Perovskite R&D at First Solar: challenges and approaches

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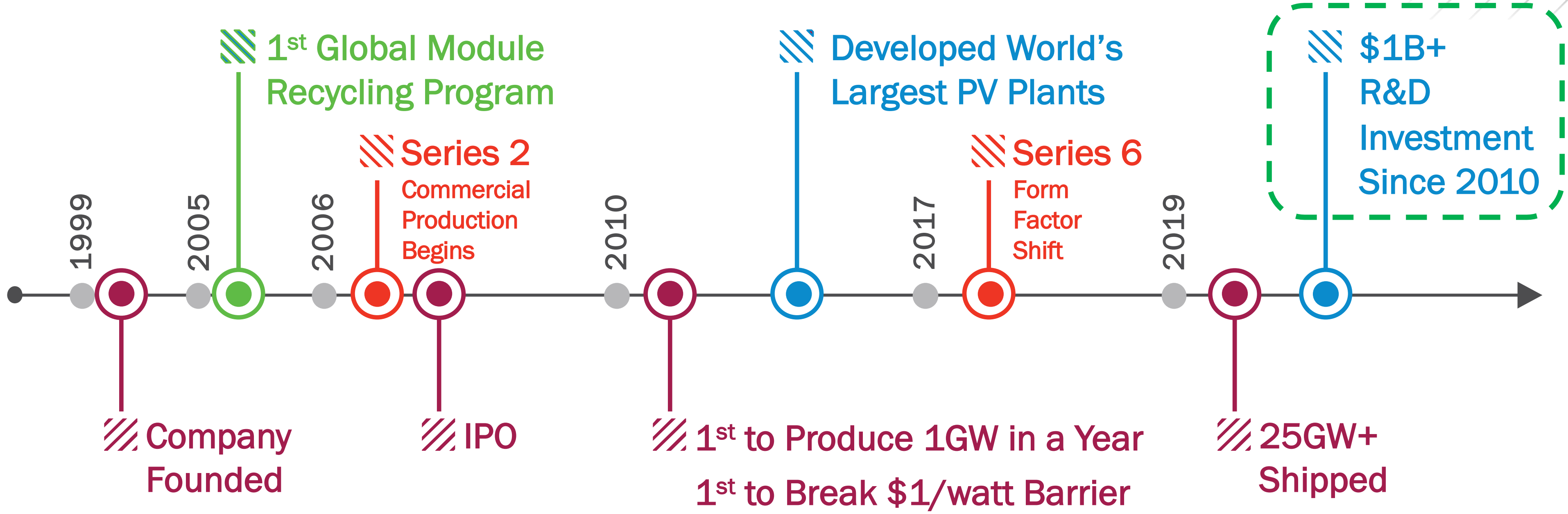
Outline

- First Solar at glance
- Perovskites R&D overview
- Characterization and modeling for fast learning
- Conclusion

The Western Hemisphere's Largest Solar Manufacturer

- Our CdTe-based thin film technology designed and developed in America
- Higher lifetime energy, with lower levelized cost of electricity (LCOE)
- Financially stable with industry leading bankability
- Lowest carbon PV technology and lowest life cycle environmental footprint

20+ Years of Innovation



Perovskite research at First Solar

- Currently, 20 people involved in perovskites
  - Small portion of R&D, but leveraging vast experience in CdSeTe-based thin film PV
- Main emphasis on stabile energy and robustness in field
  - ...before worrying about scaling and cost
- R&D test sample platform for fast learning
  - $10x10cm^2$ for high-throughput lab testing
  - $24x60cm^2$ mini-modules for field verification

