ 17	19 ~ 23	21 ~ 24	32W	37W	46W	52W
Panel/sub	4	6	6	6	6	6	6	6	6
Application	Note PC	----------------->		Monitor		----------------->	TV		

SunFab Value Proposition – 12 Lines Worldwide

- **Module Right Sizing Advantage & Flexibility**
  - Flexible panel size (¼, ½, and Full Size) serves multiple markets: residential rooftop, commercial rooftop, BIPV, and utility scale
  - SunFab full size panel (5.7m^2), world's largest, delivers the highest power out per panel 560Wp
- **Leading Technology**
  - High Efficiency Tandem Junctions, Better Energy Harvest due to lower temperature coefficients
  - High-speed, high-yield processing of thin glass substrates (2.2x2.6m)
- **Fastest to Scale**
  - World class equipment serves as foundation for Factory performance
  - <6 months from factory ready to Volume Production

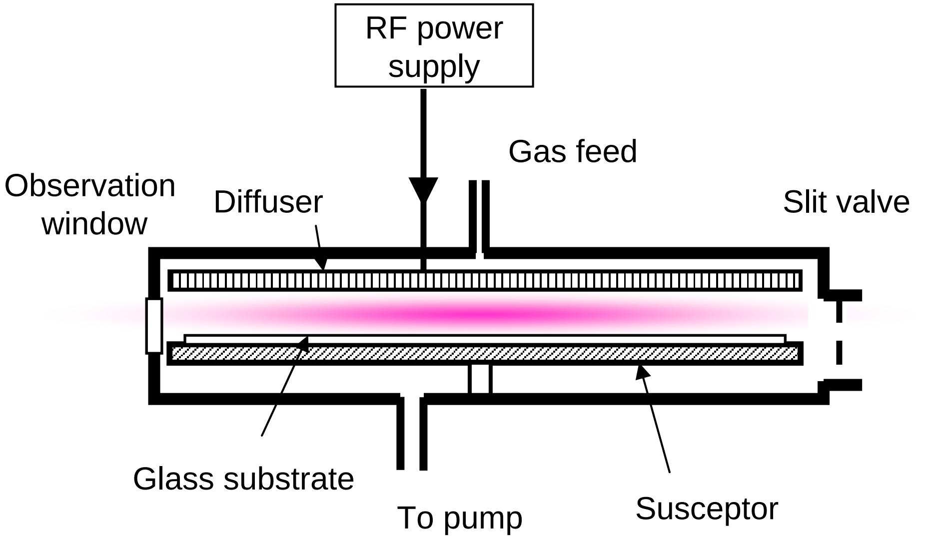


Applied SunFab Gen 8.5 PECVD

$$\frac{\text{Cost} \downarrow}{\text{Watts} \uparrow}$$

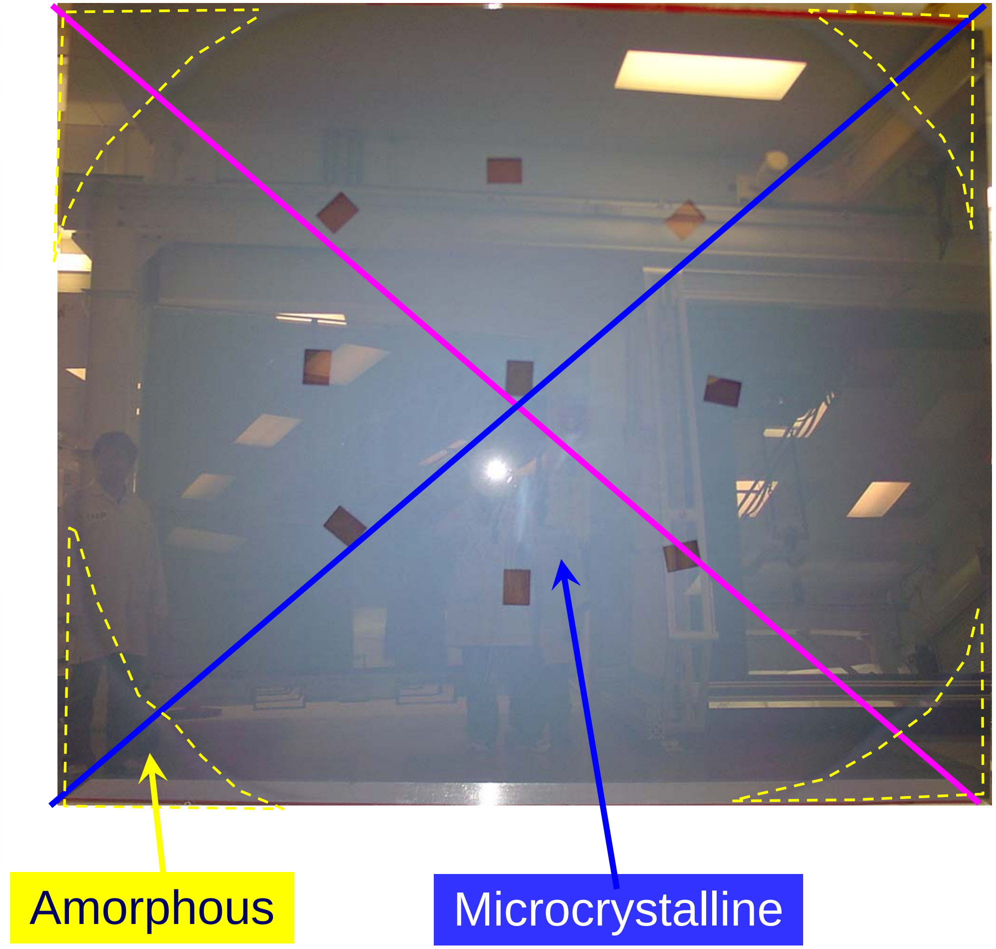
PECVD chamber structure

- Process gases:
  - SiH_4, H_2
  - Dopants (C_3H_9B for p-doping and PH_3 for n-doping)
  - Single gas feed through at the center of the chamber lid
- Diffuser:
  - Distribute gas flow
  - RF electrode
  - Proprietary hallow cathode design
    - Enhanced gas dissociation
    - Uniformly dissociated reactant gases
- Susceptor
  - Multiple heating and cooling zones
    - Ensure temperature uniformity
  - RF ground
- Slit valve for substrate loading / unloading

