Thermo-Mechanical Degradation Mechanisms Relevant for Field Failures and Solar Lifetimes

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(OPV, Perovskite and multi-junction active layers and electrodes)

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(encapsulation and optics)

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(ultra barrier films)

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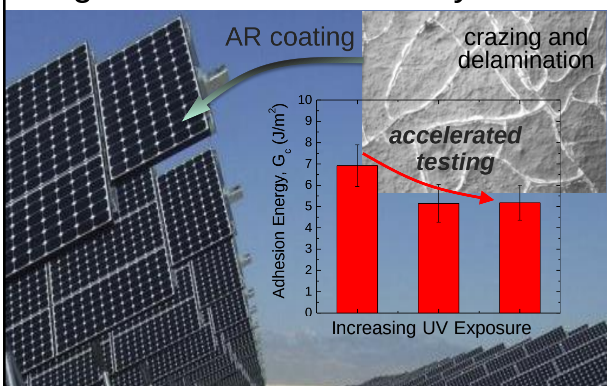
SunShot U.S. Department of Energy

Degradation and Reliability of PV Devices and Modules



operating environments:

thermal cycling, stress, moisture, chemically active environmental species, solar UV, …

coupled and often uncertain degradation kinetics and reliability models.

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  - debonding kinetics and lifetime predictions
- Reliability and Operational Lifetimes for CPV Technologies
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  - prospects for improvements

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Device Reliability and Evolution of Defects

damage propagates if mechanical stresses are large enough so that

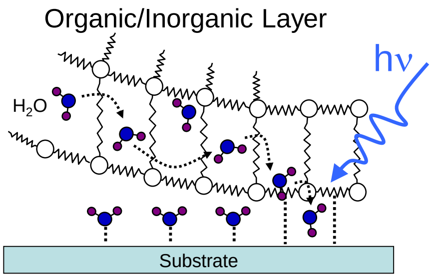
mechanical "driving force" $$G \geq G_c \left[J/m^2 \right]$$ *cohesion or adhesion*

presence of chemical species and photons, damage propagates even if

$$G < G_c \left[J/m^2 \right]$$ *environment and stress <u>accelerates</u> defect evolution*

Role of <u>coupled</u> "stress" parameters:

- *mechanical stress*
- *temperature*
- *environmental species*
- *photons (photochemical reactions)*



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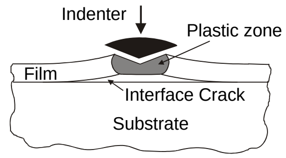
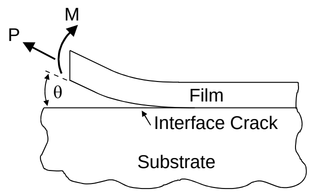
Limitations of Thin-Film Adhesion Tests

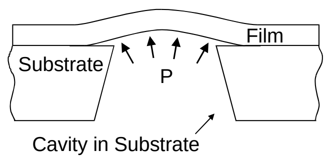
- Indentation/Scratch Test
  - complex stress and deformation fields
  - principally qualitative results
  - (nano) scratch test even less quantitative



- Peel/m-ELT Test
  - difficult to apply loads
  - plastic deformation of film
  - temperature complications in m-ELT



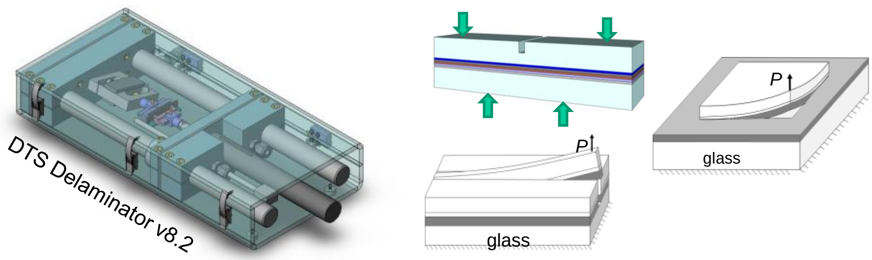
- Blister Test
  - compliant loading system
  - environmental effects
  - etching/machining of cavity difficult

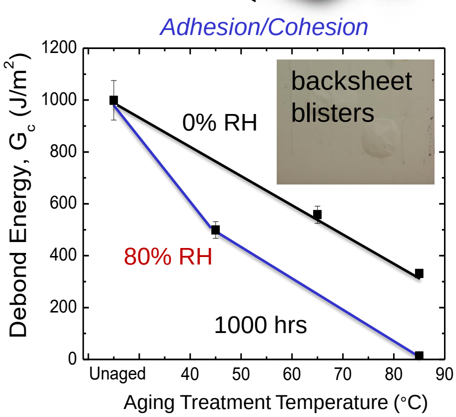


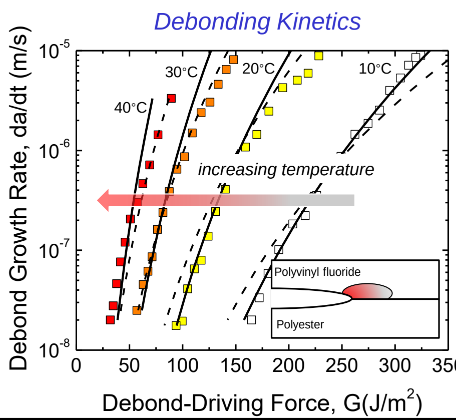
Major limitations: need detailed film properties, film stress relaxation and film plasticity

$\Rightarrow$ principally qualitative results for all above methods!

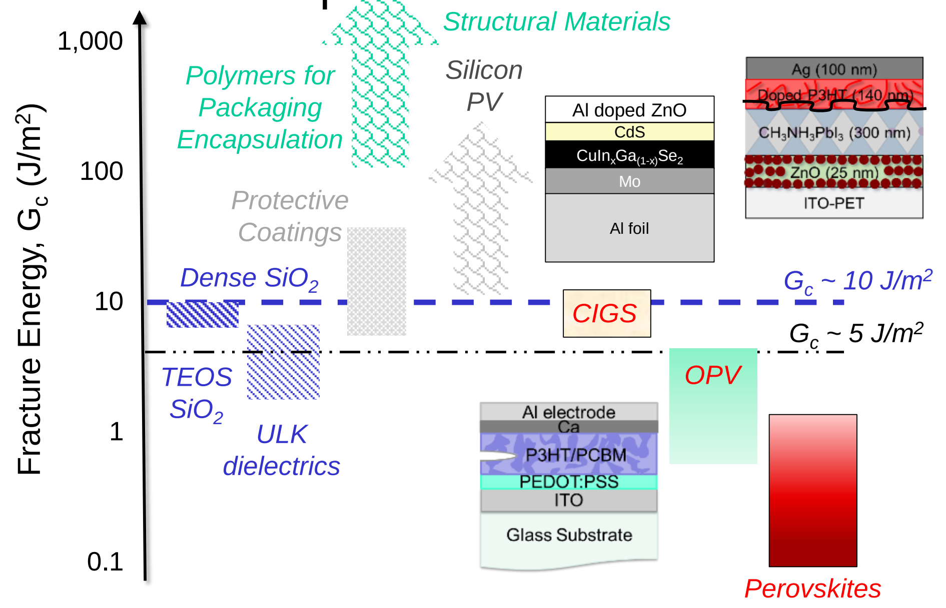
Quantitative Adhesion/Cohesion and Debond Kinetics