Device modeling in perovskites

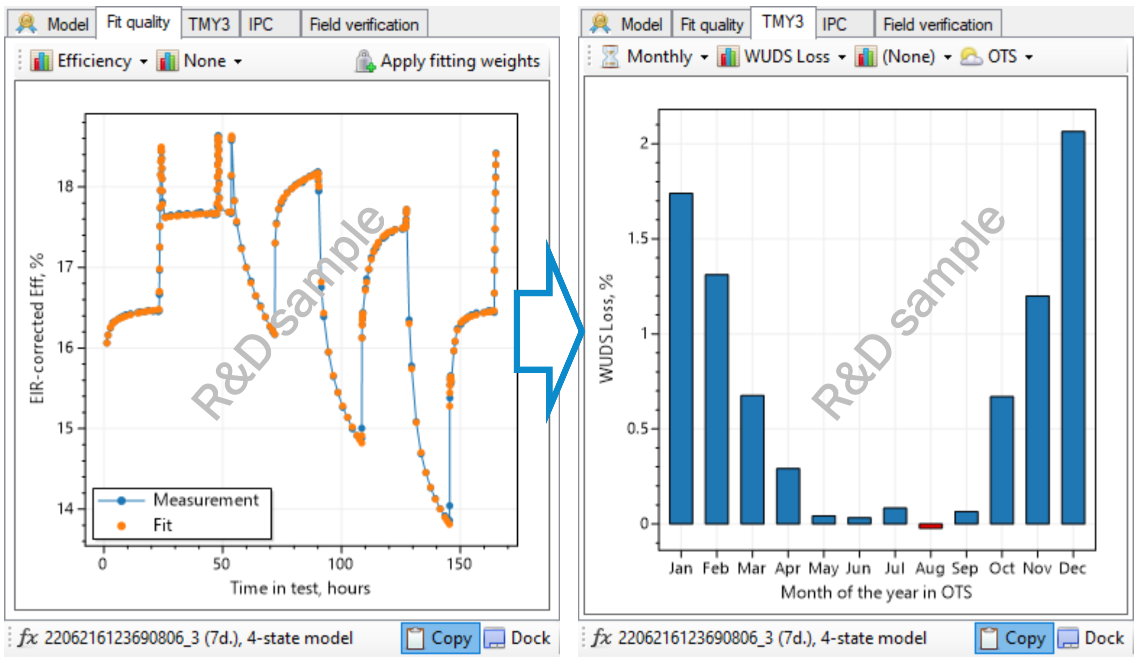
- Traditional "detailed" approach used in Cd(Se)Te absorbers is not yet applicable
  - Perovskite material system is still in flux, huge # of degrees of freedom
  - "Snapshots" of first-principle calculations not enough to model defect chemistry
- Approach #1: "Effective" defect chemistry
  - Few "effective" defect species whose diffusion/reactions define metastable distribution of electrically-active centers
  - (Possible) "irreversible" phase transforms causing evolution of band structure/alignment
- Approach #2: Physics-inspired phenomenological energy modeling
  - Coupled generic kinetic mechanisms acting simultaneously to cause metastable changes in device performance and "irreversible" degradation

Both #1 and #2 need high-fidelity test data to fit models

Characterization for fast learning

- Test objectives
  - Process control & benchmarking
  - Model parametrization for physical understanding / energy prediction
  - Early issue detection / field robustness
- Requirements for fast learning
  - Standardized test structure, test recipe, and analysis
  - Test procedure to isolate mechanisms and properties
  - High-throughput, high-fidelity characterization equipment

Process benchmarking: metastable power output



$$P = P_N \cdot S \cdot F_T(T,S) \cdot F_L(L,T)$$

$$\text{where } S(t) = \sum_{i=1}^{N} s_i(t), \quad \frac{ds_i}{dt} = \frac{s_i^{EQ}(T,L) - s_i}{\tau_i(T,L)}$$

P_N: “nominal” power
S: state (ability to produce power)
F_T: Temperature response function
F_L: Irradiance response function

- Multi-mechanism kinetic model
- Multi-T, multi-irradiance MPP tracking test

- Kinetic power model integrated against meteorological data ➔ Energy prediction
- Process benchmarking with respect to metastable energy losses

High-fidelity, high-throughput characterization

- R&D that targets energy needs lots of ALT capacity
- 1800+ coupon-sits in existing coupon-level systems supporting SC, OC, and MPP tracking w/ light and temperature feedback control

