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Exploratory Research for Advanced Silicon Photovoltaics

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NREL Si Materials and Devices Section: Silicon from wafers to thin-films

- Crystal Silicon PV
  - – heterojunctions and passivation of a-Si/c-Si
  - – crystal growth for feedstock evaluation
  - – anti-reflection treatments

- Hydrogenated amorphous Si PV
  - – lowgap a-SiGe:H cells
  - – stability

- Film Si on glass
  - – mid-term (5-10 yrs), exploratory research

Budget History

Today's topic

Project Task(s)	FY06 Total Value
Exploratory research for thin crystal silicon films	$0.8 M
Advanced wafer-Si and industry support	$1.1 M
Amorphous silicon research and industry support	$0.7 M
Grand Total	$2.6 M

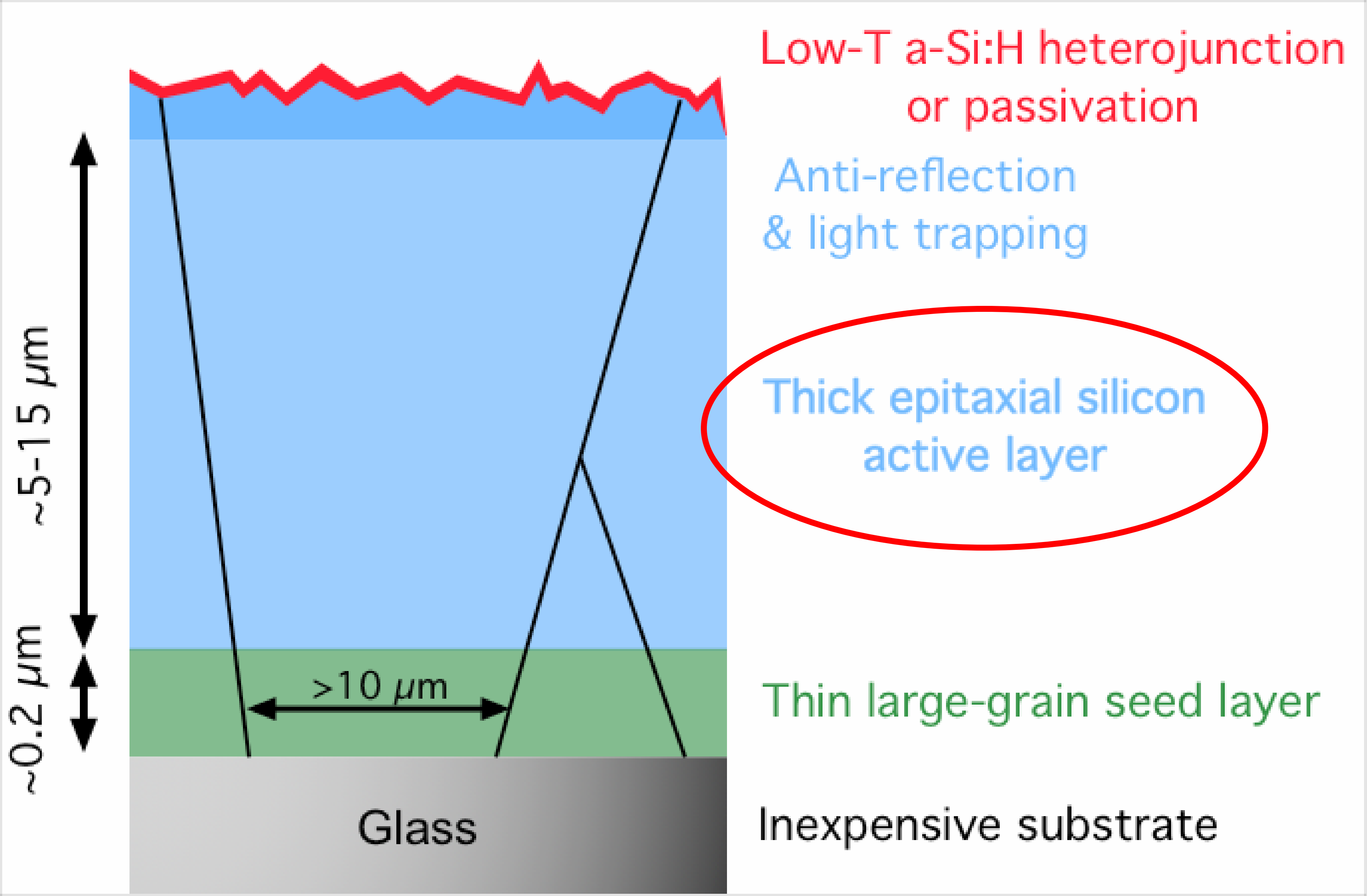
Relevance/Objective

- DOE SETP 2020 research goal will require solar modules manufactured for less than \$1/W

- Exploratory film-Si research objective:
  - crystal Si efficiencies at the area costs of a-Si:H
  - ☐ $\eta>15\%$ at below \$150/m^2 for cost <\$1/W
    - wafers are unlikely to fall below \$100/m^2
    - borosilicate glass ~\$26/ m^2 today
  - approach: film crystal silicon on glass

- Create new technologies that also benefit conventional wafer Si and a-Si:H industries (~ 98% of PV today)
  - Heterojunction passivation
  - Advanced device designs
  - Anti-reflection

Film crystal Si solar cell concept



Low-T a-Si:H heterojunction
or passivation

Anti-reflection
& light trapping

Thick epitaxial silicon
active layer

Thin large-grain seed layer

Inexpensive substrate

Summary of Activity 1

- Activity: Epitaxy at glass-compatible temperatures
  - Thick (5-15 micron) epitaxy at high-rates (20 min) on silicon
  - Demonstrate epitaxy on silicon seed on glass
  - Approach: Scalable hot-wire CVD with in-situ- and post-characterization

- Outcomes:
  - First demonstration of scalable epitaxy below 700°C
  - 11 microns grown in 100 mins at 610°C
    - also demonstrated 200 nm/min epitaxy
  - Understanding breakdown and how to avoid it
  - Epitaxy demonstrated on challenging polycrystalline seed-on-glass
    - confirms epitaxy on various surface orientations
    - Sources of better seeds identified (proprietary)

- Science: Charles Teplin, Paul Stradins, Howard Branz, Qi Wang
  - Kim Jones, Bobby To (NREL Meas. & Char)
  - E. Iwaniczko (Technician)