Fracture Properties of Device Materials



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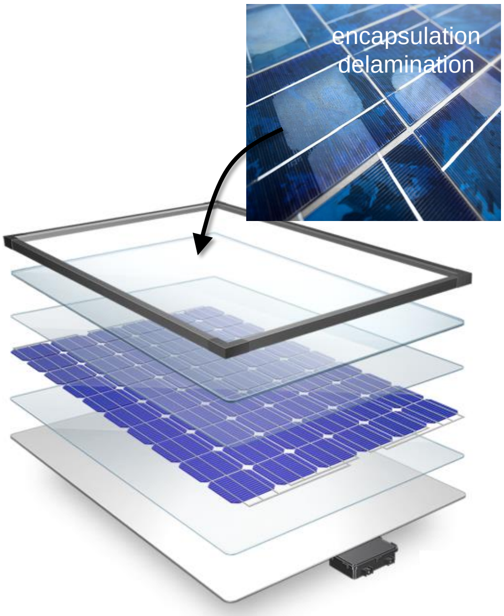
Mechanical Reliability of Module Components

- Backsheets
  - multilayered TPE
  - full-size modules
- Frontsheets
  - dyad barrier films
  - polysiloxane films
- Encapsulation
  - EVA and PVB
  - ionomers and polyolefins



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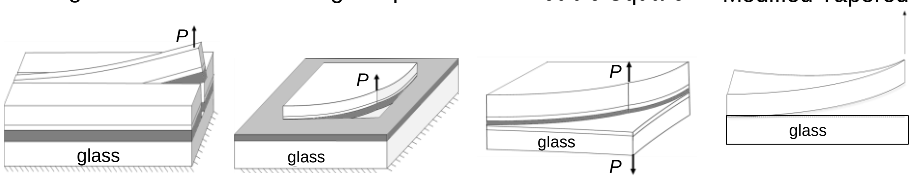
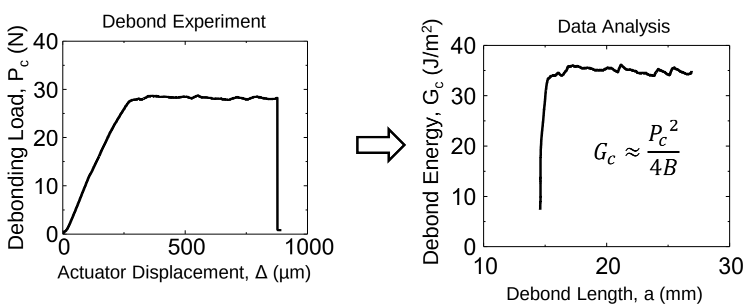
Mechanics-Based Adhesion Metrologies



Square and tapered specimens have simpler data analysis…



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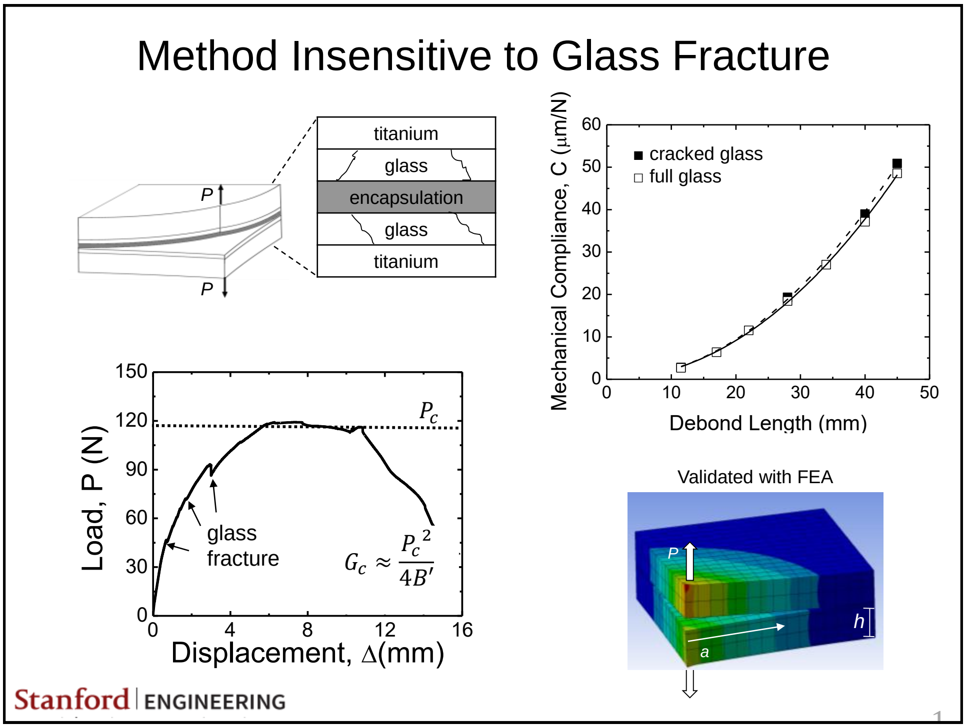
Method Insensitive to Glass Fracture
P
P
titanium
glass
encapsulation
glass
titanium
Mechanical Compliance, C (μm/N)
cracked glass
full glass
Debond Length (mm)
Load, P (N)
P_c
glass
fracture
$G_c \approx \frac{P_c^2}{4B'}$
Displacement, Δ(mm)
Validated with FEA
P
h
a
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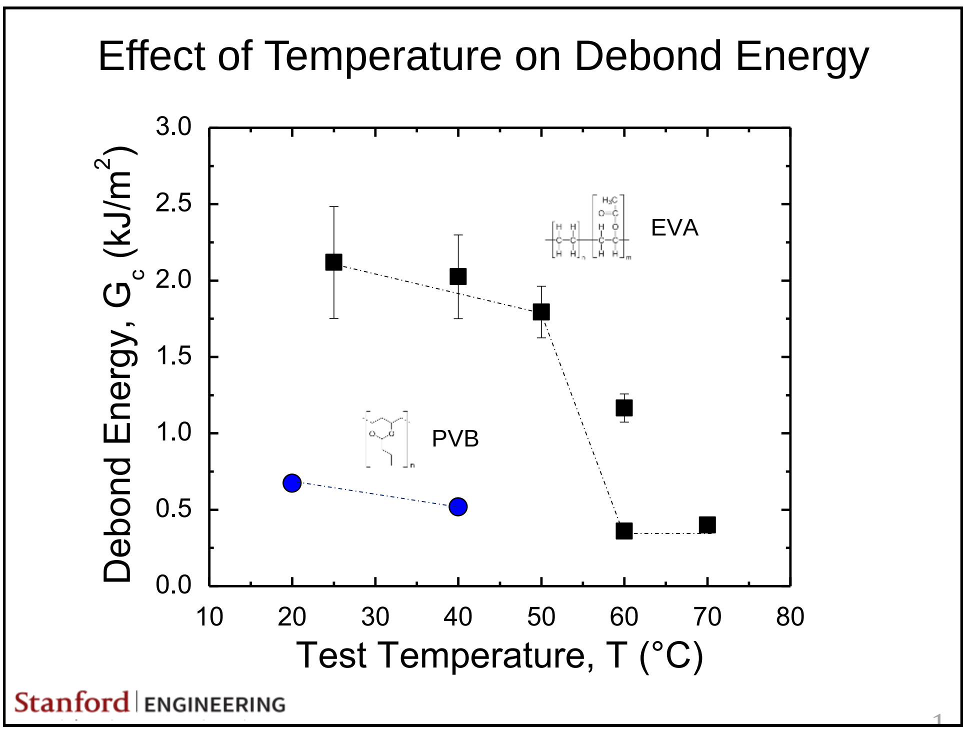
Effect of Temperature on Debond Energy
Debond Energy, G_c (kJ/m^2)
EVA
PVB
Test Temperature, T (°C)
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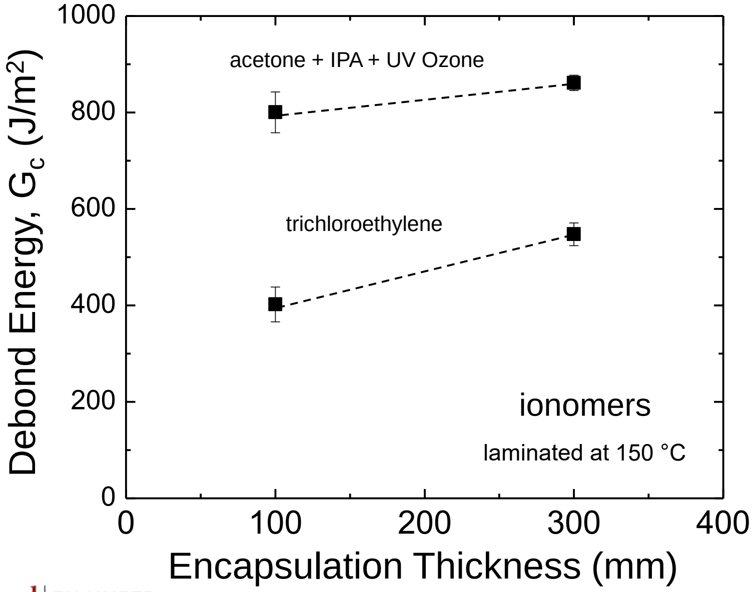
Effect of Substrate Treatment on Debond Energy