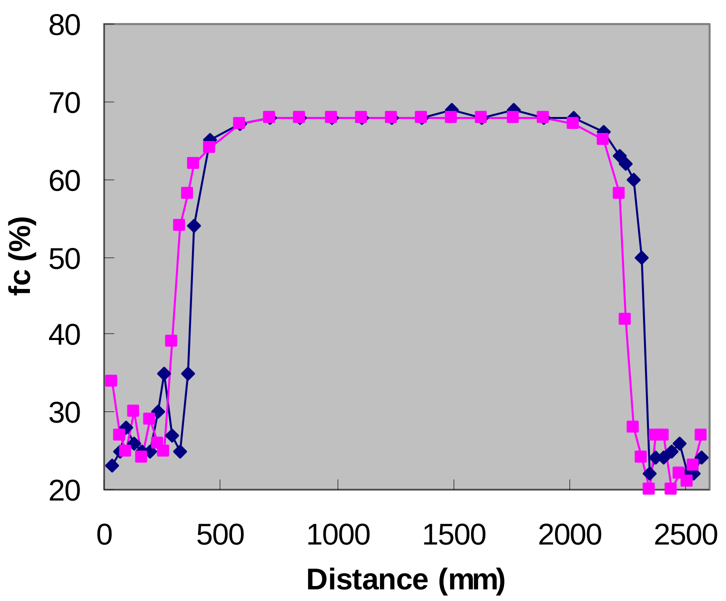


Big Challenge - 5.7m² Substrate µc-Si Film

amorphous phase at corners



Crystalline fraction along diagonal



a-Si due to lower power density

Result is lower cell J_{sc} & FF

Structure of µc-Si:H

Porous

Cracks/columns in TEM

High spin density

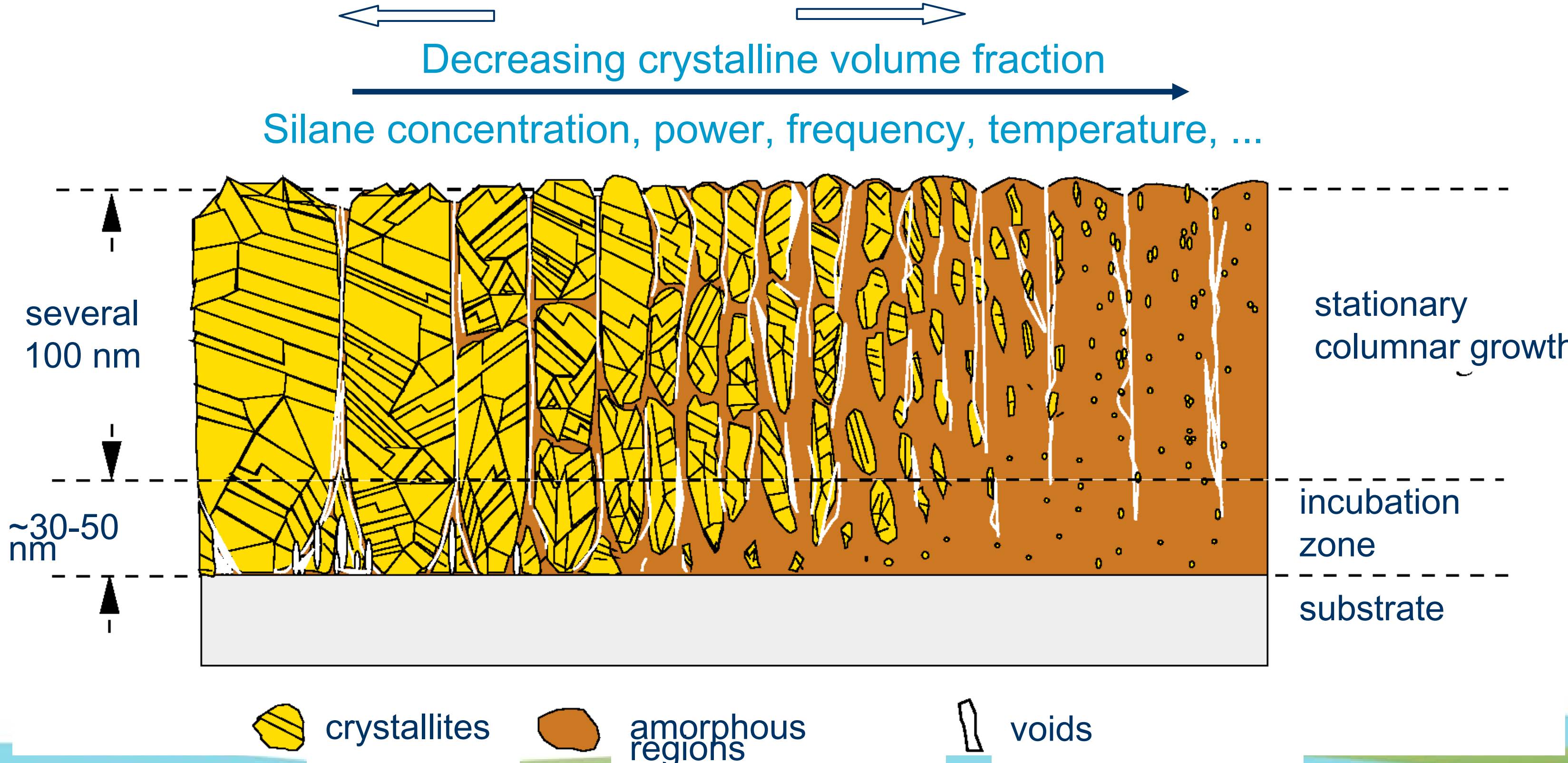
Bad solar cells

Compact

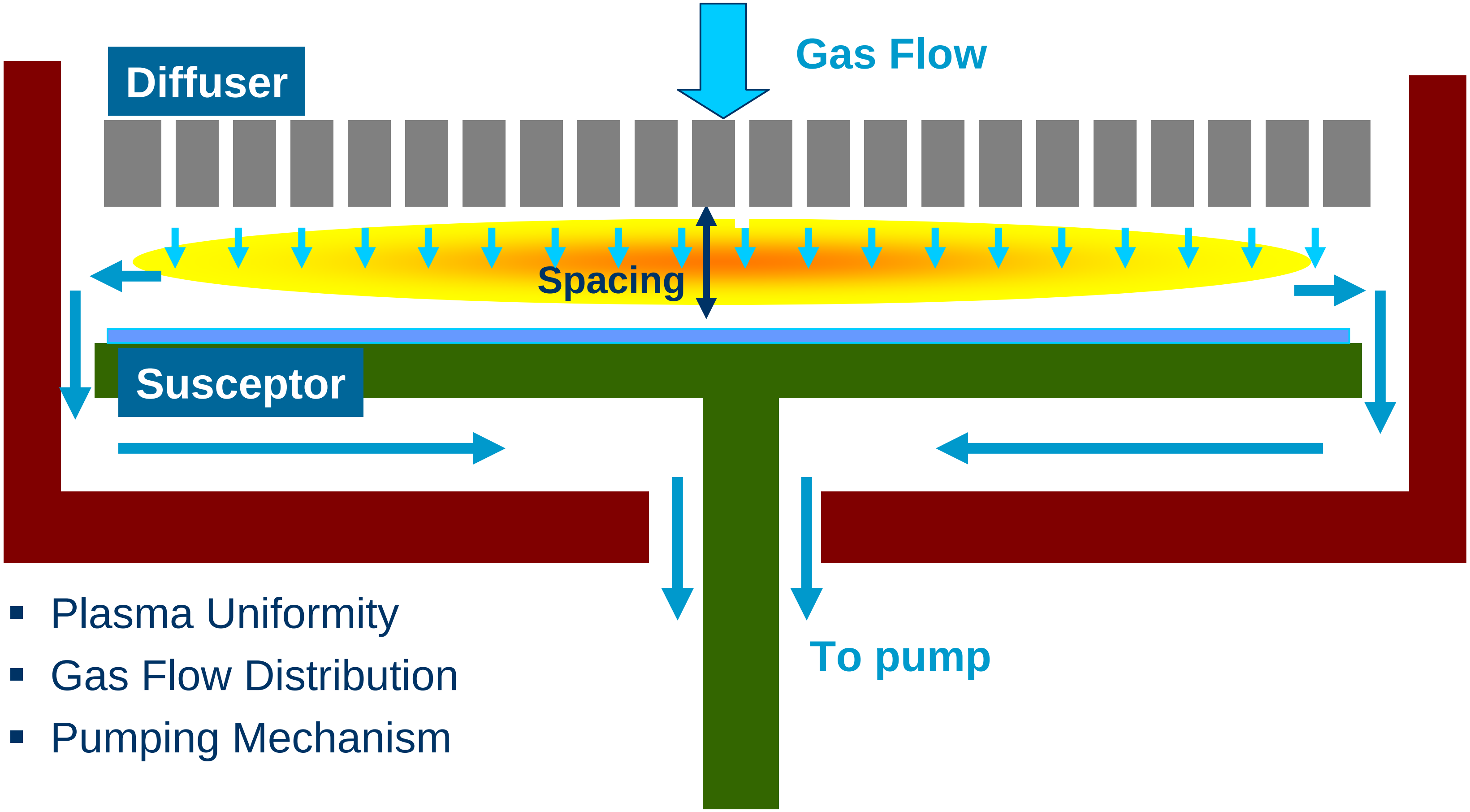
Cracks/columns in TEM

Low spin density

Good solar cells

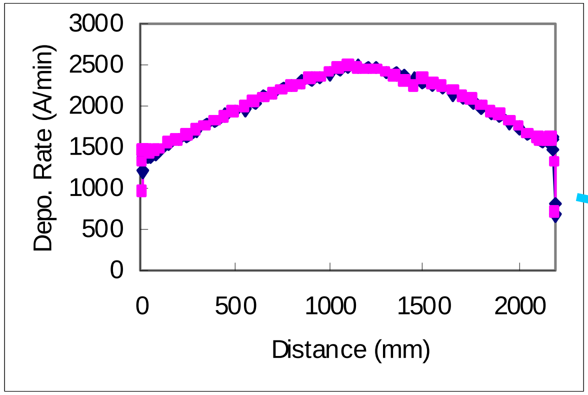


Parameters that Affect Film Uniformity

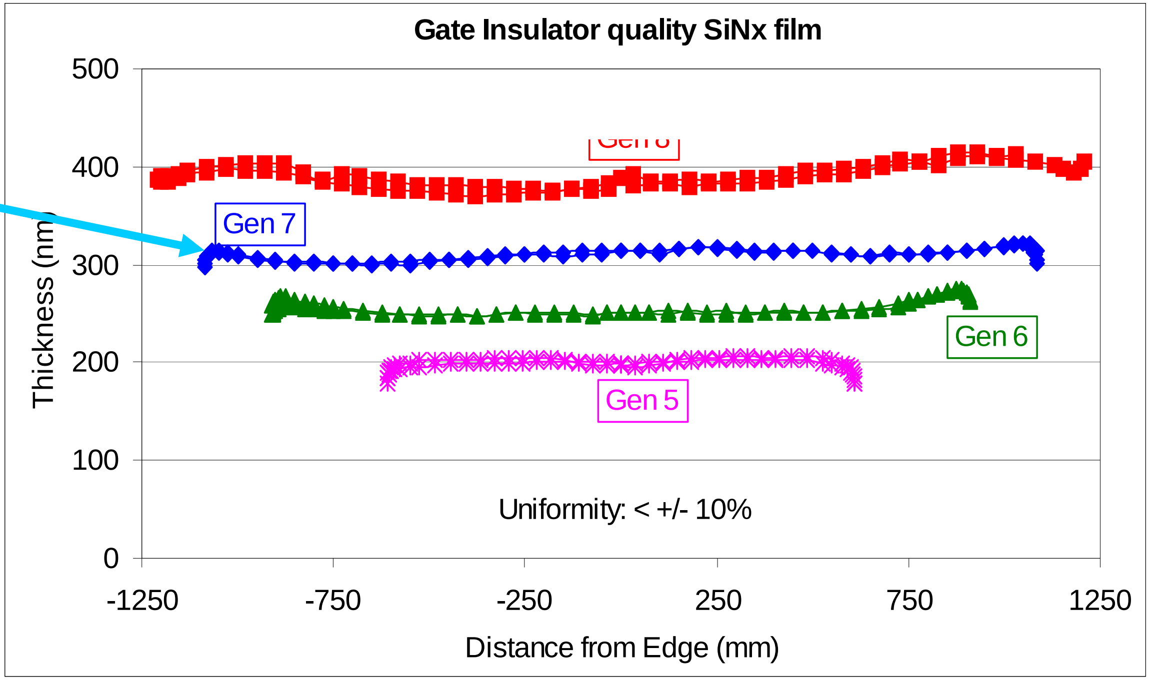


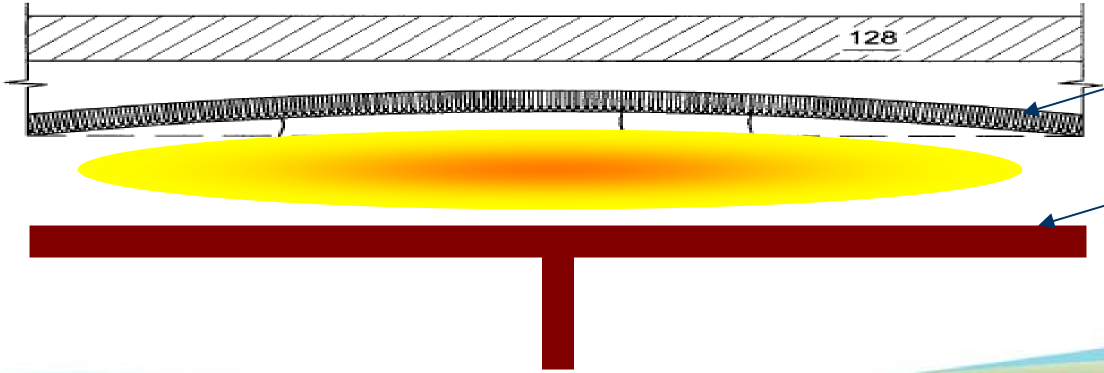
- Plasma Uniformity
- Gas Flow Distribution
- Pumping Mechanism