Wafer vs film Si production

10X thicker than needed

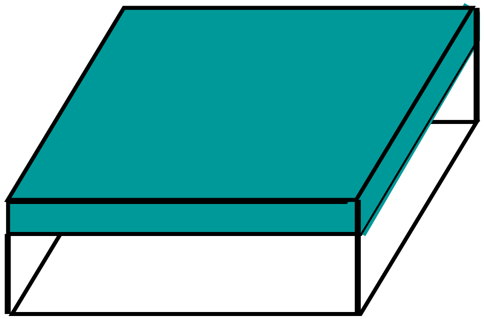
waste half

E intensive

E intensive

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

$SiHCl_3$
or SiH_4



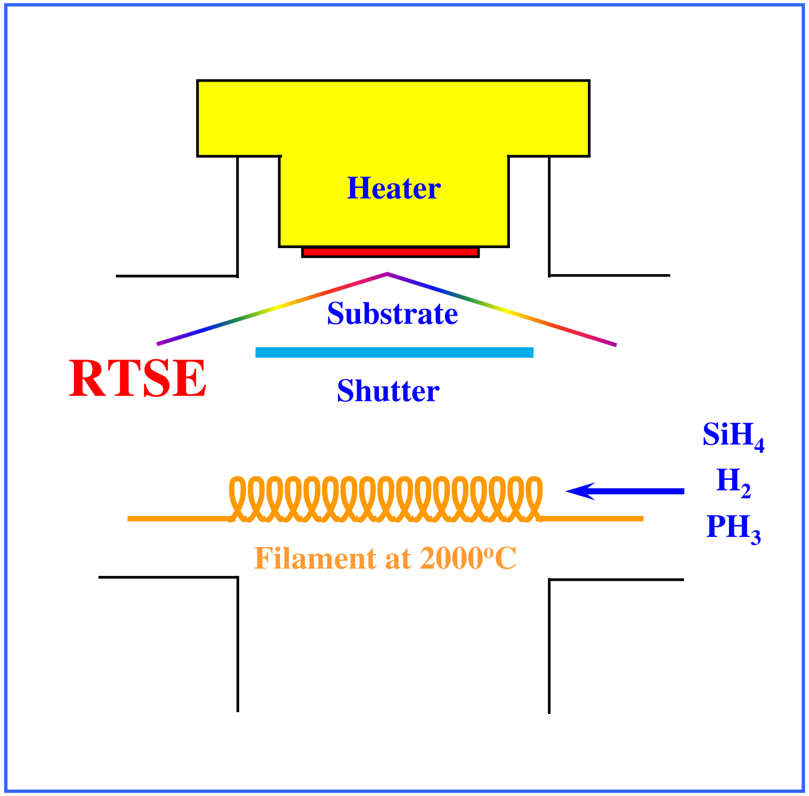
direct to silicon film

- Reduce energy use
- Waste less silicon

adapted from Ciszek, www.siliconsultant.com

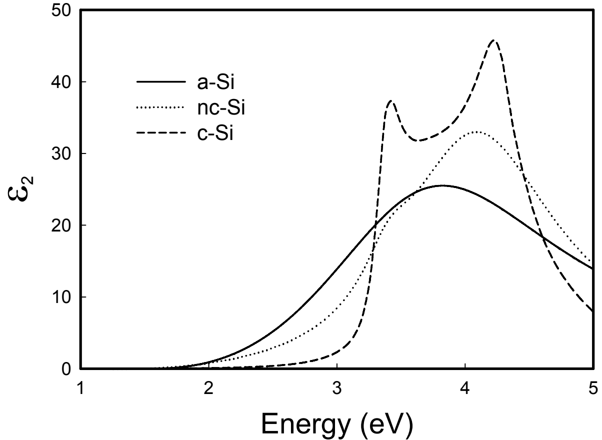
Hot-Wire CVD

- Gentler than PECVD
  - Avoid damaging high-quality Si seeds and wafers
  - No plasma start-up shock
  - No ion bombardment
- Demonstrated large-area scalability
  - Diamond films
  - Amorphous silicon