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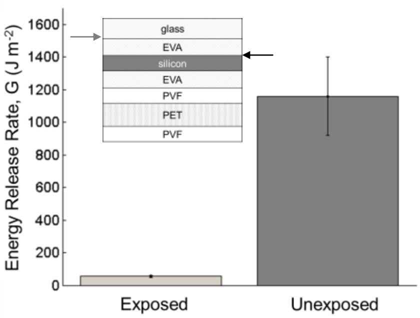
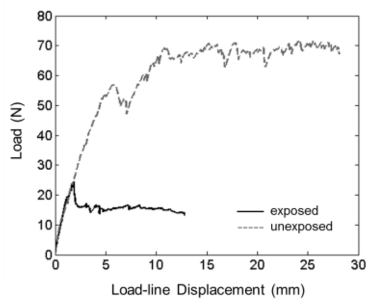
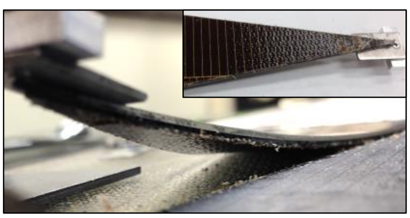
30 Year Historic Module Encapsulant Adhesion





Adhesion of EVA after 30 years in service (exposed) and storage (unexposed).

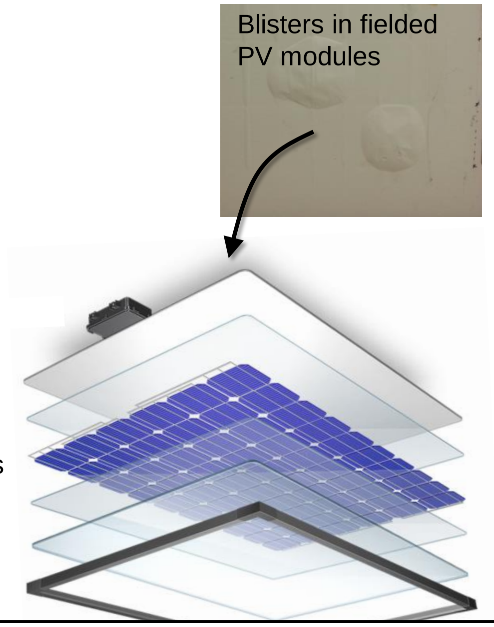


Delamination of EVA/glass – EVA brown discoloration.

Debond of EVA from cell - localized EVA deformation between grid lines.

Mechanical Reliability of Module Components

- Backsheets
  - multilayered TPE
  - full-size modules
- Frontsheets
  - dyad barrier films
  - polysiloxane films
- Encapsulation
  - EVA and PVB
  - ionomers and polyolefins



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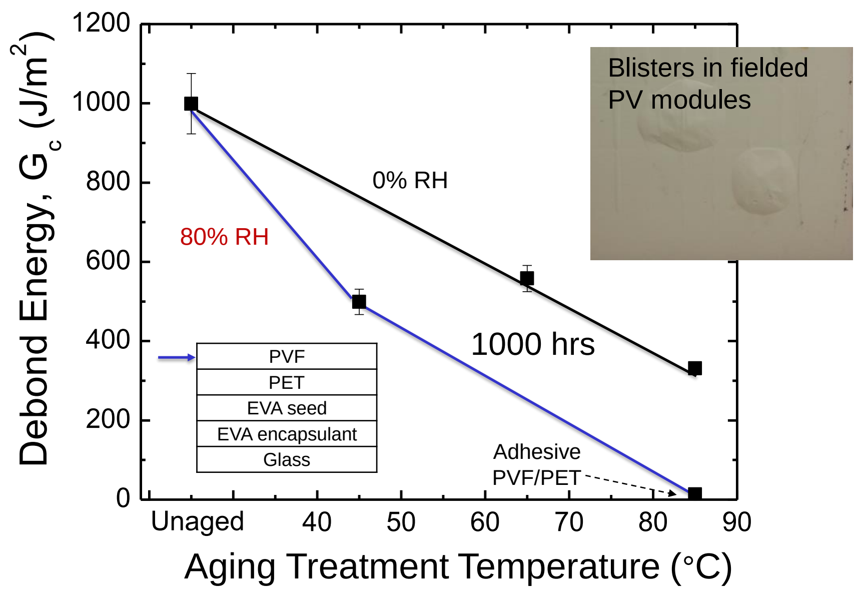
Effect of Aging T and RH on Backsheet Adhesion