Plasma Uniformity - Proprietary Electrode Design



Before standing wave correction

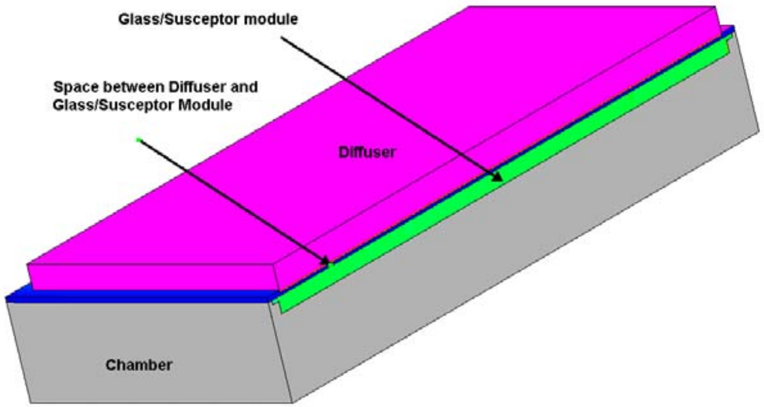


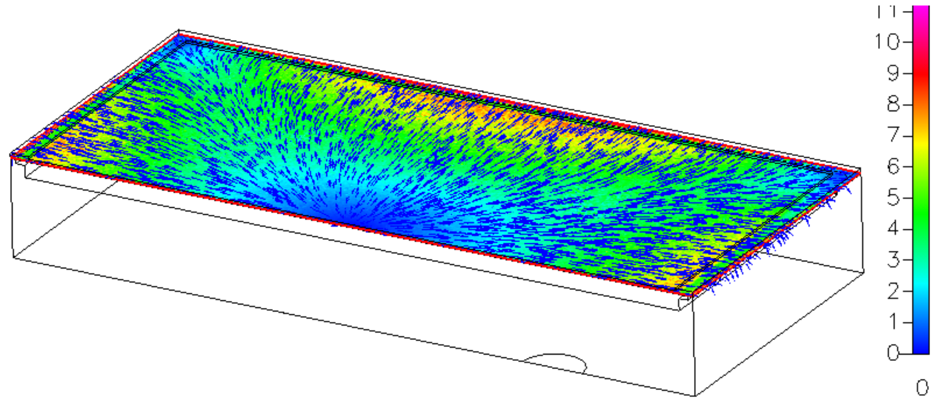


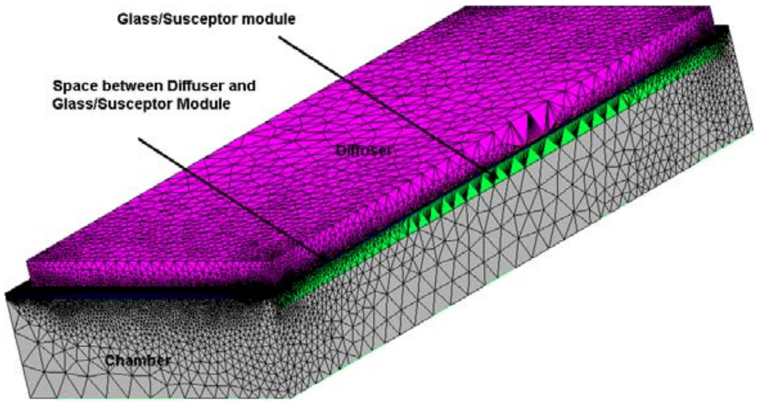
Diffuser Profile Change

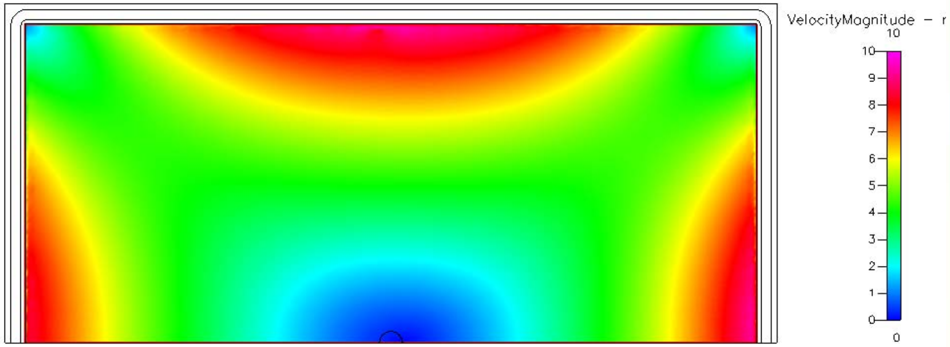
Susceptor

Chamber Flow Simulation





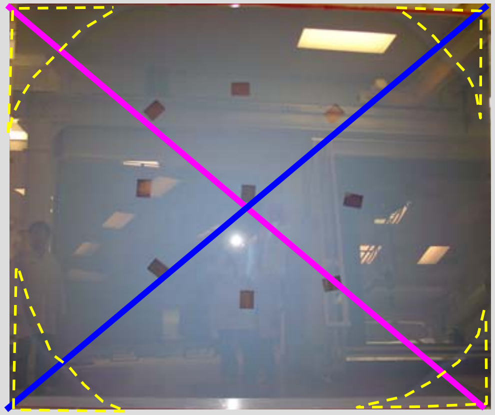




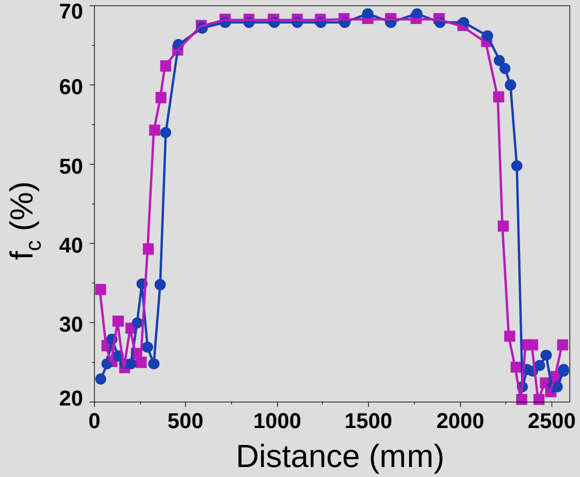
- Chamber pumping flow simulation indicated non-uniform flow distribution

Full Size 5.7m² uc-Si Film

µc-Si layer with LCD Hardware

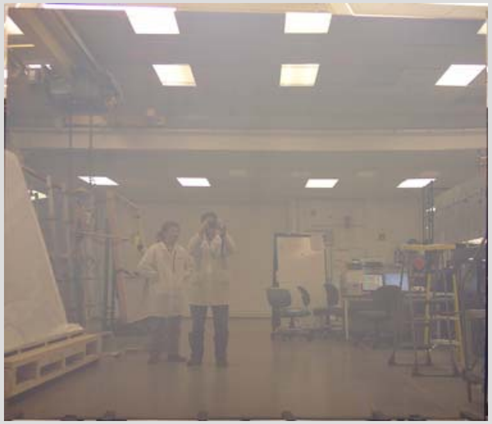


Crystalline Fraction (f_c)

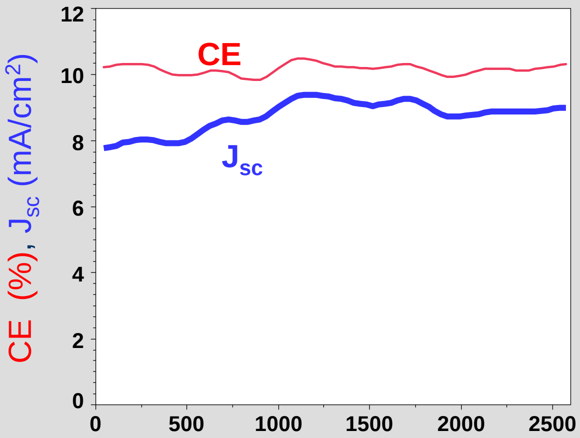


- a-Si deposition in the corners due to lower power density
- Result is lower cell V_{oc} & FF

µc-Si layer with New Hardware



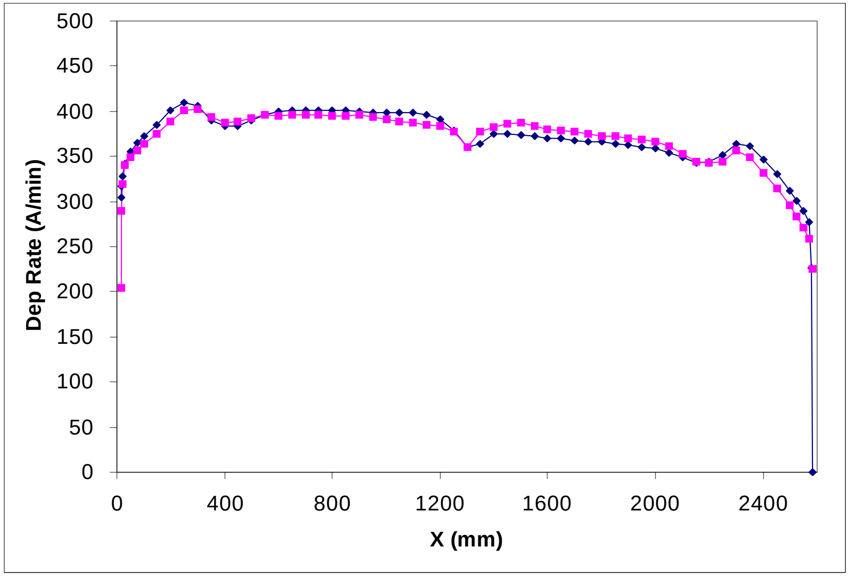
TJ Cell Efficiency & J_{sc}



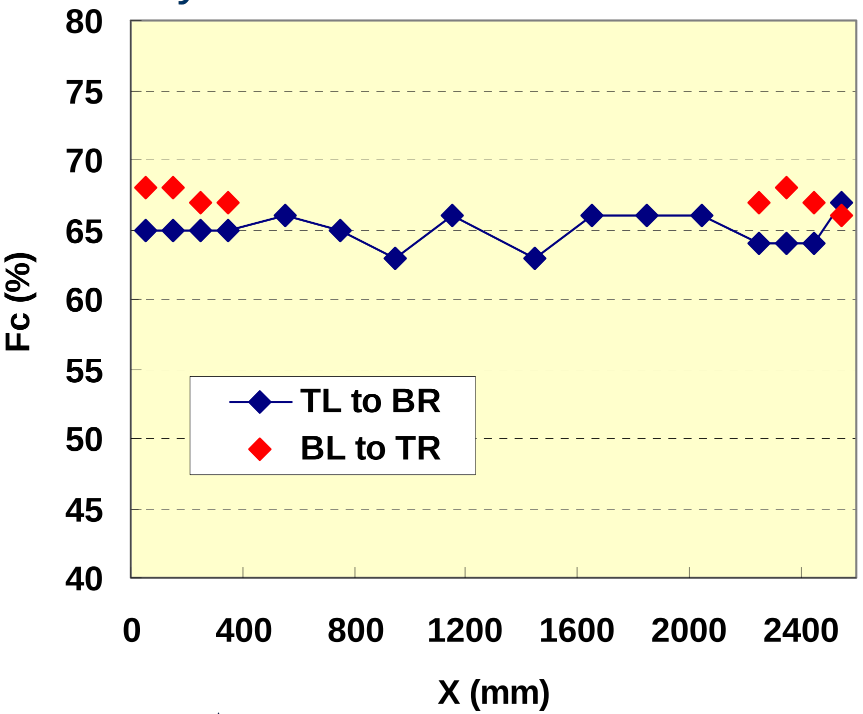
- New Hardware improved uniformity and crystalline fraction
- Results in better homogeneity and higher efficiency