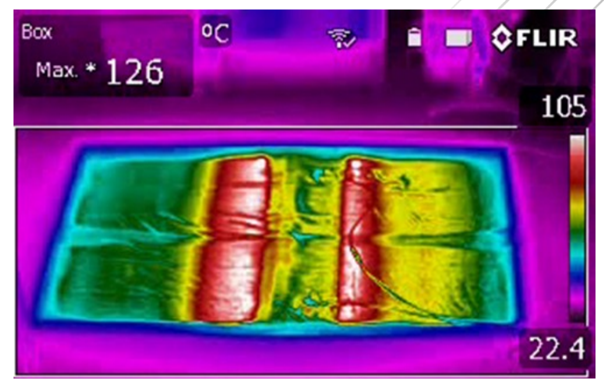
Test purpose	Light, Sun	T range, C	Ambient	Capacity
Process benchmark	Binary (0/1)	RT to +85	Air	1728
Process benchmark	1 Sun only	-15 to +105	CDA,RH	64+
Technology model	Analog (0:1.2)	-15 to +105	CDA	64+

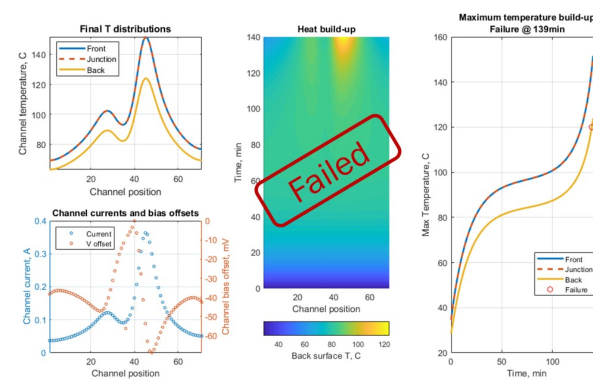
- All high-fidelity, high-throughput ALT instruments accept same (standardized) 10x10 cm coupon layout and packaging

New ALT system in assembly

Robustness against abnormal operating conditions
Early issue detection

- As compared to CdTe and Si, perovskites are low-T materials less robust against overheat
- Local hot spots / thermal run-away resulting from abnormal operation could become major challenge
- RCOL test, partial shading test, etc., should be implemented for early problem detection
- Module-level material uniformity, intelligent layout, scribing, bussing and ballast design: key components of robustness

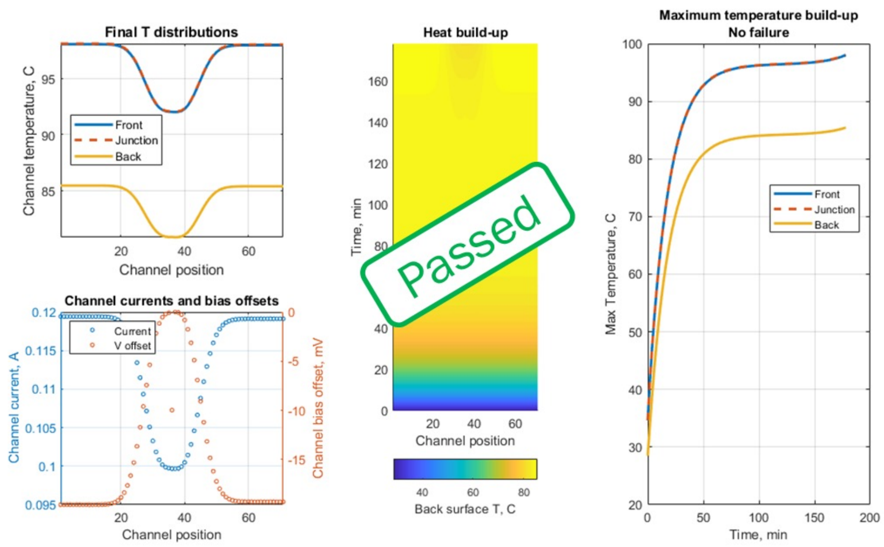




Instead of conclusion

He will win who prepared himself
— Sun Tzu, The Art of War

- Peak efficiency is for feasibility demonstration; Customer needs energy + reliability
- High-throughput, high-fidelity characterization is key to fast learning
- Multiple challenges are still ahead – we win when we are prepared



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