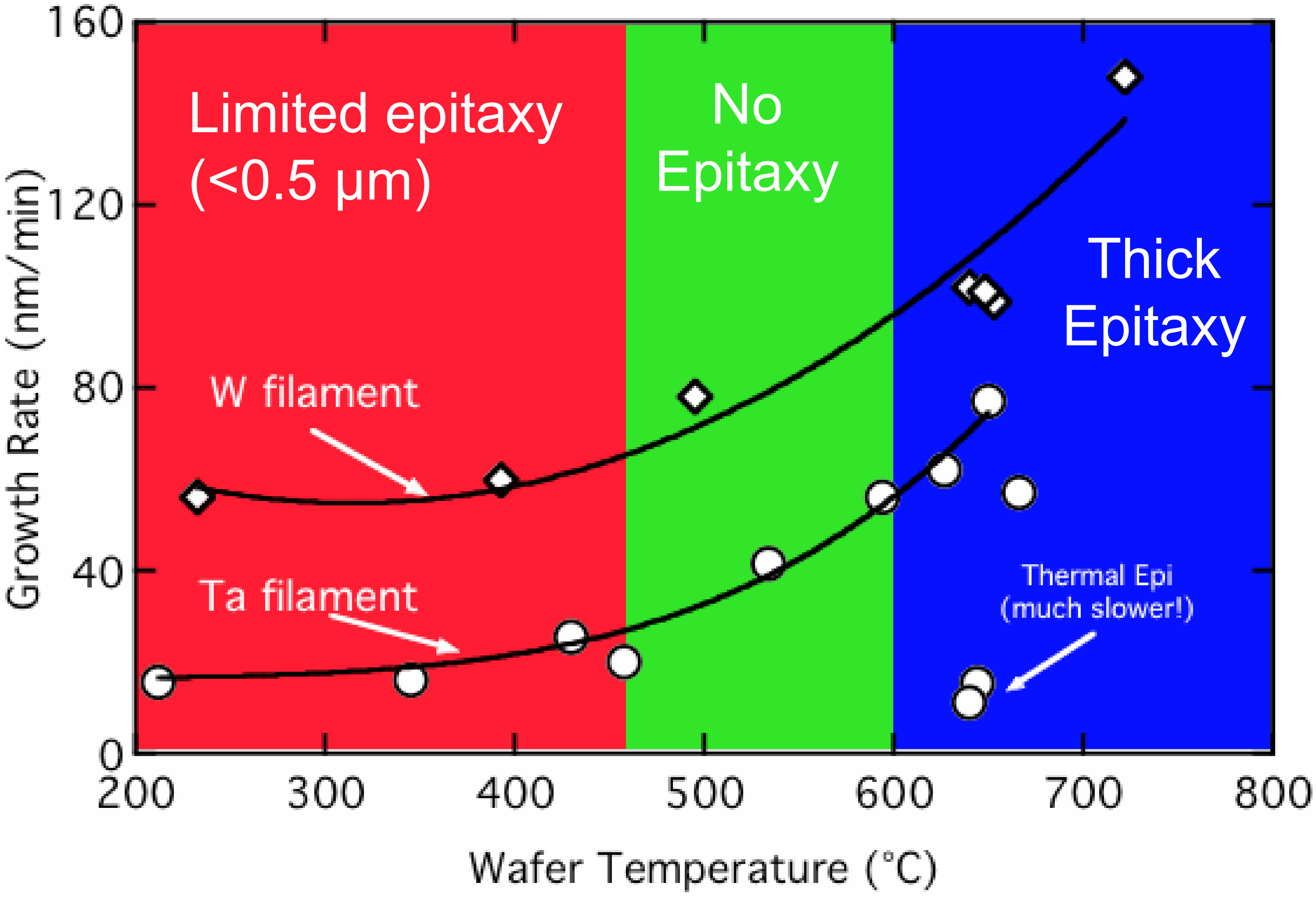
Real-Time Spectroscopic ellipsometry

- Layer-by-layer crystallinity
- Monitoring of thickness and roughness

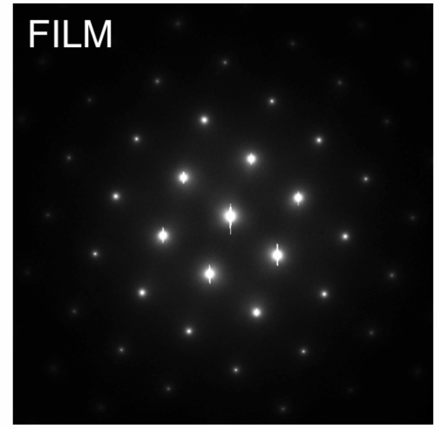


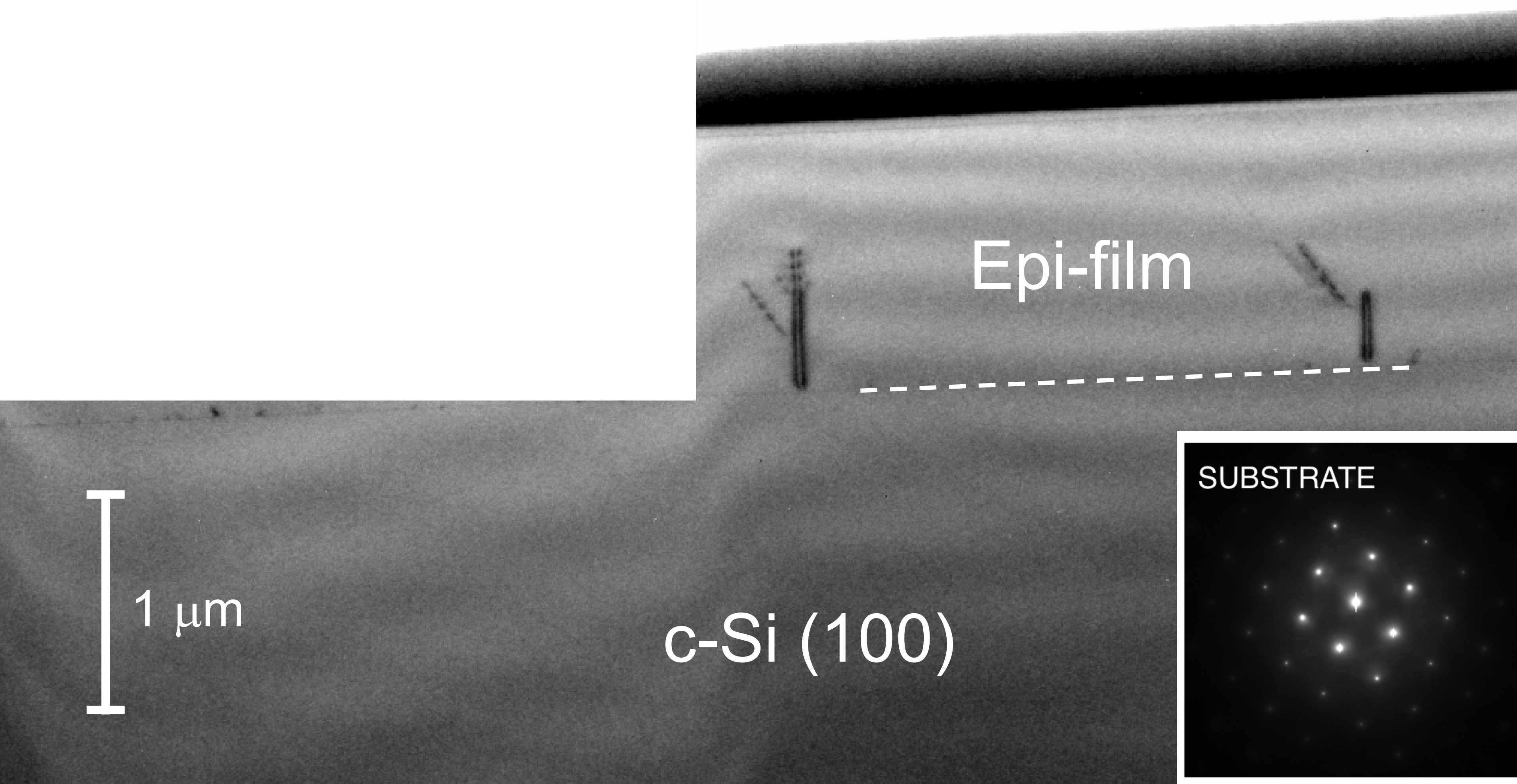
Fast and unlimited epitaxy above 620°C

- Phase diagram for HWCVD growth on (100) c-Si



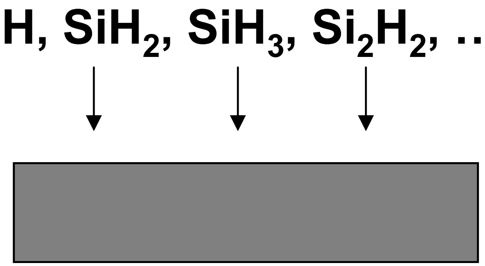
Epitaxial (100) Si grown at 630°C



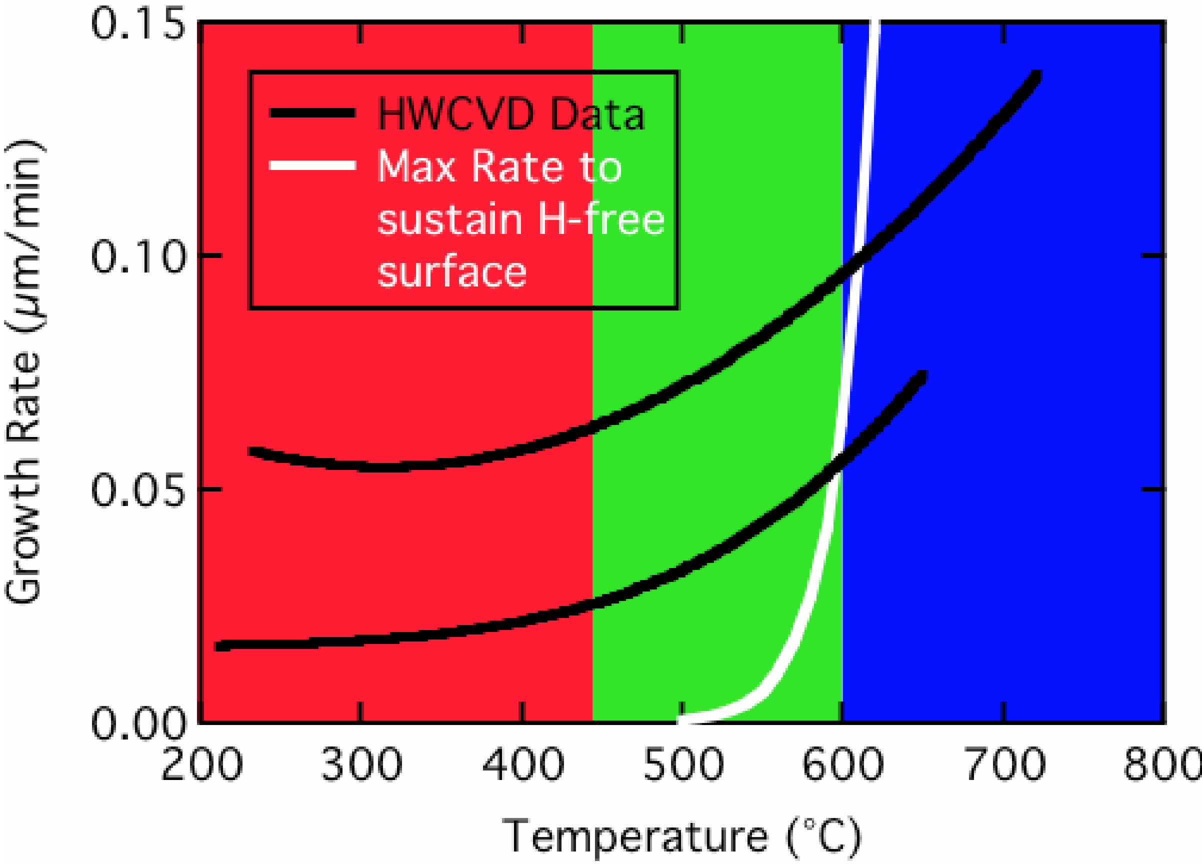


H desorption above 600°C permits HWCVD epitaxy

- **HW produces H-rich precursors:**



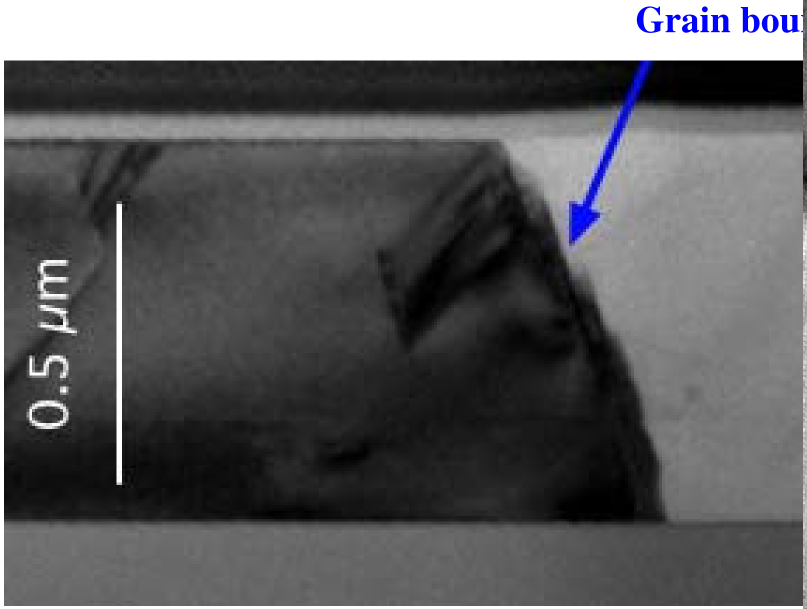