Two Remaining Issues:

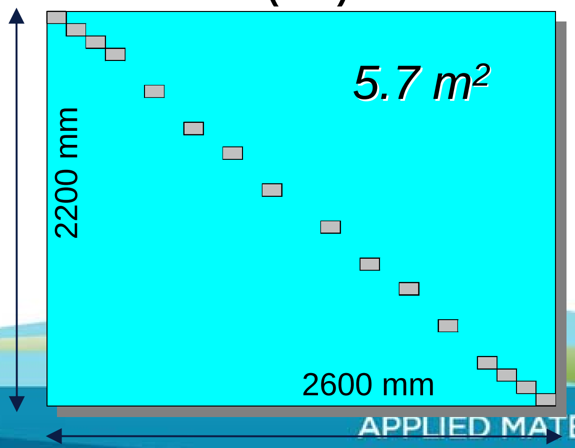
Thickness Across Panel



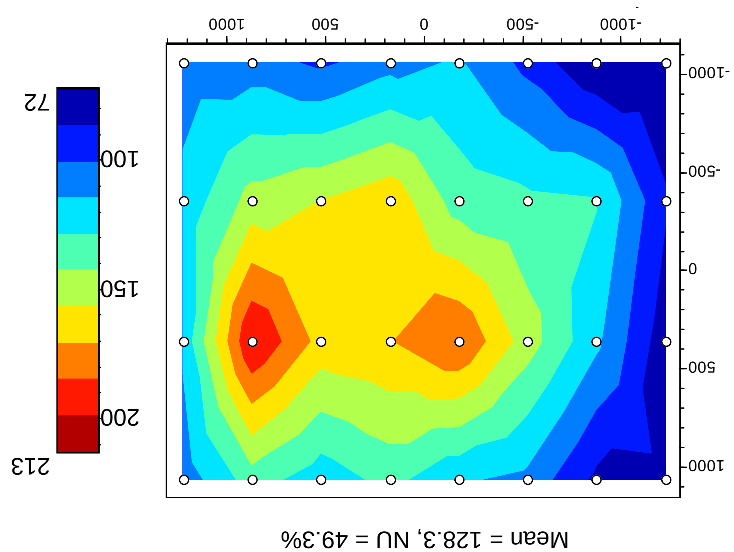
Crystalline Fraction Across Panel

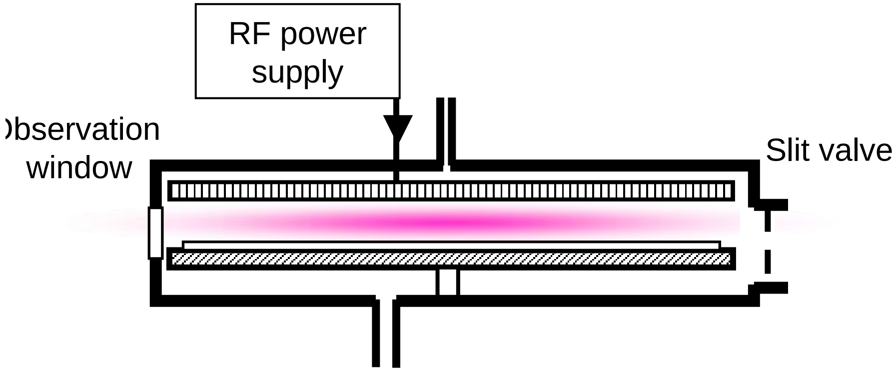


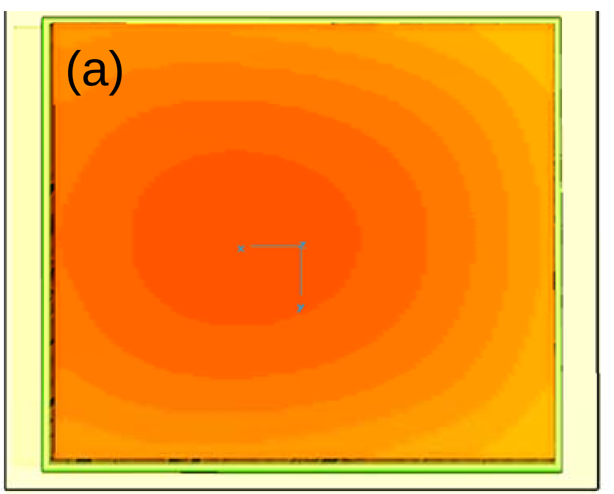
- Asymetry of uc-Si Crystalline Fraction Uniformity
- Corner low dep rate