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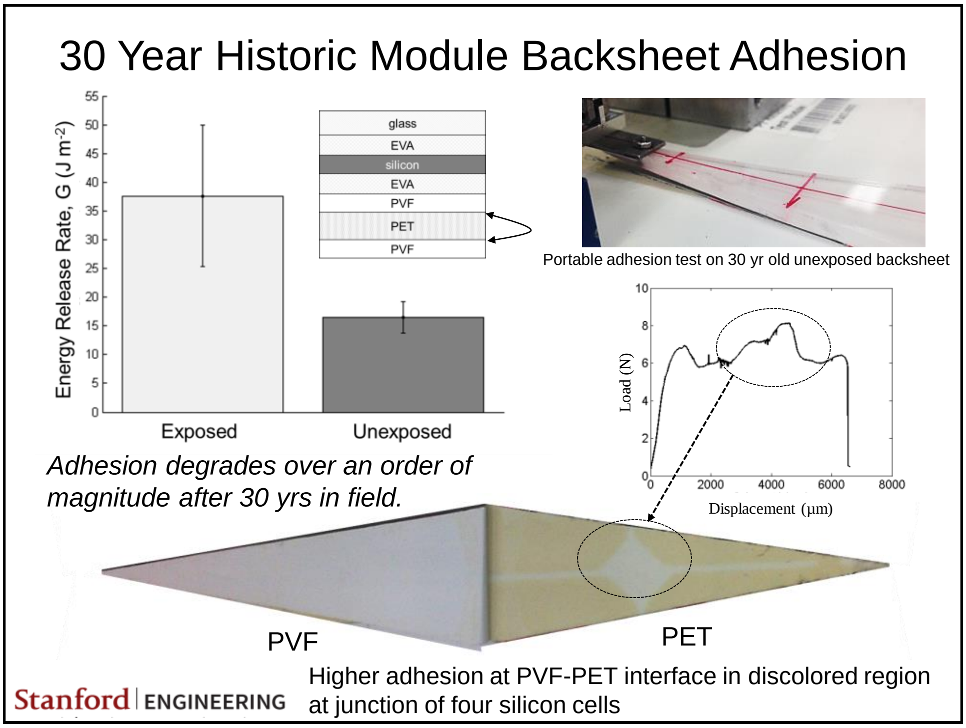
30 Year Historic Module Backsheet Adhesion
Energy Release Rate, G (J m^{-2})
glass
EVA
silicon
EVA
PVF
PET
PVF
Exposed
Unexposed
Adhesion degrades over an order of magnitude after 30 yrs in field.
Portable adhesion test on 30 yr old unexposed backsheet
Load (N)
Displacement (μm)
PVF
PET
Higher adhesion at PVF-PET interface in discolored region at junction of four silicon cells
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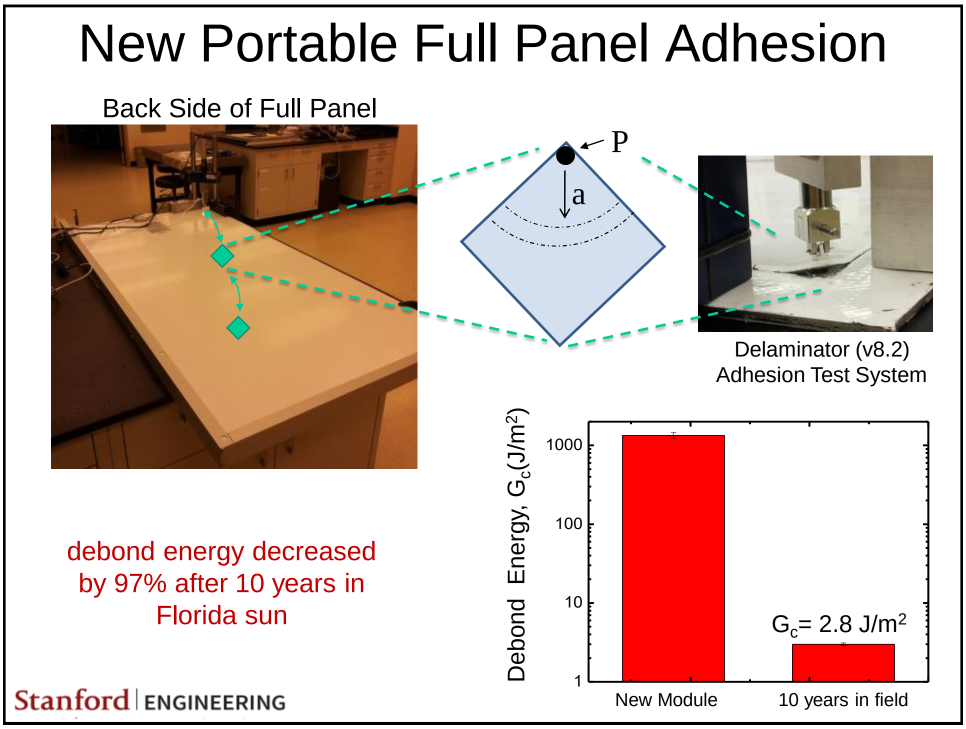
New Portable Full Panel Adhesion
Back Side of Full Panel
P
a
Delaminator (v8.2)
Adhesion Test System
debond energy decreased by 97% after 10 years in Florida sun
Debond Energy, G_c(J/m^2)
G_c= 2.8 J/m^2
New Module
10 years in field
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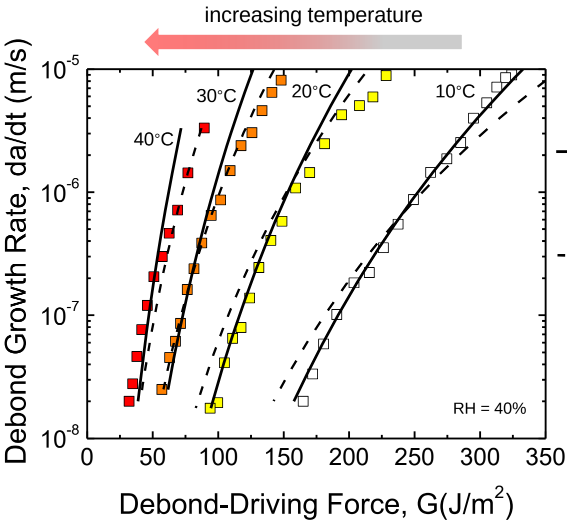
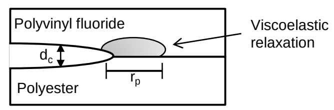
Temperature-Activated Backsheet Debond Growth



Debond Relaxation Model

$$\frac{da}{dt} = \frac{\pi}{8}\frac{\delta_c}{\varepsilon_y(\delta_c\,\varepsilon_y)^{1/n}}\left(\frac{G}{E_0(RH)}\right)^{\frac{1}{n}} \underbrace{e^{-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)}}_{\text{Arrhenius}}$$

$$\frac{da}{dt} = \frac{\pi}{8}\frac{\delta_c}{\varepsilon_y(\delta_c\,\varepsilon_y)^{1/n}}\left(\frac{G}{E_0(RH)}\right)^{\frac{1}{n}} \underbrace{10^{\frac{C_a(T-T_g)}{C_b+(T-T_g)}}}_{\text{Williams-Landel-Ferry (1955)}}$$



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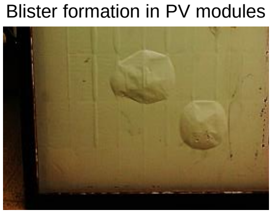
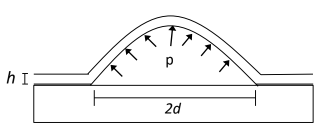
Defect-Tolerant Lifetime Estimation

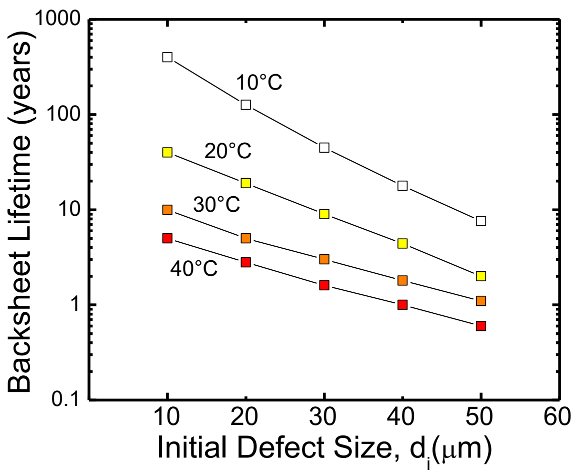
Blister formation in PV modules



Blister mechanics



$$G = \frac{3}{32}\frac{(1-\upsilon^2)pd^4}{Eh^3}$$



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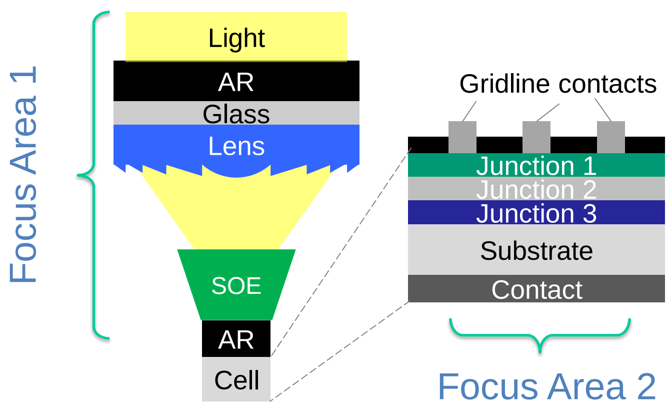
Coupled Thermo-Mechanical and Photo-Chemical Degradation Mechanisms that Determine the Reliability and Operational Lifetimes for CPV Technologies