H, SiH_2, SiH_3, Si_2H_2, …

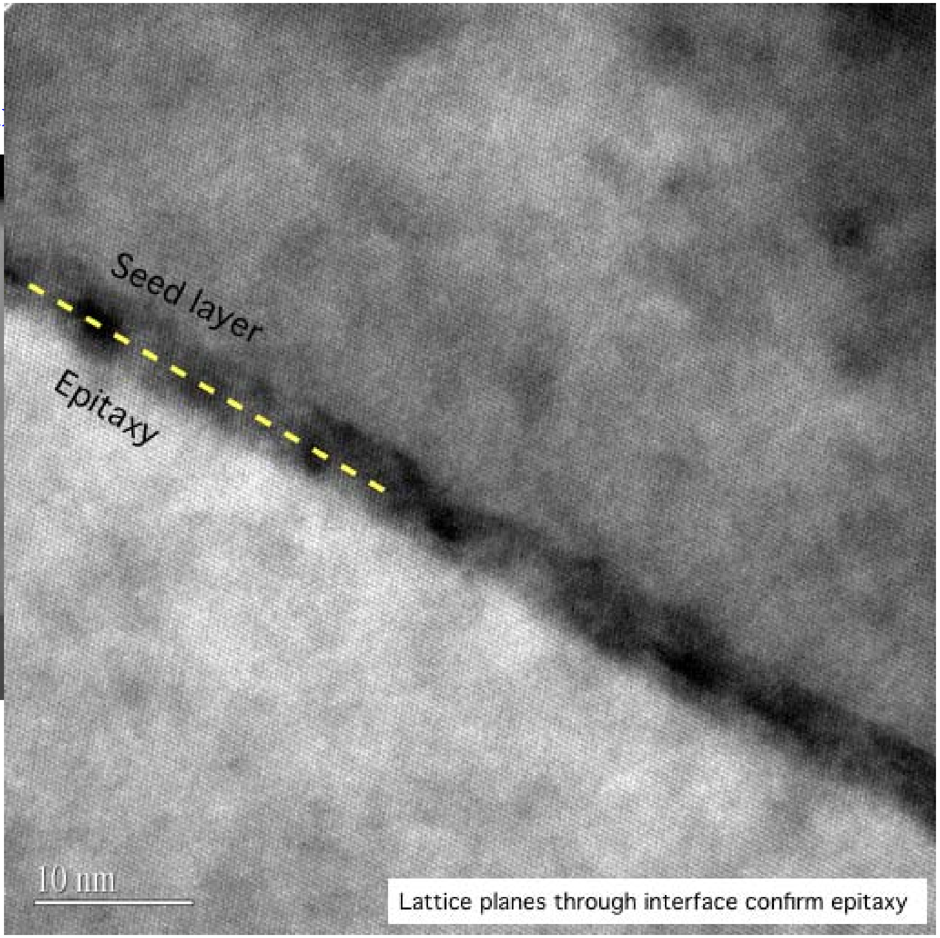


- **Above white (H) curve:**
  - **Si dimers and Si-H mix with dihydride rows**
  - **Epitaxy eventually fails on disordered surface**
- **Below white (H) curve**
  - **Sustained epitaxy**

HW epitaxy on seed-on-glass

- Seed layer: 200 nm of Al-induced Si on borosilicate glass
  - 15 x 5 μm^2 grains with near-random orientations
  - from S. Gall, Hahn-Meitner Inst, Berlin
- HW epitaxy at ~ 650°C





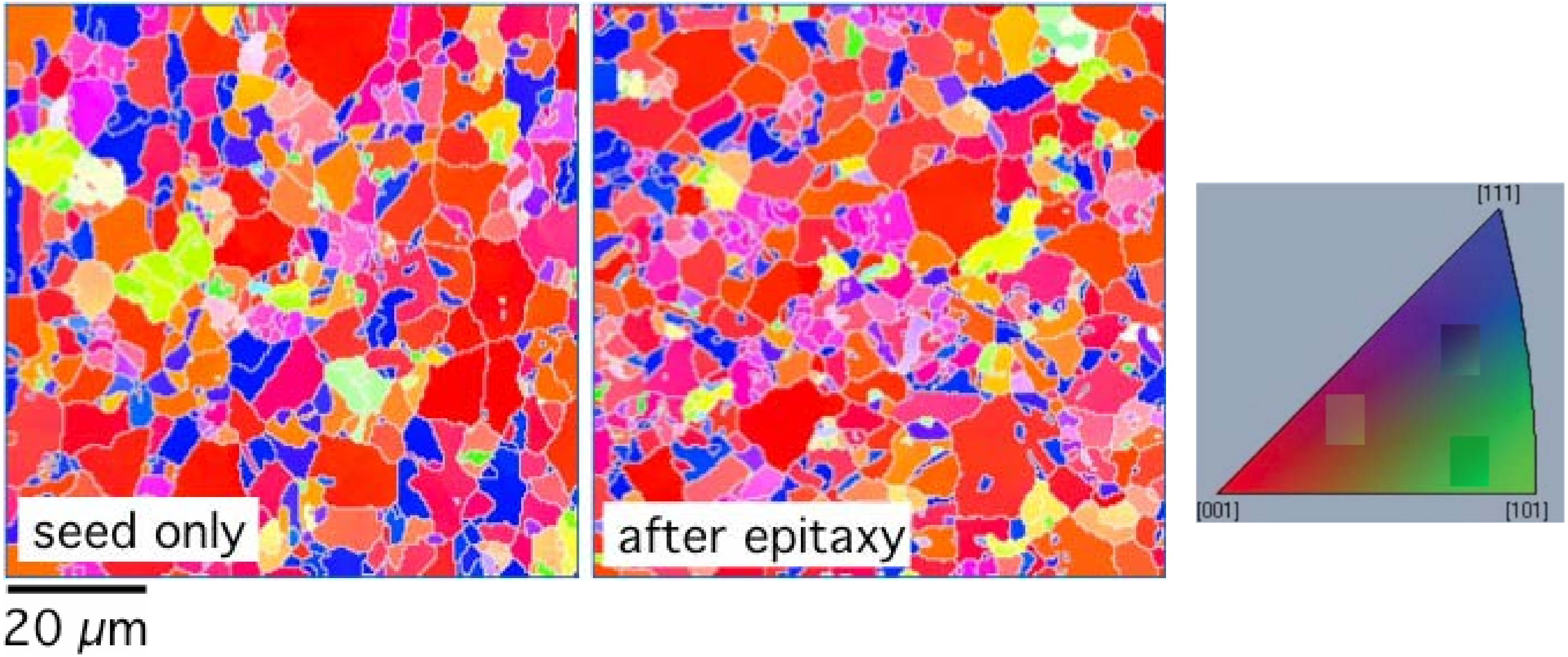
Lattice planes through interface confirm epitaxy