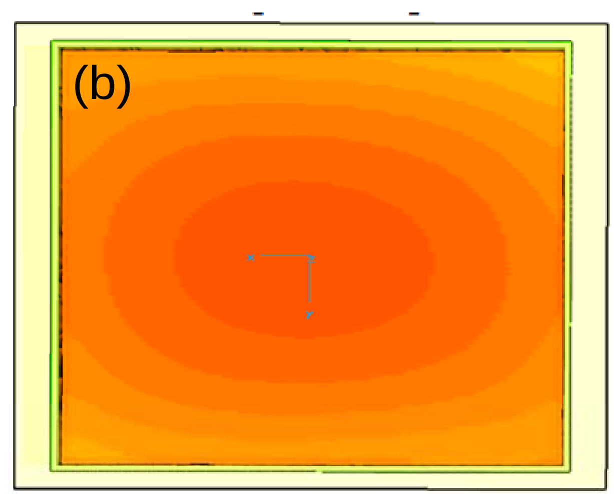
Balance the Plasma – Unbalance the Feed







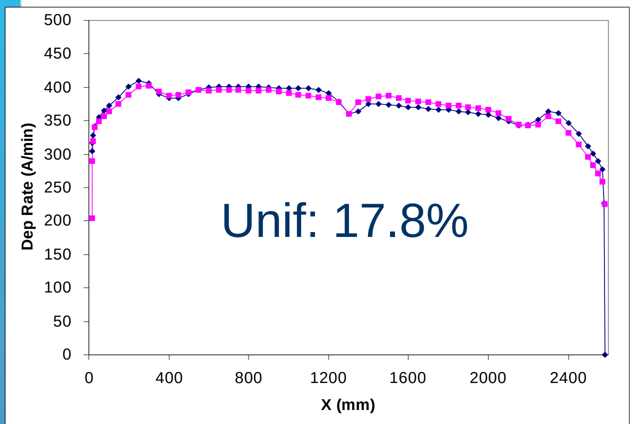
RF field intensity w/ original RF feed



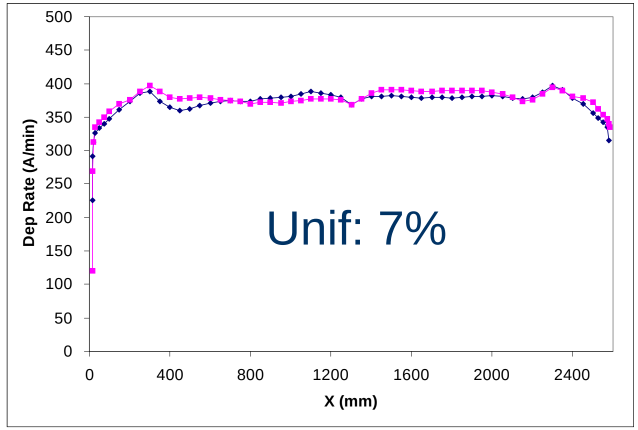
RF field intensity w/ displaced RF feed

RF Fee Location Effects on mc-I Thickness and Fc Uniformity

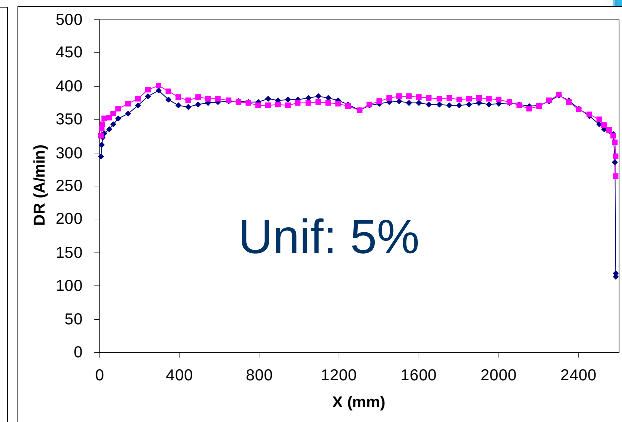
BKM RF Feed

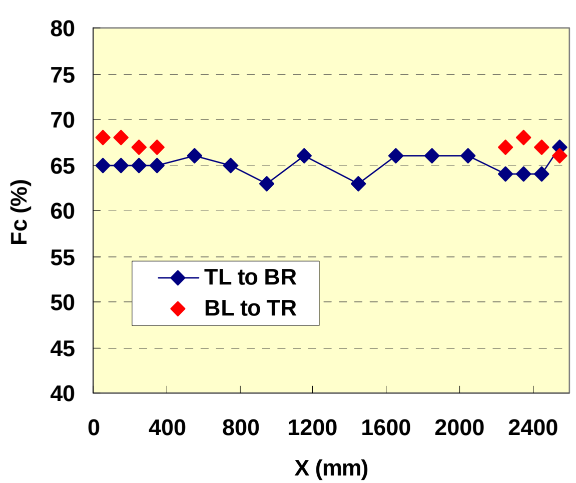


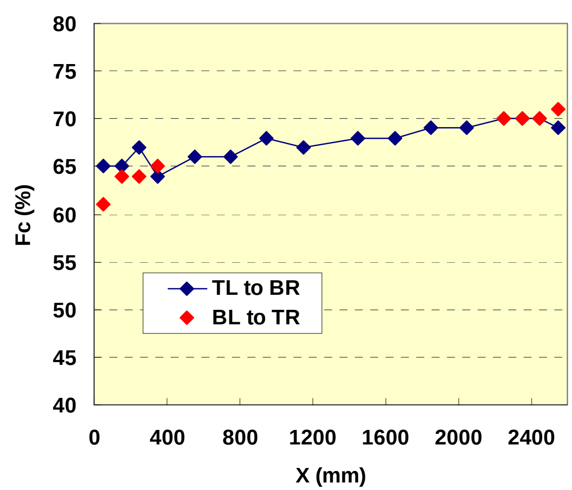
RF Feed Rev1

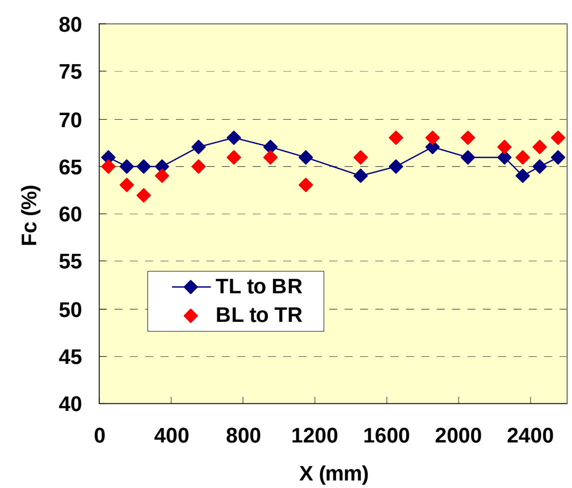


RF Feed Rev2









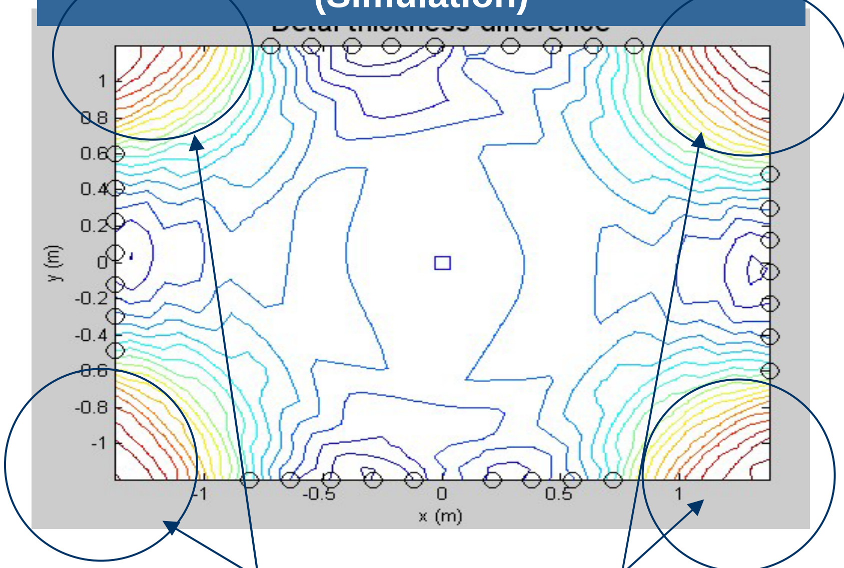
Rev2 RF Feed improved thickness and fc uniformity

Local RF Density Enhancement – Grounding

Approach: modify grounding configuration to modulate the electrical field at corners.

Thickness delta map

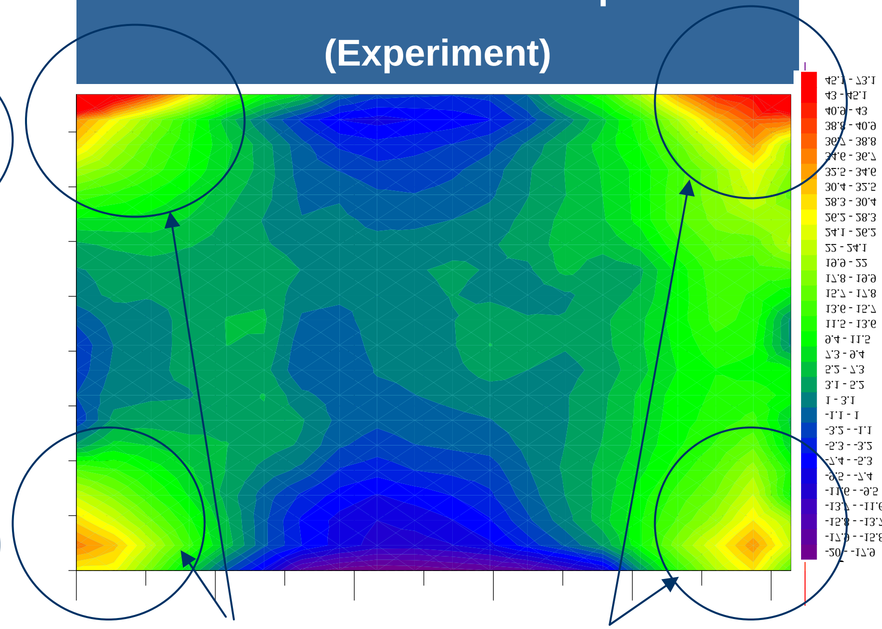
(Simulation)



Corner RF straps removed

Thickness delta map

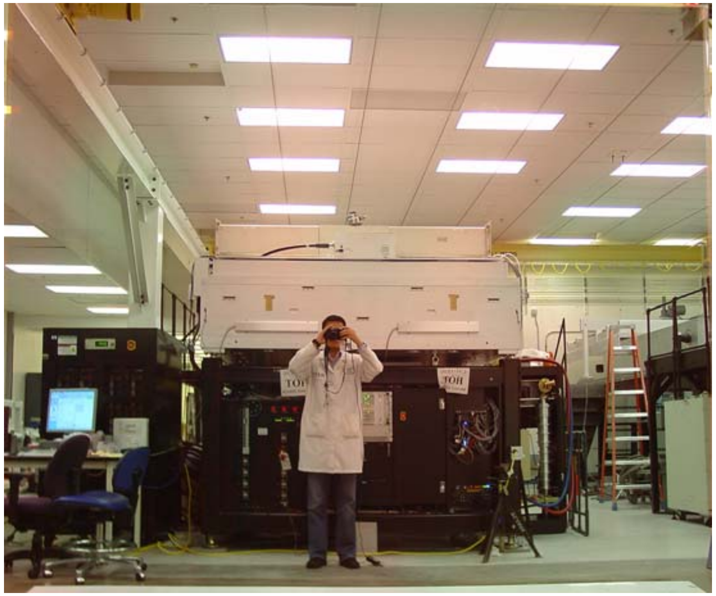
(Experiment)



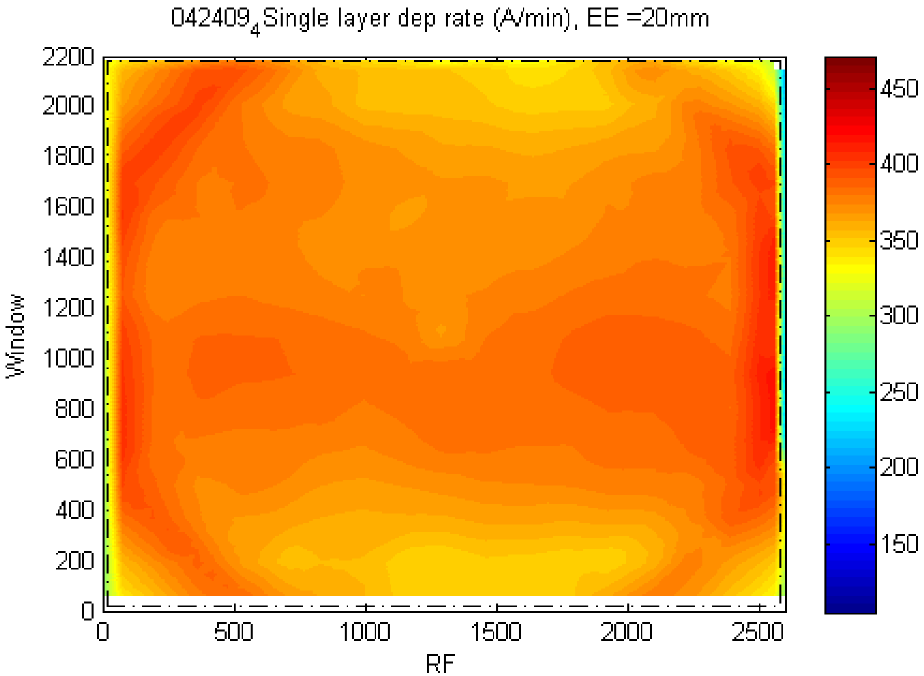
Corner thickness increase

Good correlation between simulation and experiment

Uniform Large-Area uc-Si Film



Uniform uc-Si coating



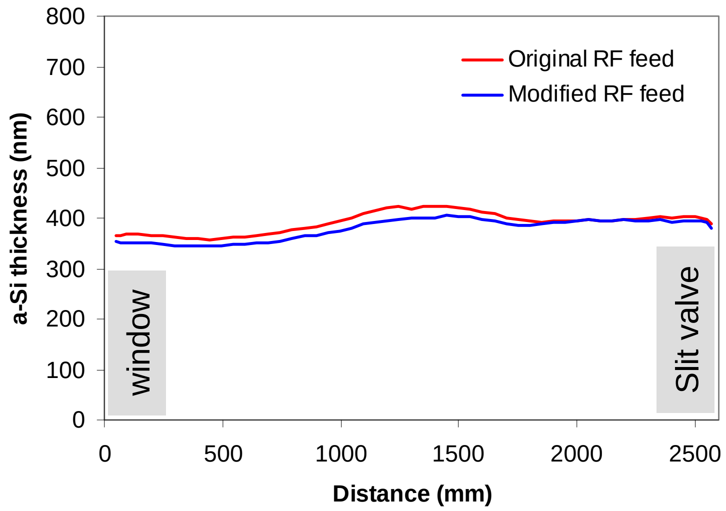
Unif: 5% (1s, 400pts)