Dauskardt / Stanford; Miller and Kurtz / NREL; Hebert and Ermer / Spectrolab

DOE Geoffrey Kinsey (Program Manager), Inna Kozinsky (Senior Technical Advisor)

PREDICTS Program



CPV is ideal PV test vehicle with elevated "stress" parameters for reliability studies

- elevated thermal, moisture, light intensities, mechanical stresses

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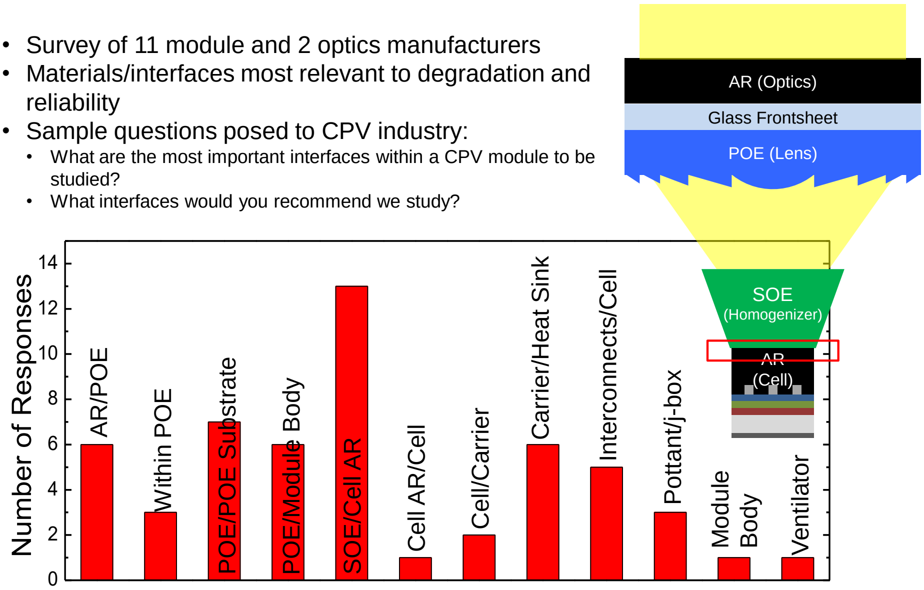
Survey of Materials and Interfaces Relevant to CPV Industry

- Survey of 11 module and 2 optics manufacturers
- Materials/interfaces most relevant to degradation and reliability
- Sample questions posed to CPV industry:
  - What are the most important interfaces within a CPV module to be studied?
  - What interfaces would you recommend we study?



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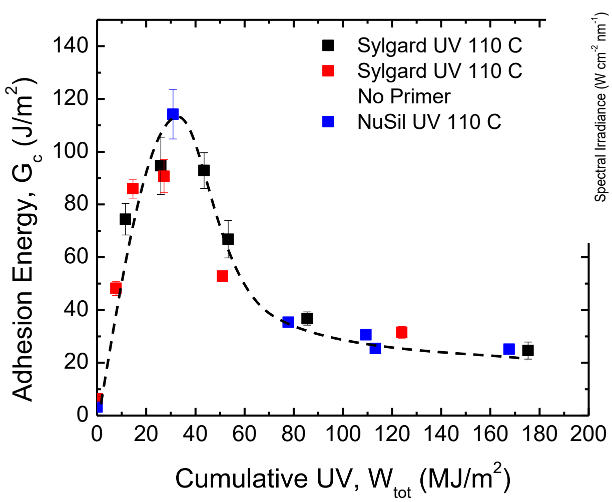
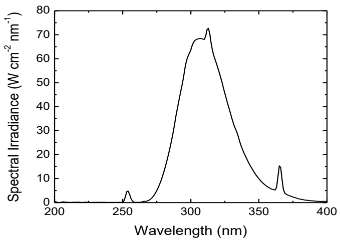
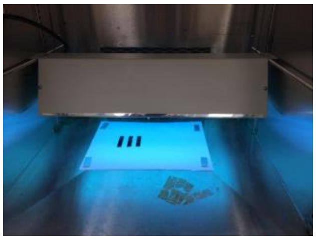
Role of Time and Temperature during In-Door UVB Exposure







80ºC/10% RH, 50ºC/10% RH, 110 ºC/10% RH at 4.5 mW/cm^2 from 200 nm to 400 nm wavelength UV

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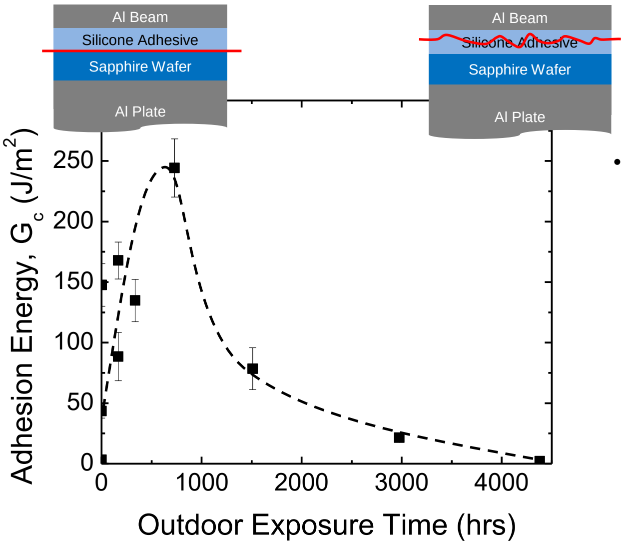
Role of Out-Door Concentrated Solar Exposure



- Sylgard adhesive aged in outdoor concentrator at 1100x solar flux

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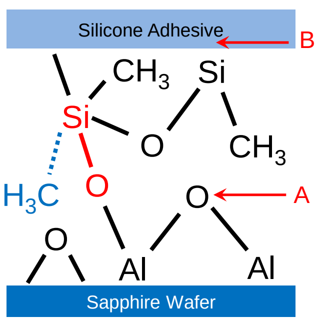
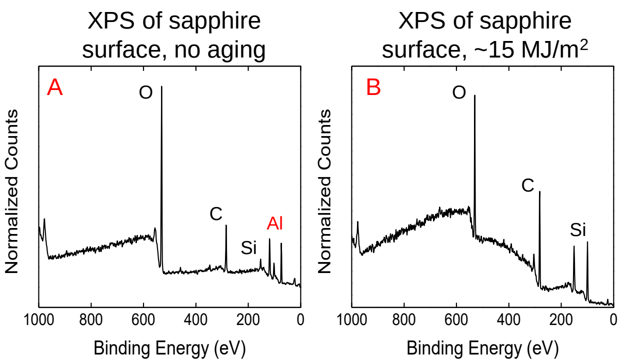
UV Mediated Chemical Degradation at Interface





- XPS characterization of sapphire surface after mechanical testing
- thickness of residual silicone layer on sapphire grows with increase in aging time
- suggests formation of bonds at interface between sapphire and silicone adhesive