- Need better seed layer!

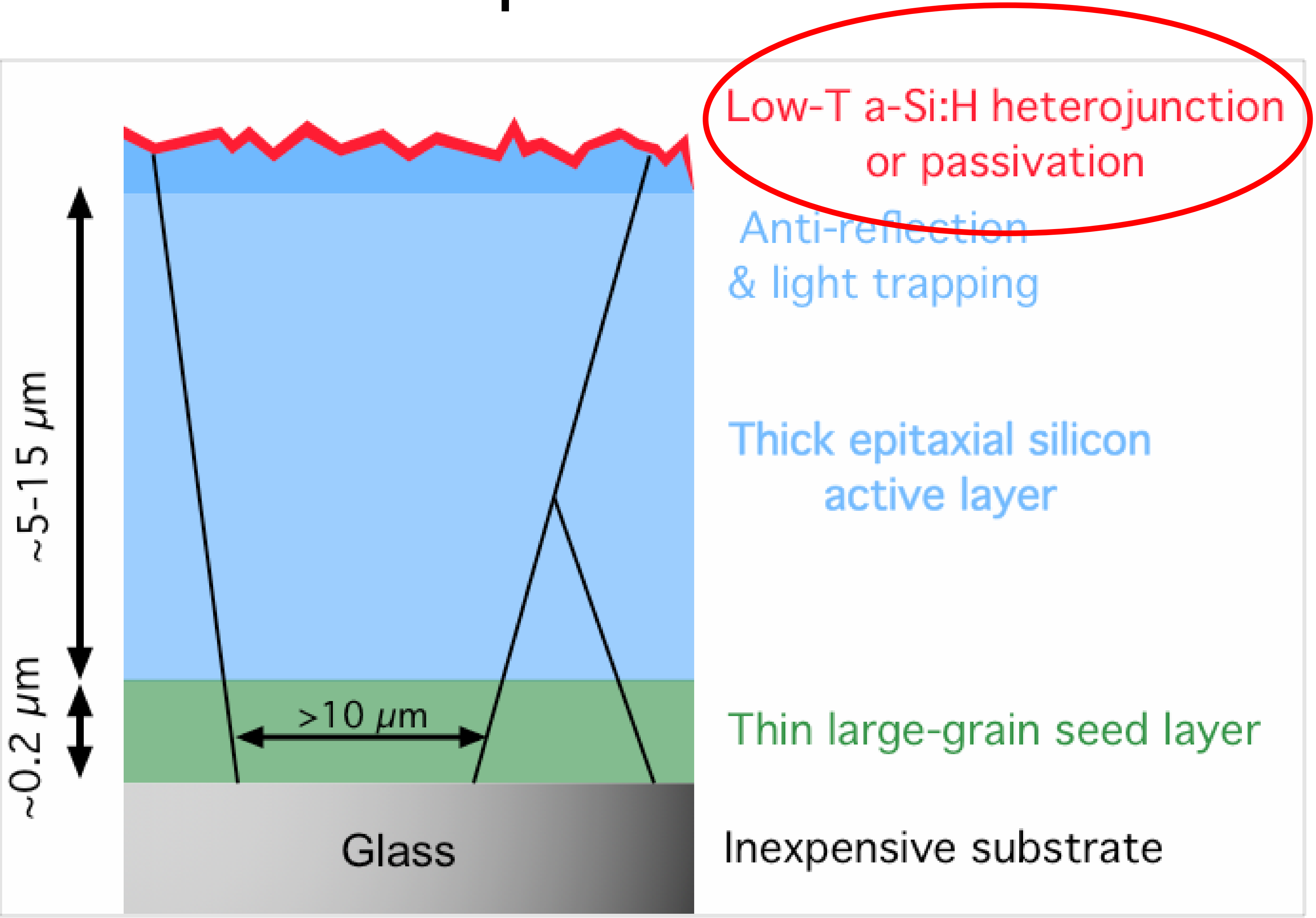
Epitaxial growth on all orientations

- HW epitaxy on Al-induced crystallization seed

Electron backscattered diffraction (EBSD) reveals crystal orientations:



Next: Low-T passivation



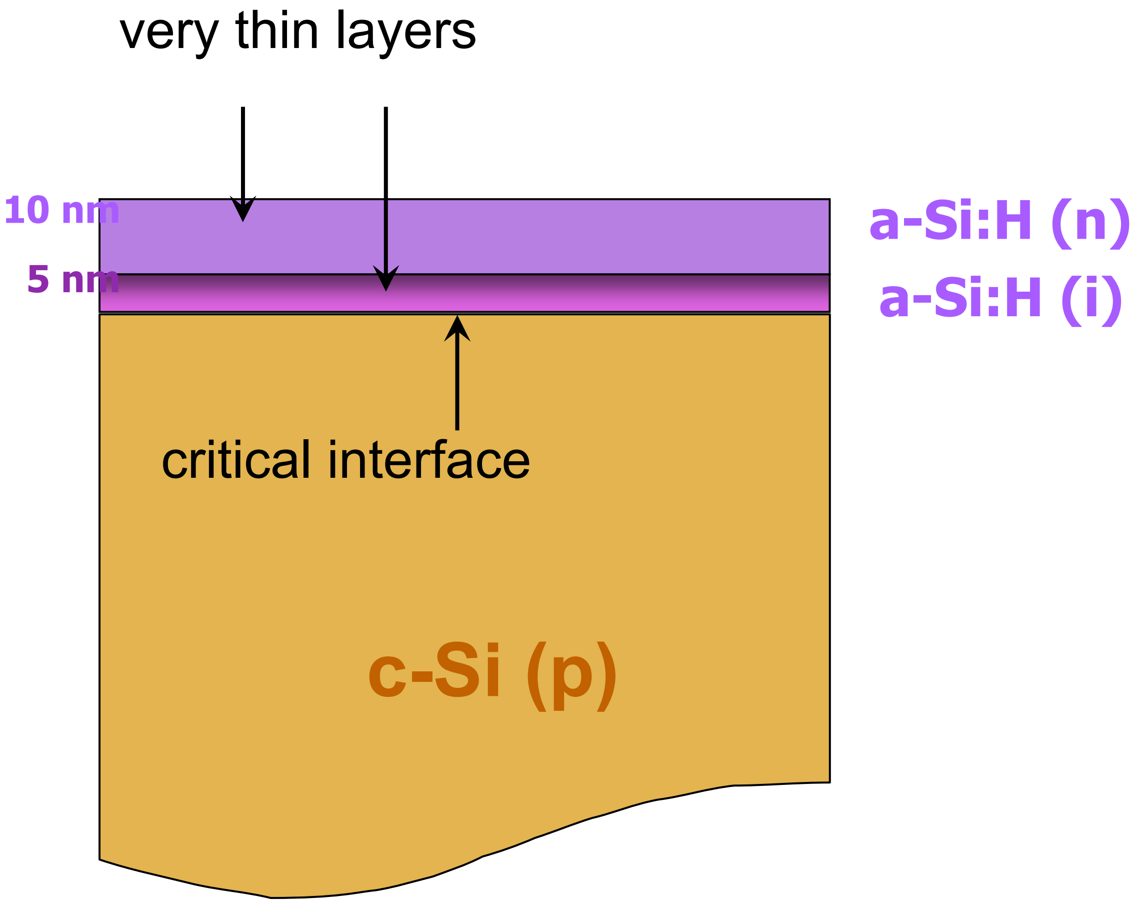
Summary of Activity 2

- Activity: Heterojunction cell development
  - Improved c-Si passivation at low temperatures
    - Needed for film c-Si
    - Emitters without bowing thin wafer-Si
  - Approach: Hot-wire CVD with integrated characterization
  - New interdigitated cell designs under development

- Outcomes:
  - Record p-wafer heterojunction cell of 18.2%
  - Record hot-wire CVD heterojunction cell
  - Excellent V_{oc} of 691 mV on n-type Si
  - Understanding of keys to a-Si passivation to S=20 cm/s

- Science: Qi Wang, Matt Page, Tihu Wang, Y. Xu, Dan Meier
  - Yanfa Yan & Dean Levi (NREL Meas. & Char)
  - L. Roybal, E. Iwaniczko, R. Bauer (Technicians)

Heterojunction emitter on p-wafer



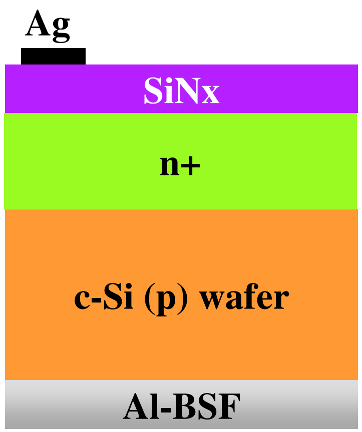
- All processing below 200°C
- Low impurities