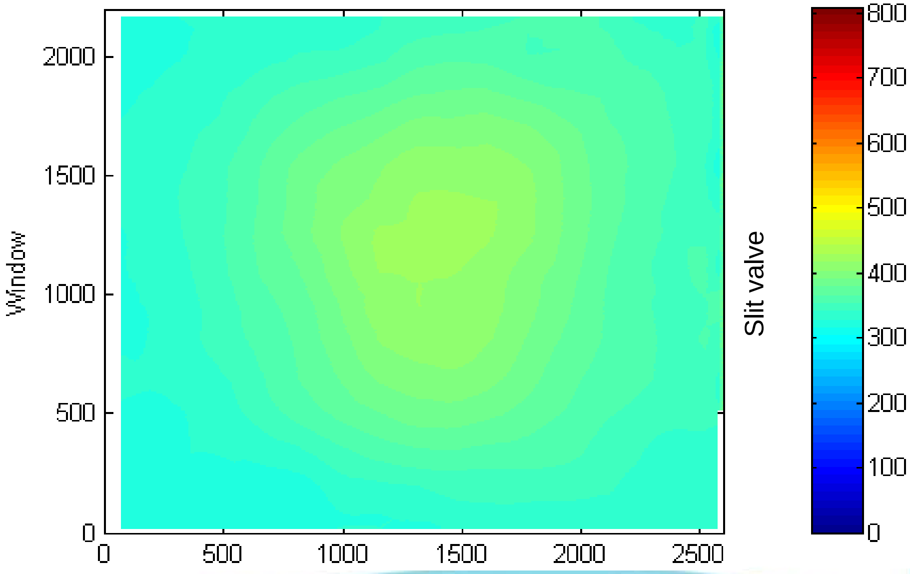
a-Si:H single layer uniformity change

- With original RF feed
  - Average thickness 390 nm
  - Standard deviation of thickness, σ_t = 20 nm
  - Non-uniformity = 4.3%

$$\text{non-uniformity (NU)} = \frac{t_{max} - t_{min}}{t_{max} + t_{min}}$$

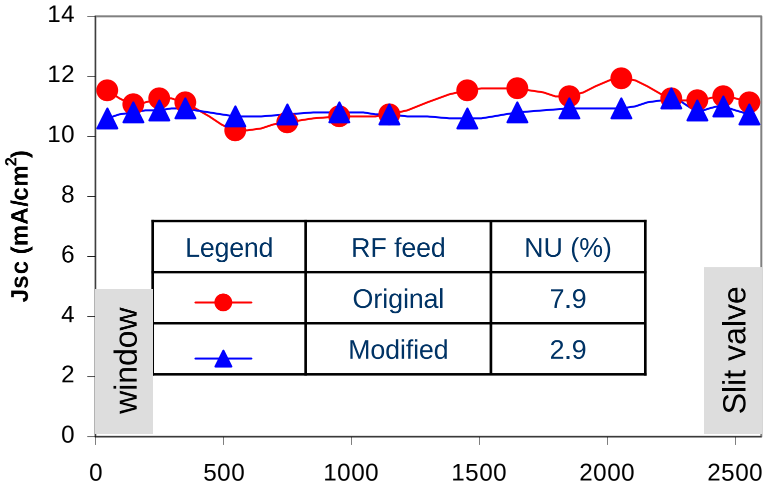
- After modifying the RF feed location
  - Average thickness unchanged
  - σ_t = 21nm
  - Non-uniformity was 3.2%
- Insignificant change in thickness profile and uniformity

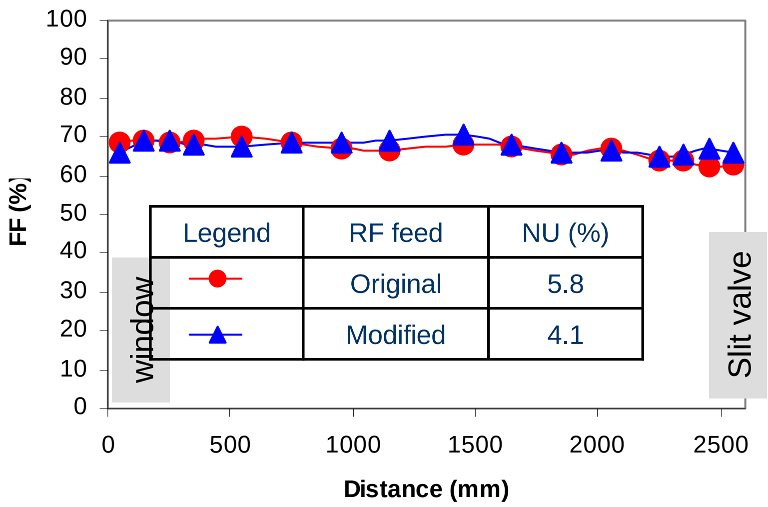


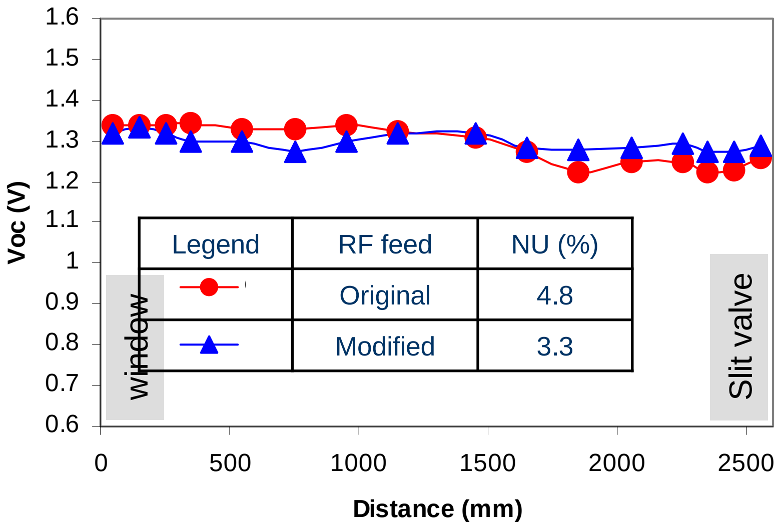


Solar cell performance uniformity

- Uniformity of Jsc
  - Improved from 7.9% to 2.9%
- Uniformity of Voc
  - Improved from 4.8% to 3.3%
- Uniformity of FF
  - Improved from 5.8% to 4.1%







Development of High Dep Rate uc-Si Processes

Conventional Approach [1]
- High H_2 dilution ratio, R~100
- High total flow
- Medium RF power (0.5~0.7W/cm^2)

Results
- Good cell efficiency
- Medium deposition rate
- Large area

[1] B. Rech, etc., Solar Energy Materials & Solar cells 66 (2001) 267-273.

Pure Silane Approach [2]
- Zero H_2 dilution ratio, R=0
- Very low total flow
- Small RF power

Results
- Good cell efficiency
- Medium deposition rate
- Small area

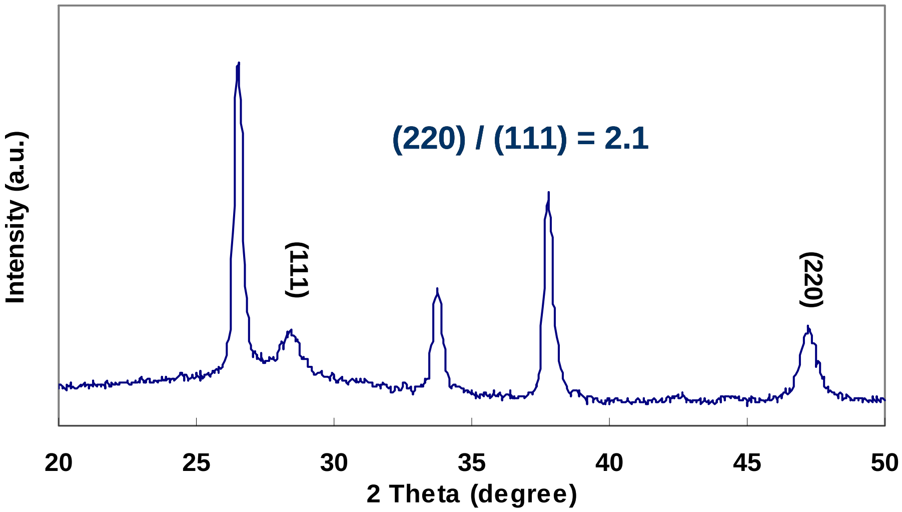
[2] M. N. Donker, etc., J. Mater. Res., Vol. 22. No. 7, Jul 2007.

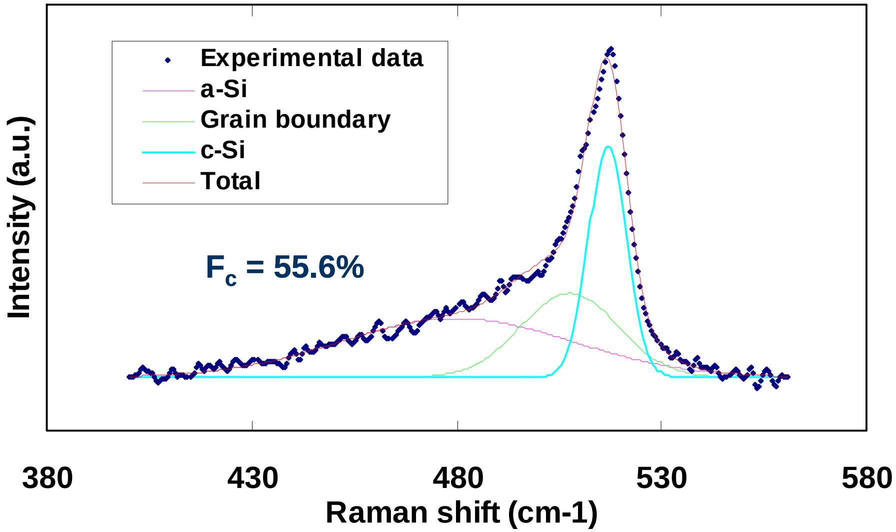
COMPROMISING

Compromising Approach
- Low H_2 dilution ratio, R~30
- Medium total flow
- High RF power

Results
- Good cell efficiency
- High deposition rate
- Large area

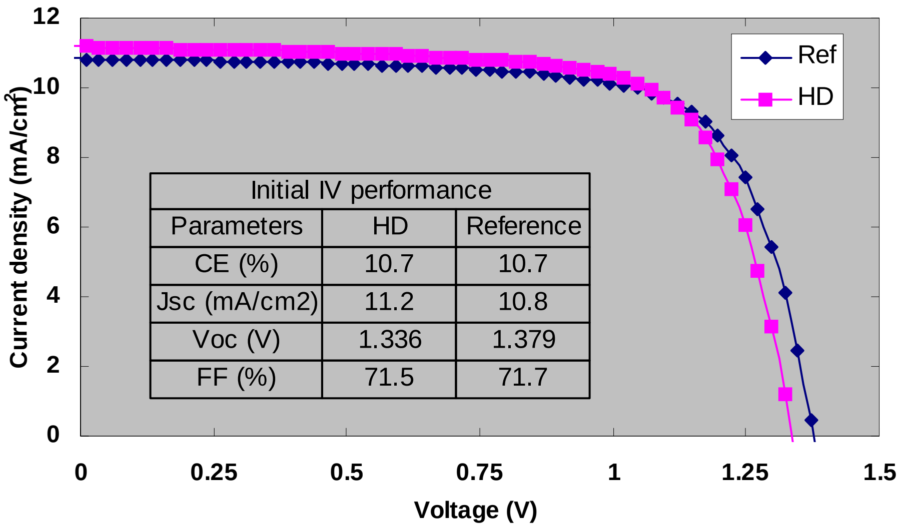
Film properties at high deposition rate



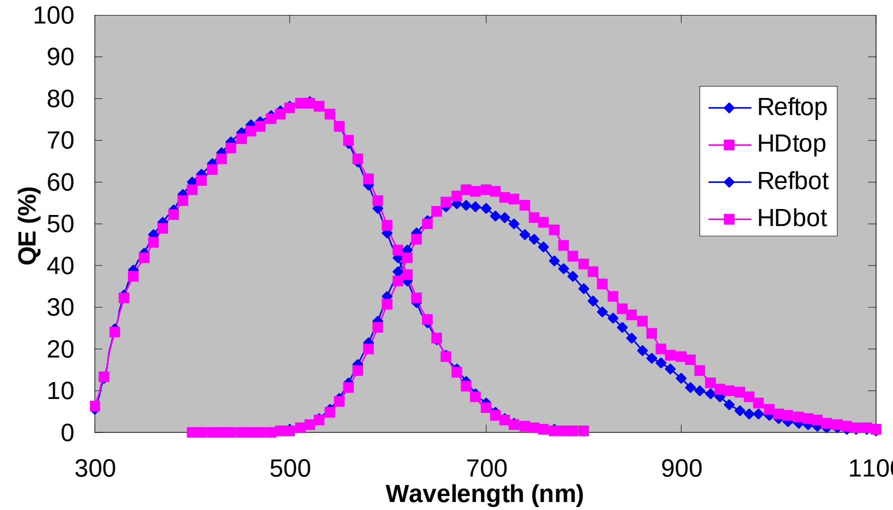


TEM shows clear column structure, which agrees with XRD and Raman measurement.