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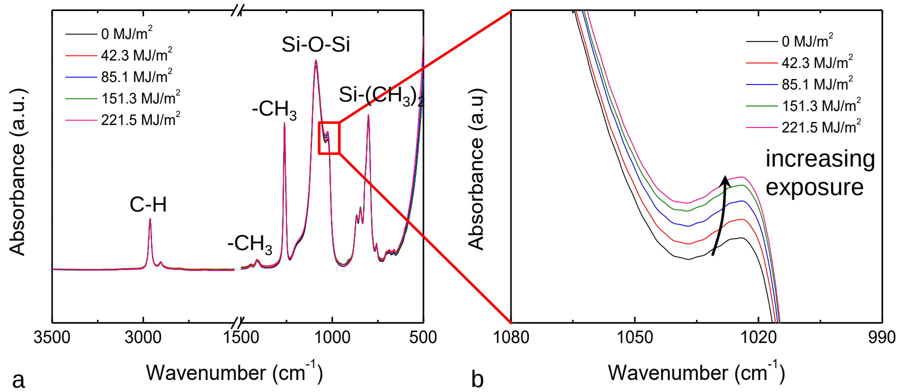
UV Mediated Chemical Degradation in Bulk



- transmission FT-IR shows increase in Si-O-Si peak with increased UV exposure
- suggests formation of oxygen bridges and crosslinking between chains, leading to embrittlement

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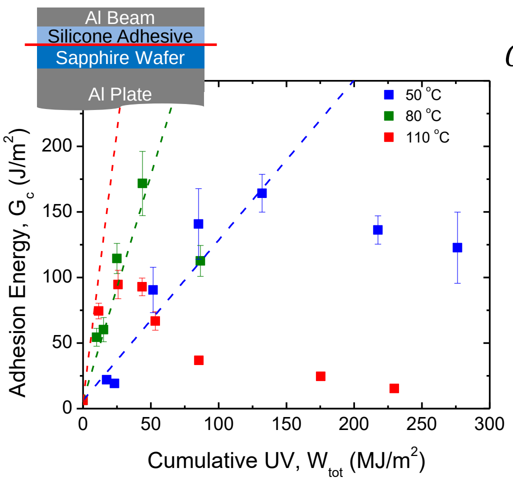
Increase in Adhesion as a Result of Crosslinking



$$G_{adhesion} = kN_{crosslinks} + G_0$$

adhesion energy dependent on number of bonds between silicone and sapphire substrate

$$N_{crosslink} = k_{uv} W_{tot} e^{-\frac{E_a}{k_b T}}$$

linear relation between number of crosslinks and UV dosage

$$G_{adhesion} = k_1 W_{tot} e^{-\frac{E_a}{k_b T}} + G_0$$

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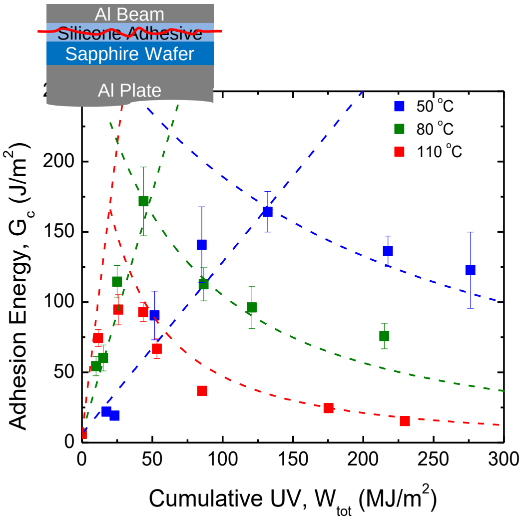
Decrease in Cohesion as a Result of Crosslinking



$$G_{cohesion} = k\left(M_w^{\frac{3}{2}}\right) = \frac{k_2}{(k_3+N_{crosslink})^{3/2}}$$

adhesion energy dependent on molecular weight between crosslinks

$$N_{crosslink} = k_{uv} W_{tot} e^{-\frac{E_a}{k_b T}}$$

linear relation between number of crosslinks and UV dosage

$$G_{cohesion} = \frac{k_2}{\left(k_3 + W_{tot} e^{-\frac{E_a}{k_b T}}\right)^{3/2}}$$

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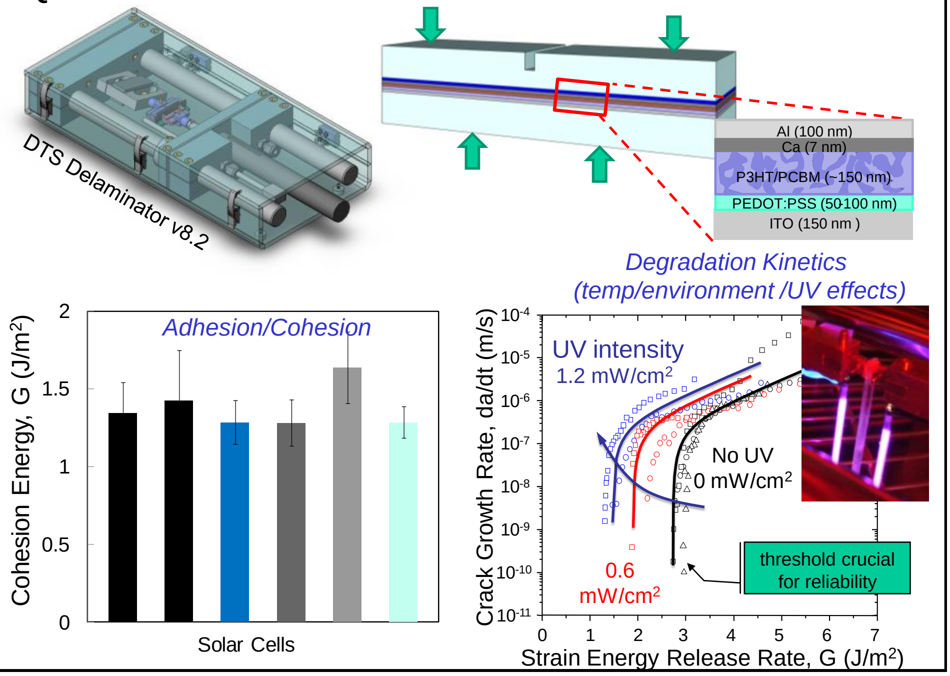
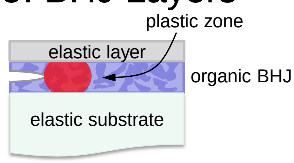
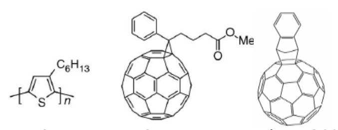


Factors Effecting Cohesion of BHJ Layers

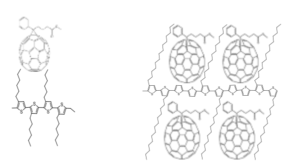
- Heterojunction layer thickness
  - is cohesion in organic layers sensitive to layer thickness?