Hot-wire SHJ Progress at NREL

Diffused Junction

Baseline →

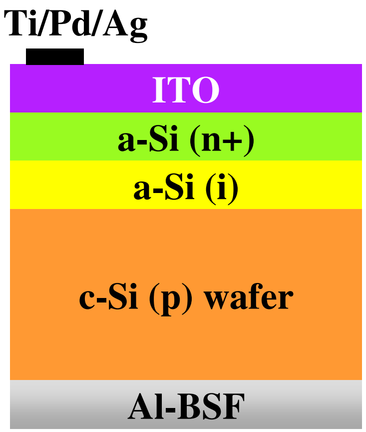
630 mV, 17.2%



Single-side flat

SHJ emitter →

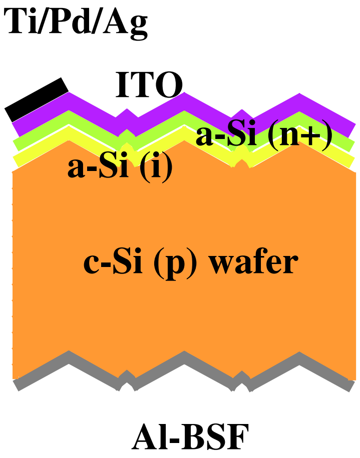
650 mV, 16.9%



Single-side textured

boost J_{sc} →

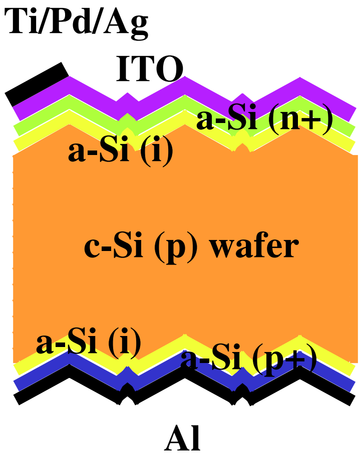
35 mA/cm^2, 17.1%



Double-side textured

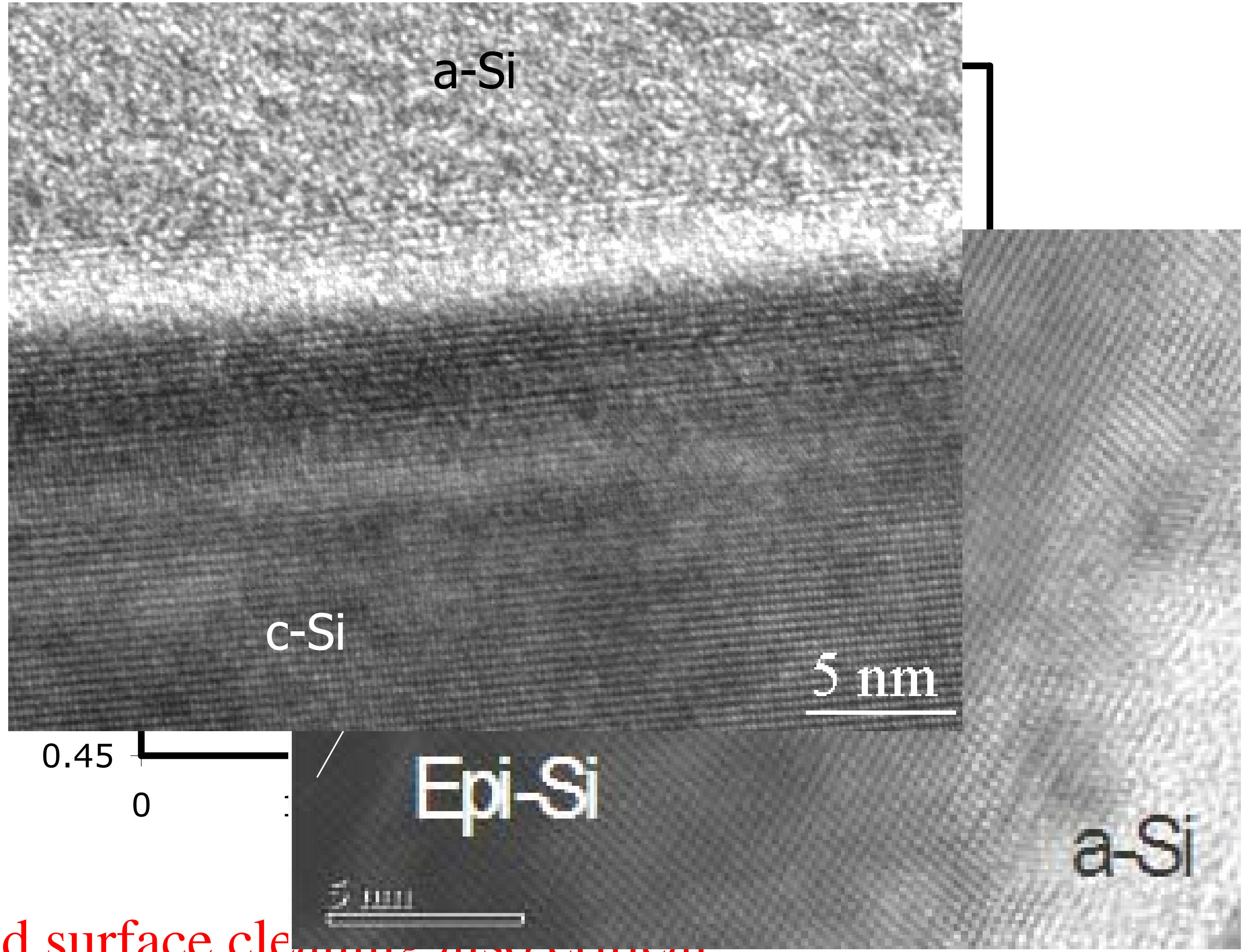
V_{oc} and efficiency

667 mV, 18.2%



Thanks to A. Rohatgi and V. Yelunder (GaTech) for substrates and Al-BSF

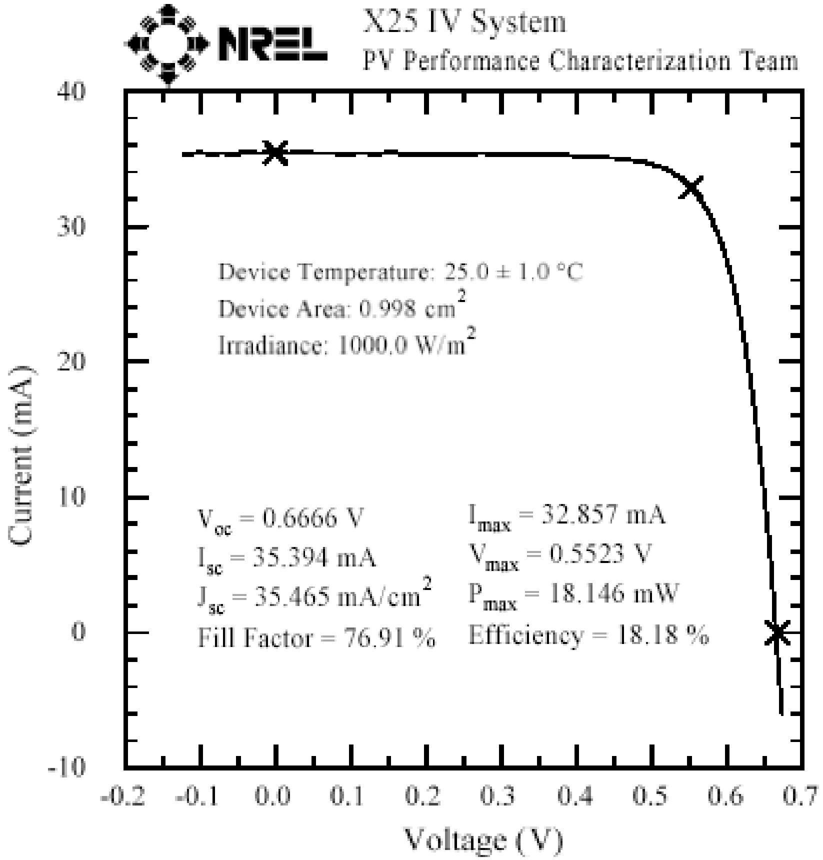
Abrupt a-Si:H key to high V_{oc} (avoid epitaxy)



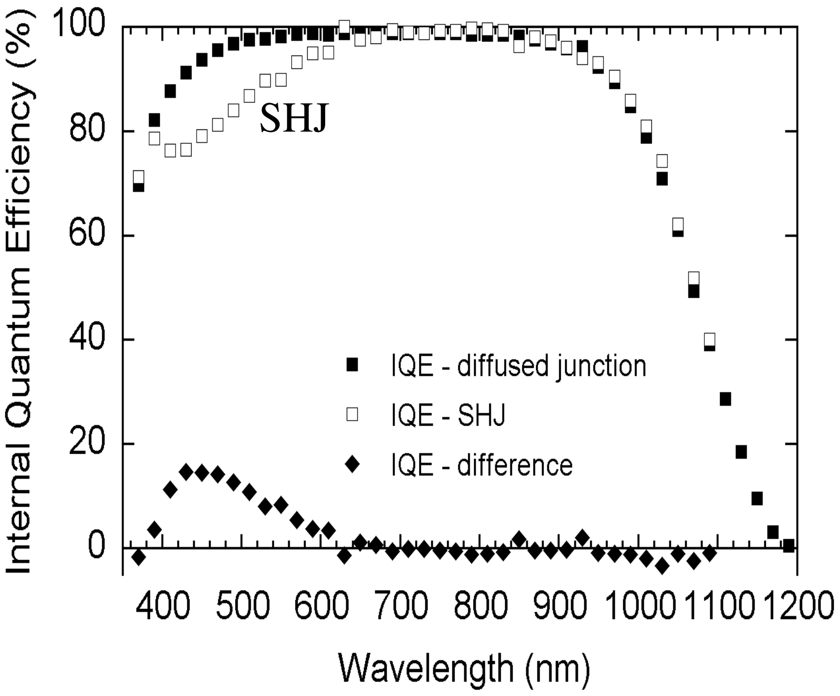
Good surface cleaning also critical.