IV and QE performance comparison



Initial IV performance		
Parameters	HD	Reference
CE (%)	10.7	10.7
Jsc (mA/cm2)	11.2	10.8
Voc (V)	1.336	1.379
FF (%)	71.5	71.7



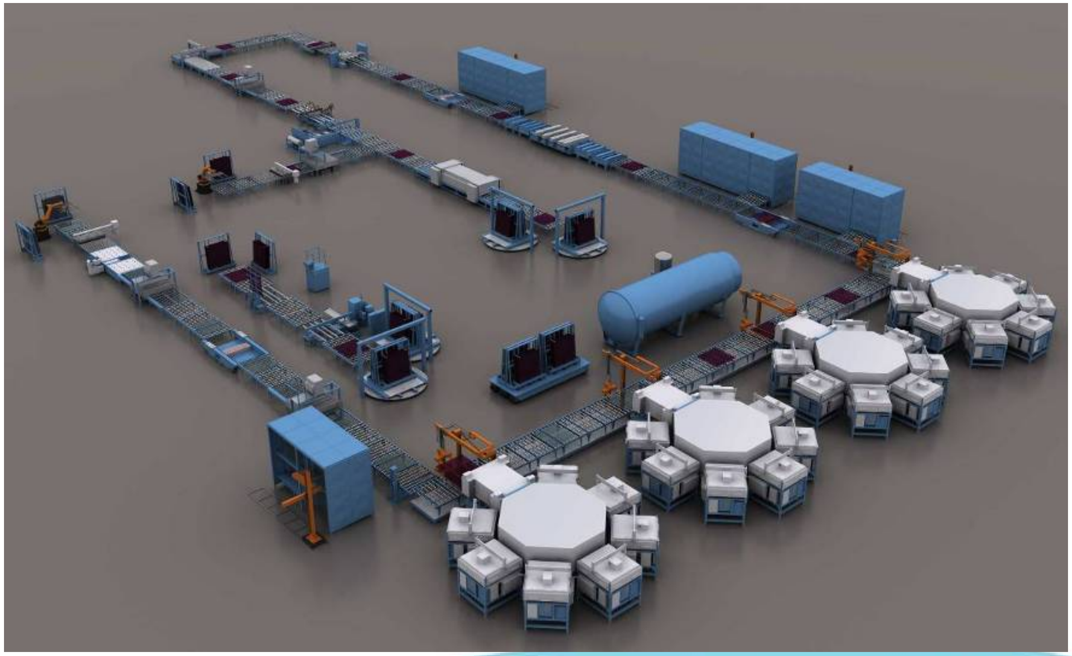
- ❑ The high deposition rate one (HD with DR=660A/min) have initial IV performance comparable to its reference with DR=400A/min.
- ❑ All the data shown is taken 6 months after cell fabrication, high deposition rate ones show stable performance same as reference.
- ❑ LID (two sun light intensity, 300 hours, 50°C) performance is the same for high deposition rate and its reference. (Data not showing here.)

- ❑ Same top cell QE response for all the cells. No obvious damage/change to top cell under high deposition rate for bottom cell I layers.
- ❑ High deposition rate bottom cells have QE response comparable to its reference.

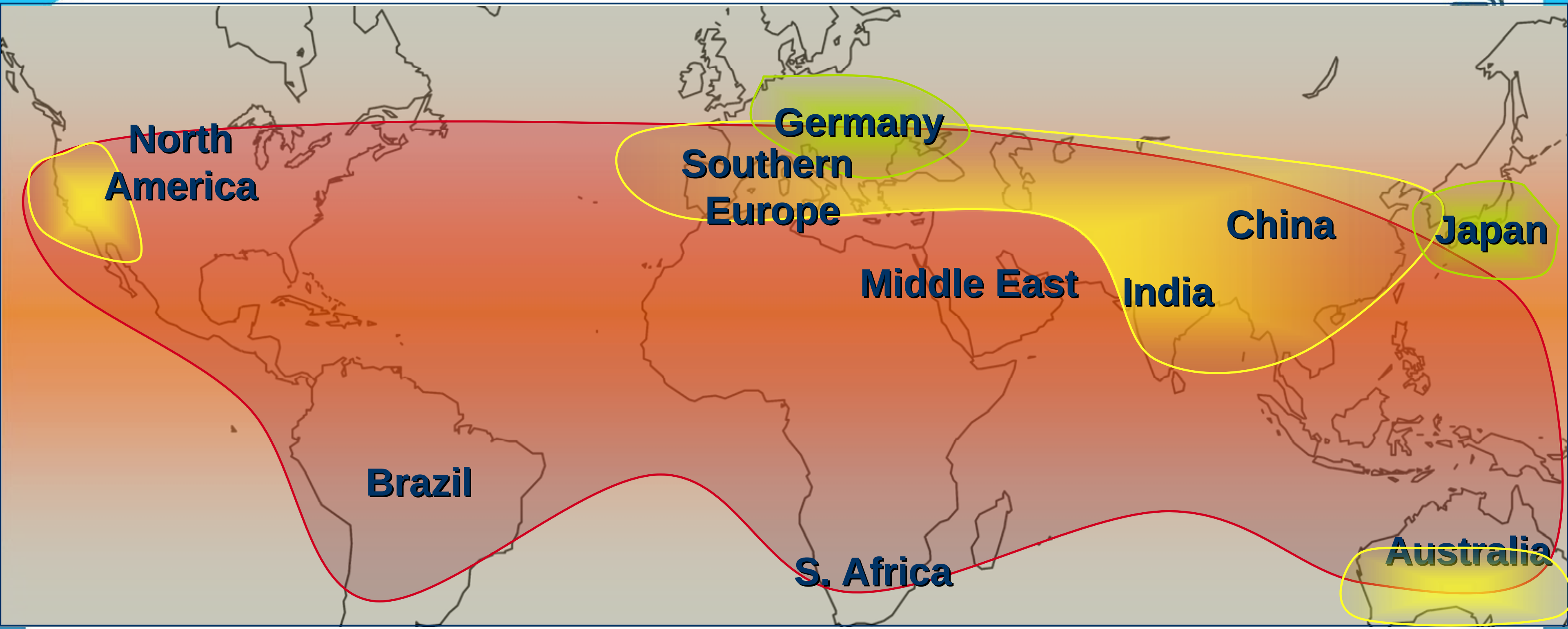
SunFab: Unlocking Cost Reduction

SunFab Solar Projected Output

- 60 MWp (TJ) per year
- 0.75 km^2 of panels per year
- 5.7m^2 panels – largest in the world
- >20,000 homes (3kWp each)
- $1/Watt Production Cost 2010




signet solar
clean affordable renewable energy
The world's first
Gen 8.5 Module
May 23, 2008
APPLIED MATERIALS