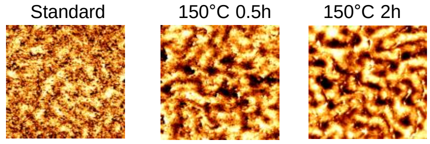
- Composition of the heterojunction layer
  - limited bonding to fullerene
  - polymer/PCBM ratio makes stronger layer



- Molecular intercalation
  - manipulating the types of intermolecular interactions



- Annealing
  - morphology of the BHJ layer changes with annealing



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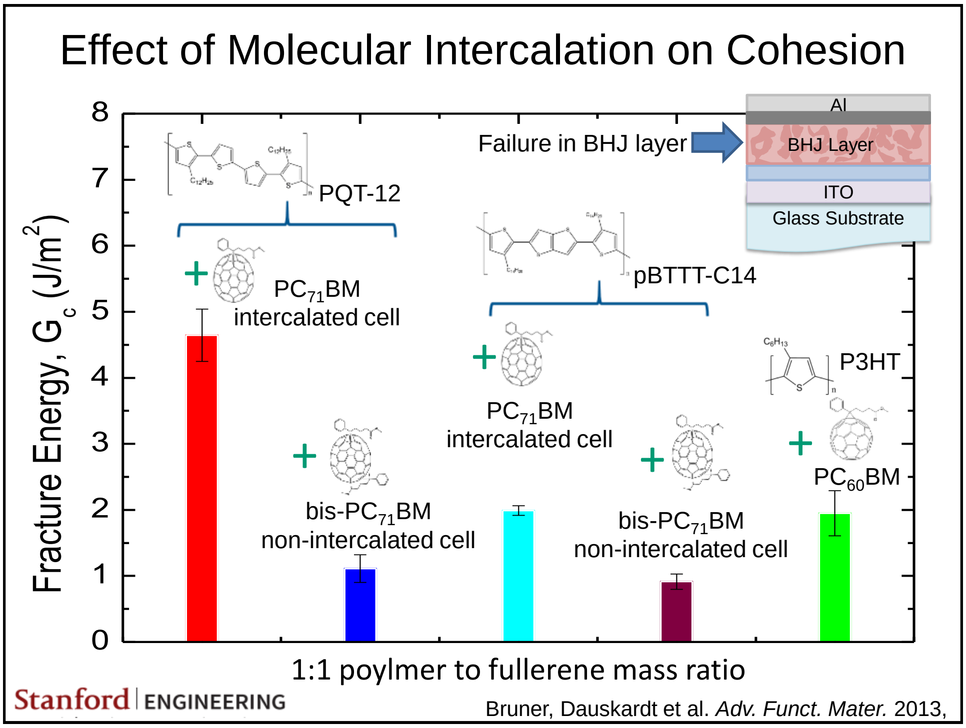

Effect of Molecular Intercalation on Cohesion
Fracture Energy, G_c (J/m^2)
Failure in BHJ layer
Al
BHJ Layer
ITO
Glass Substrate
PQT-12
PC$_{71}$BM intercalated cell
bis-PC$_{71}$BM non-intercalated cell
pBTTT-C14
PC$_{71}$BM intercalated cell
bis-PC$_{71}$BM non-intercalated cell
P3HT
PC$_{60}$BM
1:1 poylmer to fullerene mass ratio
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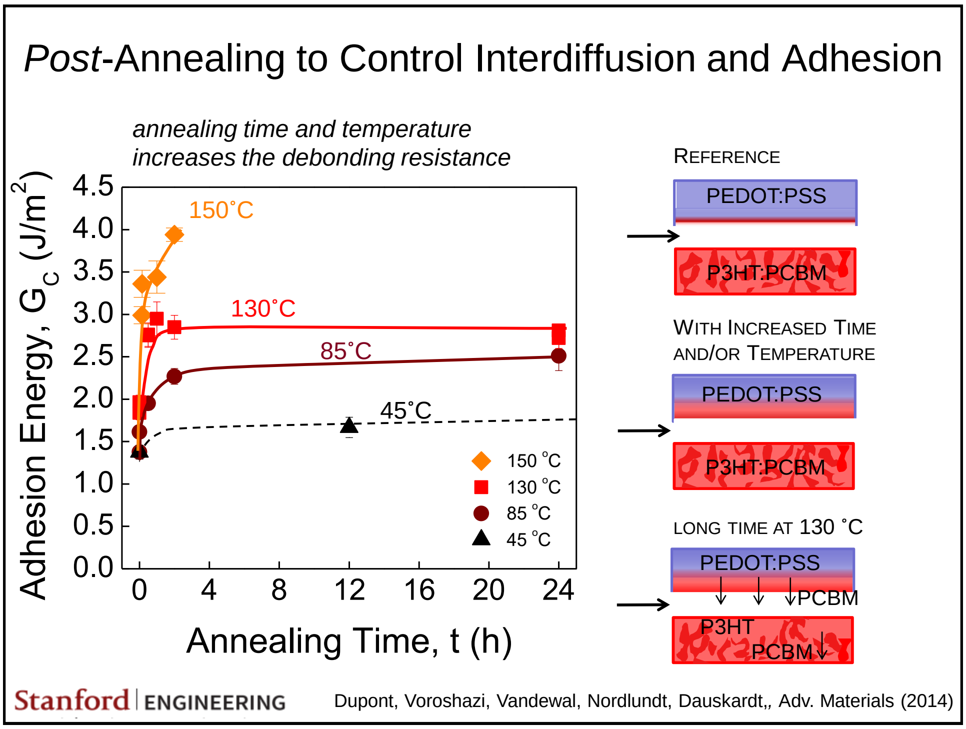
Bruner, Dauskardt et al. *Adv. Funct. Mater.* 2013,



Post-Annealing to Control Interdiffusion and Adhesion
annealing time and temperature increases the debonding resistance
Adhesion Energy, G_C (J/m^2)
Annealing Time, t (h)
150˚C
130˚C
85˚C
45˚C
REFERENCE
PEDOT:PSS
P3HT:PCBM
WITH INCREASED TIME AND/OR TEMPERATURE
PEDOT:PSS
P3HT:PCBM
LONG TIME AT 130 ˚C
PEDOT:PSS
PCBM
P3HT
PCBM
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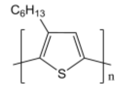
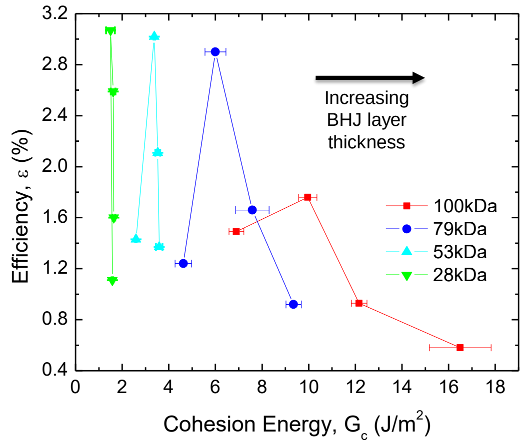
Dupont, Voroshazi, Vandewal, Nordlundt, Dauskardt,, Adv. Materials (2014)

Efficiency vs. Cohesion



P3HT

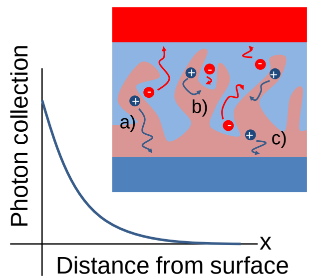
Bruner, Dauskardt, et al. *Macromolecules* 2014.



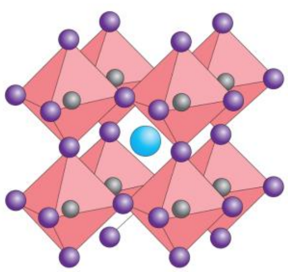
$$\varepsilon = \frac{V_{OC} J_{SC} FF}{P_{in}}$$

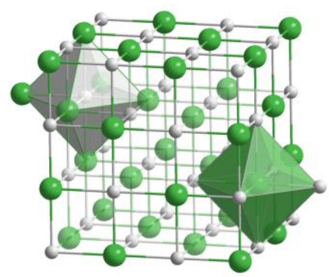
Thin BHJ layer - low efficiency due to lower photon harvesting