Confirmed 18.2% *p*-type SHJ cell

`Page et al, Proc 16th c-Si workshop, 2006`

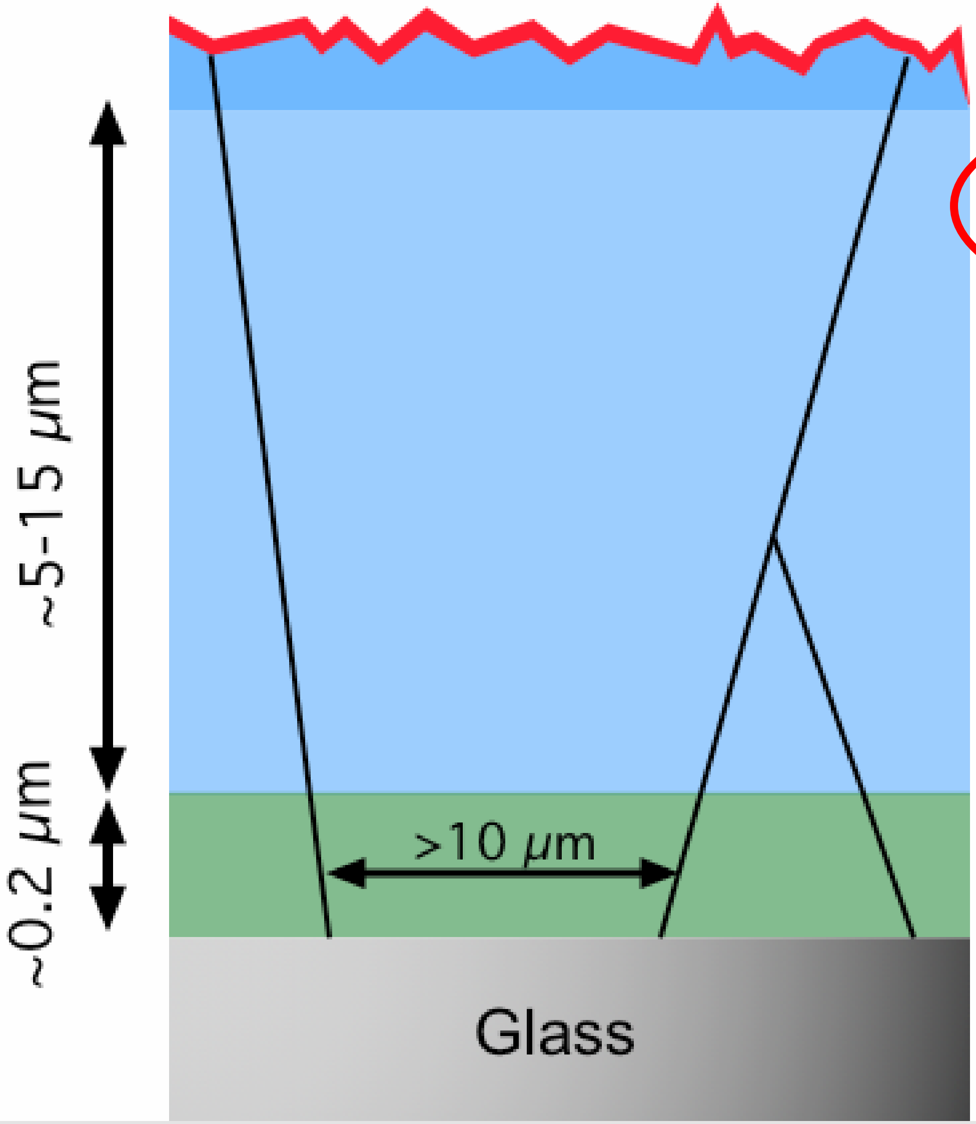


SHJ vs. diffused junction



- high V_{oc} of 667 mV
- Next: reduce parasitic absorption in a-Si:H and reflection losses

Next: Anti-reflection



Low-T a-Si:H heterojunction
or passivation

Anti-reflection
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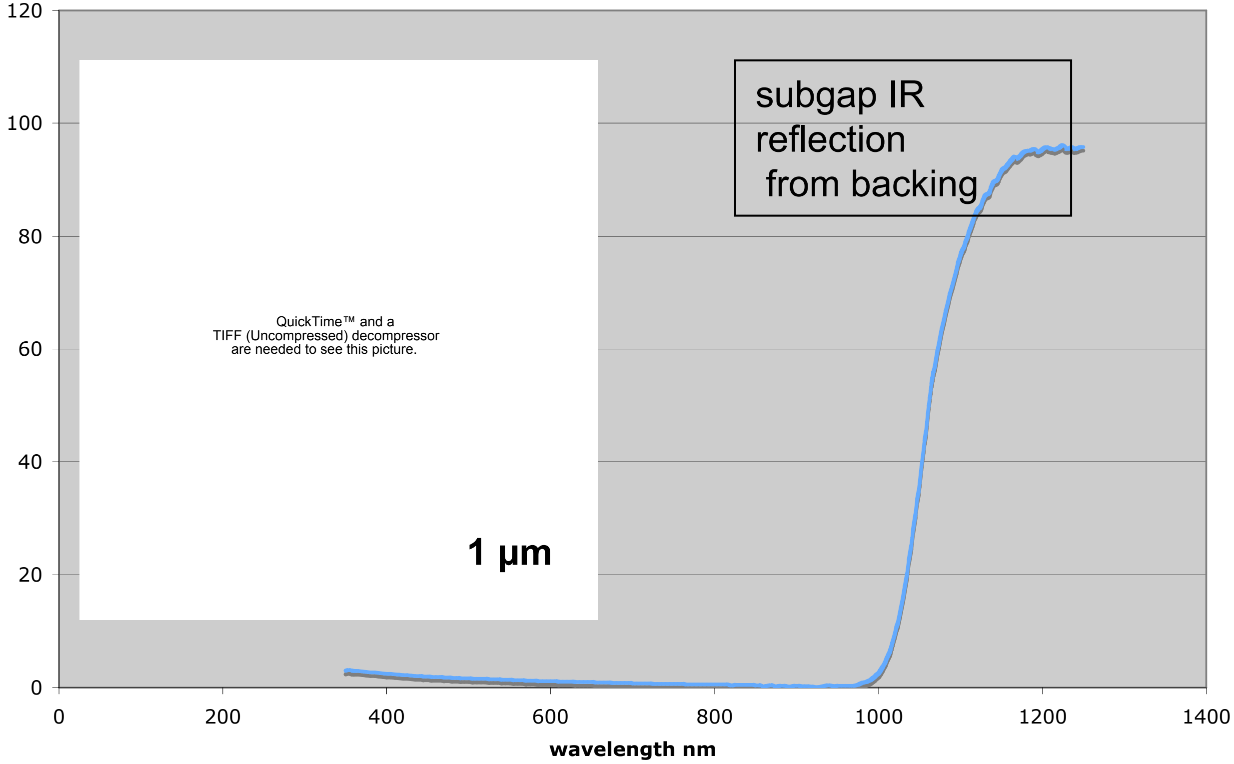
Summary of Activity 3

- Activity: Anti-reflection etching compatible with thin silicon
  - Improvements to published "black Si" etching
  - Removes less than 1 micron of silicon
- Outcomes:
  - Two records of invention filed on proprietary methods
  - Reflectivity < 2% across usable spectrum
  - Applicable to wafer crystal Silicon
- Science: Howard Branz, Dan Meier, Vern Yost
  - Bobby To (NREL Meas. & Char)

“Black Si” texturing

- Total reflectance:



- 2Å Au evaporation followed by H_2O_2/HF etch

  Koynov et al, APL 2006

- Linear grade in index to about 300 nm deep is deep black
  - very wide anti-reflectance acceptance angle

- NREL has now developed more ‘industrial’ approaches (still proprietary)

Group's other Si projects inform our film c-Si approaches

- High-rate HWCVD a-SiGe:H lowgap solar cells
  - collaborate with Uni-Solar on a-Si:H tandems
- Recrystallization of HWCVD a-Si:H
  - developing hydrogenation for film Si passivation
- Understanding of light-induced metastability
  - a-Si:H and O-B pairs in p-type crystal Si
- Test new Si feedstock approaches
- Interdigitated SHJ cells

Accomplishments

- Progress toward fast scalable epitaxy
  - 11 µm of epitaxy at glass-compatible temperatures
  - 150 nm/min epitaxy at 620°C with reduced defect density
  - Successful epitaxy of seed-on-glass substrate on all crystal orientations

- Low-temperature options for heterojunctions and surface passivation
  - 18.2% p-wafer SHJ cells with V_{oc}=667 mV
  - V_{oc}= 691 mV on n-type wafer

- Shallow Si antireflection etching by new industrially-compatible method

- 20 journal papers on silicon
  - 6 in Applied Physics Letters
  - also, Phys Rev Lett, Phys Rev B, and J Appl Phys

- 10 conference talks, including 3 invited talks on film crystal silicon
  - attracting many (often proprietary) offers of seed layers!

Schedule of Major Events/Milestones

- FY07 Milestones
  - ✓ Thick Si epitaxy with reduced defects
  - 19% silicon heterojunction solar cell
  - ✓ SHJ open-circuit voltage of 690 mV
  - Operation of 6-inch silicon cluster tool in PDIL

- Future events and milestones
  - Epitaxy on high-quality seed-on-glass (FY08)
  - Solar cells on 6-inch cluster tool (FY08)
  - Contribute to United Solar SAI TPP (FY08)
  - Film silicon solar cells above 12% efficient (FY10)
  - FY09 evaluate and decide best application of heterojunction passivation (film silicon, multicrystal wafer, or interdigitated)

Future Directions

- Seed layers on glass with epitaxial thickening
  - Obtain/develop improved seed layers
  - Improve high-rate epitaxy
    - methods to characterize opto-electronic quality
  - Optimize anti-reflection and contacting
  - 15% cells at less than $1/W manufactured

Thank you