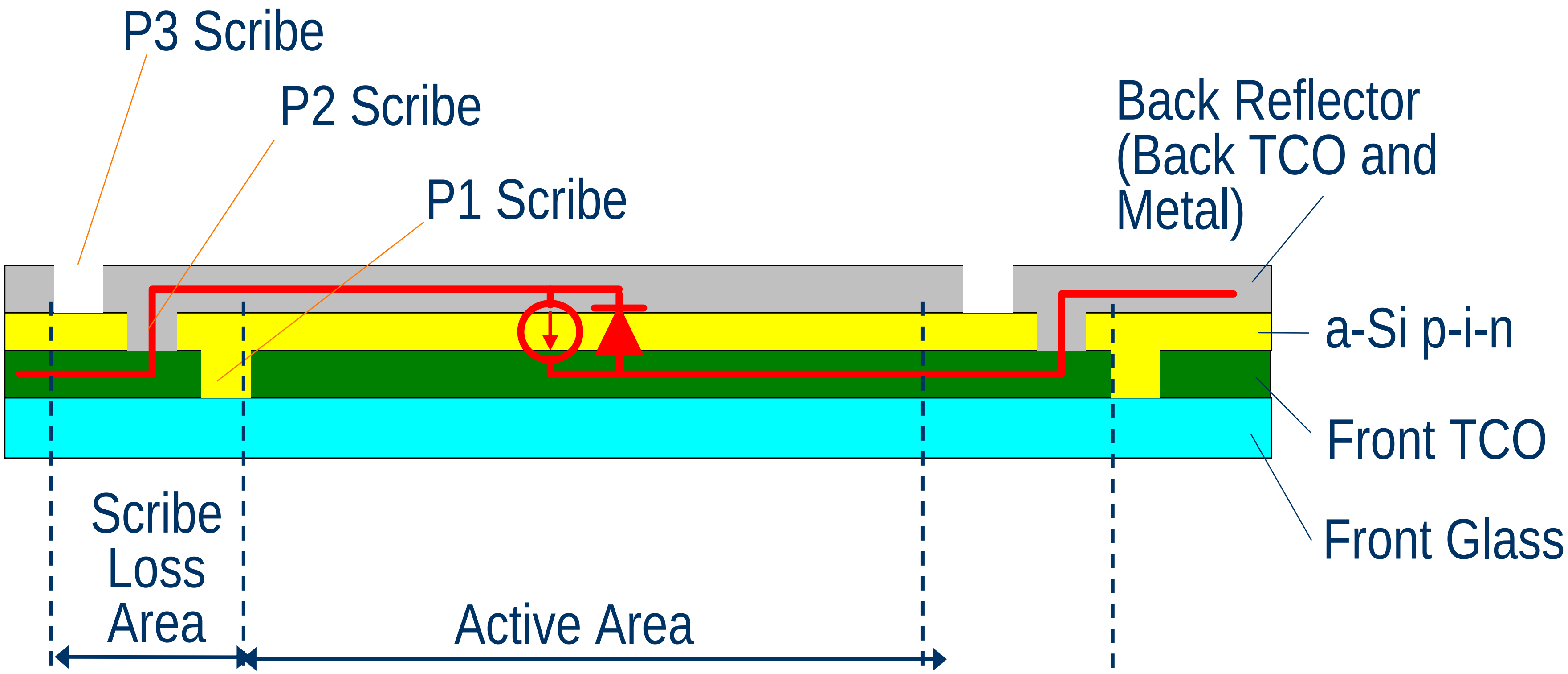


1min of Solar energy > 1 year of world energy consumption

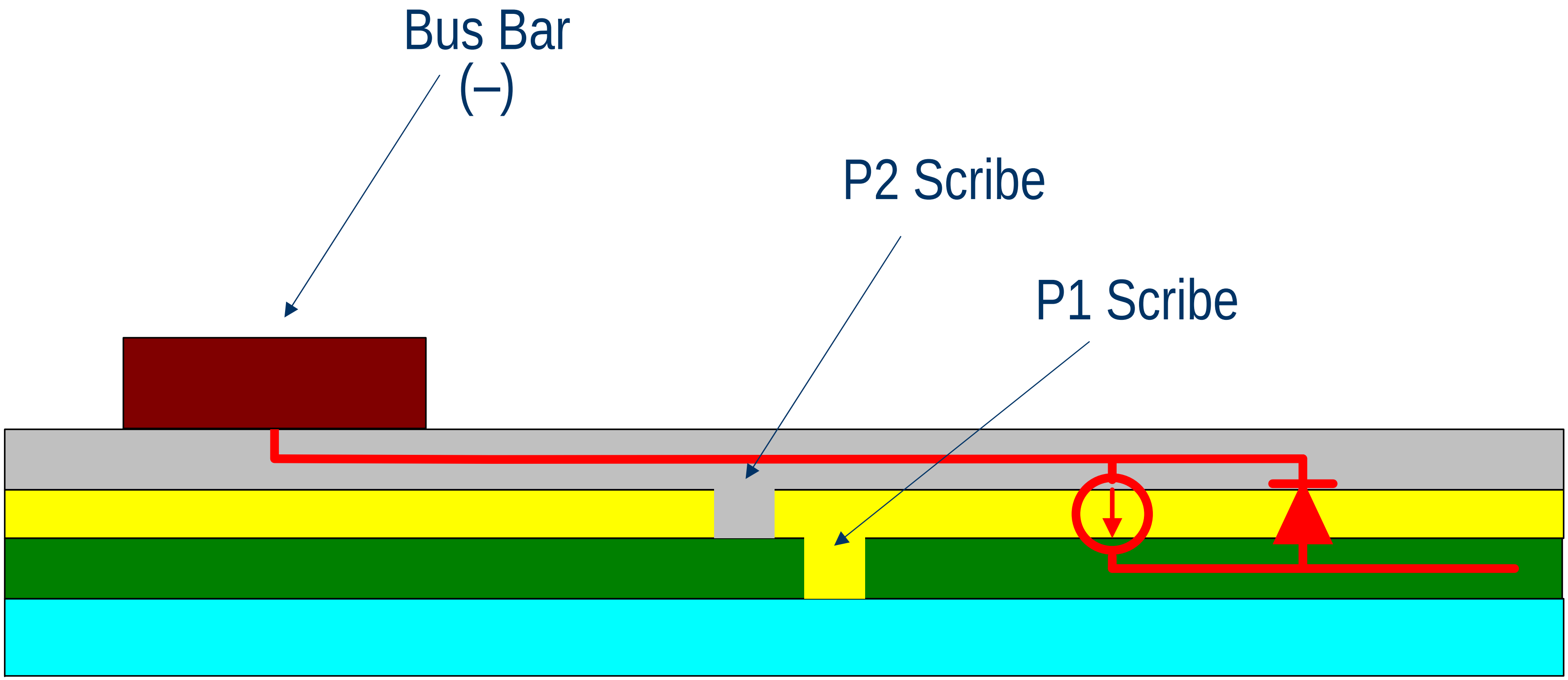
think it. apply it.™

APPLIED MATERIALS.

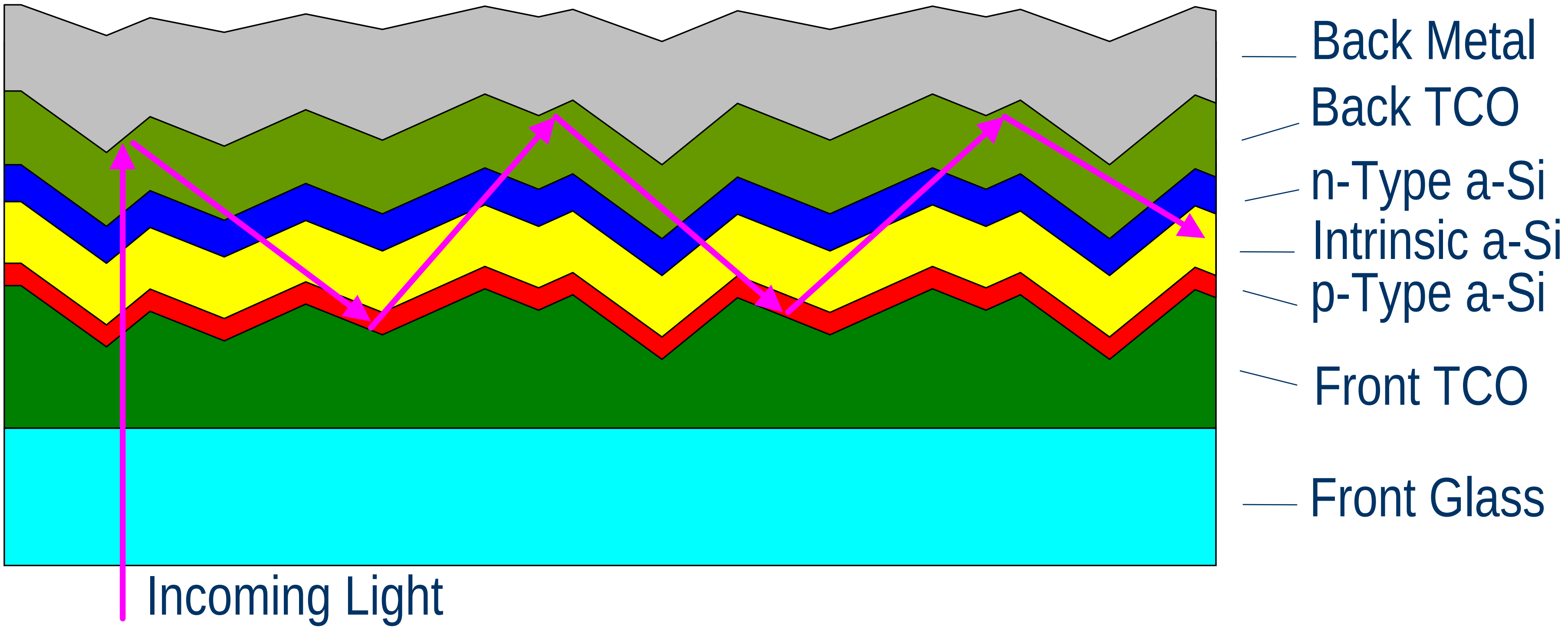
Cell to Cell Connection



End Scribe



Light trapping

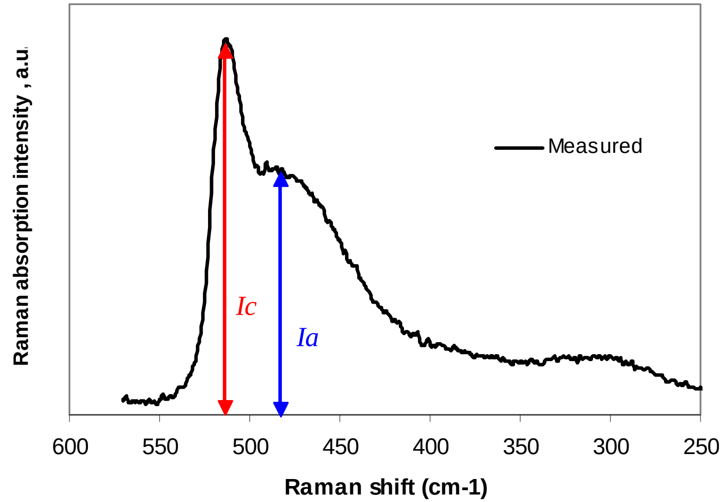


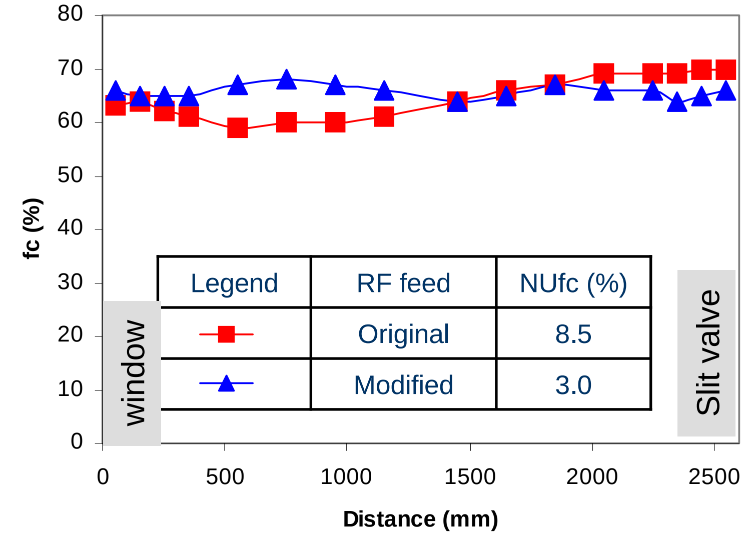
μc-Si:H layer uniformity change

- No significant thickness change
- Fc: crystalline fraction
  - Calculated from film Raman absorption spectrum
  - Raman condition:
    - Laser wavelength = 532 nm
    - Temperature = -49 °C
  - fc is defined as:*

$$fc = \frac{I_c \times 100}{I_c + \left(0.1 + \exp\left(-\frac{100}{250}\right)\right) I_a}$$

- With modified RF feed
  - fc non-uniformity significantly improved from 8.5% to 3.0%





* R. E. I. Schropp and M. Zeman, Amorphous and microcrystalline silicon solar cells, Kluwer Academic Publishers, 1998