Thicker BHJ layer - greater degree of charge carrier recombination



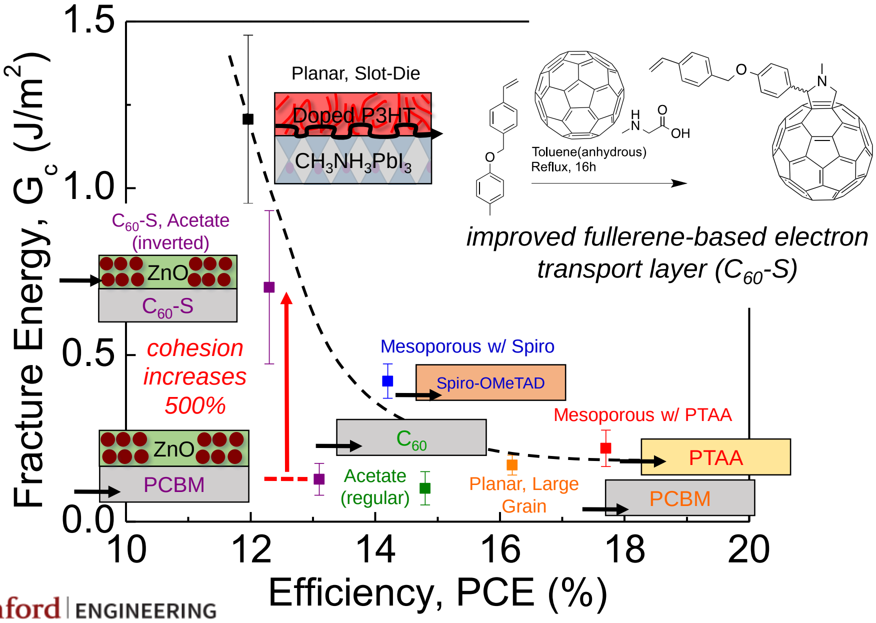
Perovskite: Not Just Your Average Salt





Material	$CH_3NH_3PbI_3$	NaCl
Density	4.29 g/cm³	2.16 g/cm³
Fracture Energy, G_c	???? J/m^2	0.6-1.8 J/m^2
Solar Cell Efficiency	~20%	0%

C60-S Increases Device Cohesion



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Factors Influencing Perovskite Films

- Morphology/Processing
  - Grain size
  - Mesoporous vs. planar
  - Substrate temperature
  - Precursor ratio
- Deposition method
  - Roll to roll vs. blade coating
- Exposure conditions
  - Humidity
  - Temperature
- Molecular Additives

How do these factors affect perovskite film cohesion?

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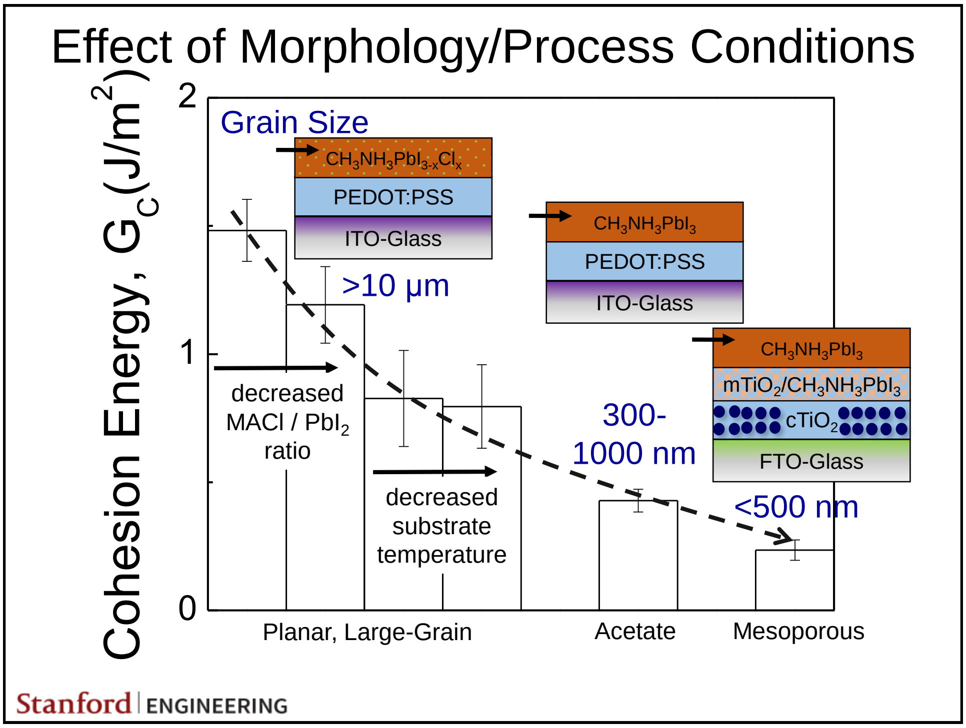

Effect of Morphology/Process Conditions
Cohesion Energy, G_C (J/m^2)
Grain Size
$CH_3NH_3PbI_{3-x}Cl_x$
PEDOT:PSS
ITO-Glass
>10 μm
decreased MACl / PbI_2 ratio
decreased substrate temperature
$CH_3NH_3PbI_3$
PEDOT:PSS
ITO-Glass
300-1000 nm
$CH_3NH_3PbI_3$
$mTiO_2/CH_3NH_3PbI_3$
$cTiO_2$
FTO-Glass
<500 nm
Planar, Large-Grain
Acetate
Mesoporous
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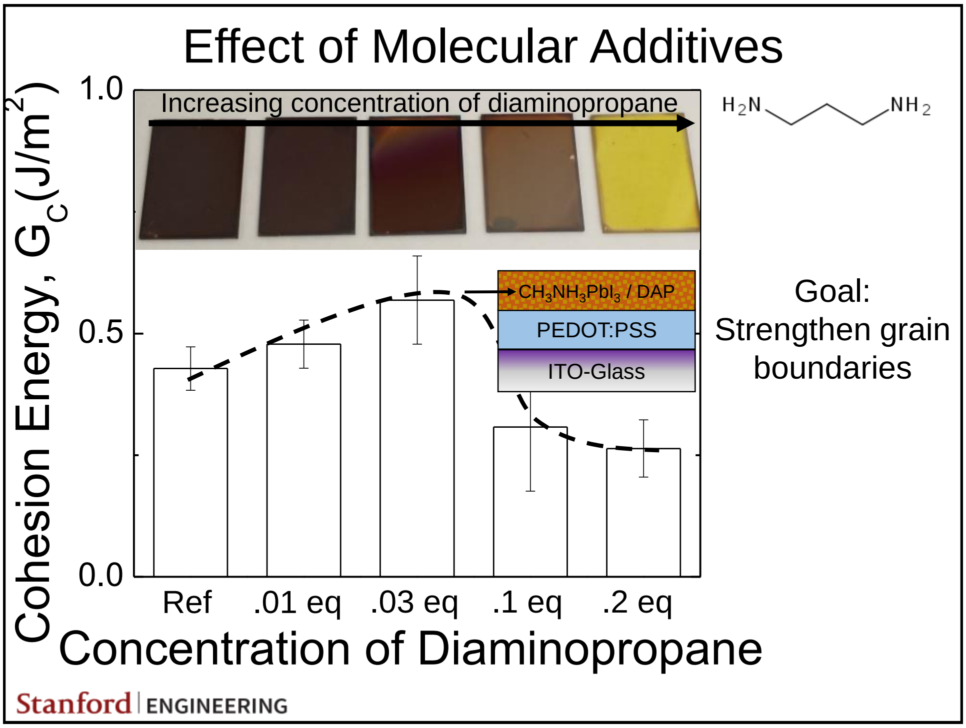

Effect of Molecular Additives
Cohesion Energy, G_C (J/m^2)
Increasing concentration of diaminopropane
H_2N NH_2
$CH_3NH_3PbI_3$ / DAP
PEDOT:PSS
ITO-Glass
Goal: Strengthen grain boundaries
Ref
.01 eq
.03 eq
.1 eq
.2 eq
Concentration of Diaminopropane
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