US DOE, Office of Basic Energy Sciences

Center for Advanced Molecular Photovoltaics
STANFORD UNIVERSITY

Adhesion and Thermomechanical Reliability for PV Devices and Modules

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William Hou and Yang Yang (UCLA)

Industry collaborators include Colin Reese, Shawn Scully and Juanita Kurtin (SpectraWatt), Steve Lin (Vitex), Matthew Robinson (Nanosolar), Christine McGuiness and Darin Laird (Plextronics).

Solar Outlook

Then…

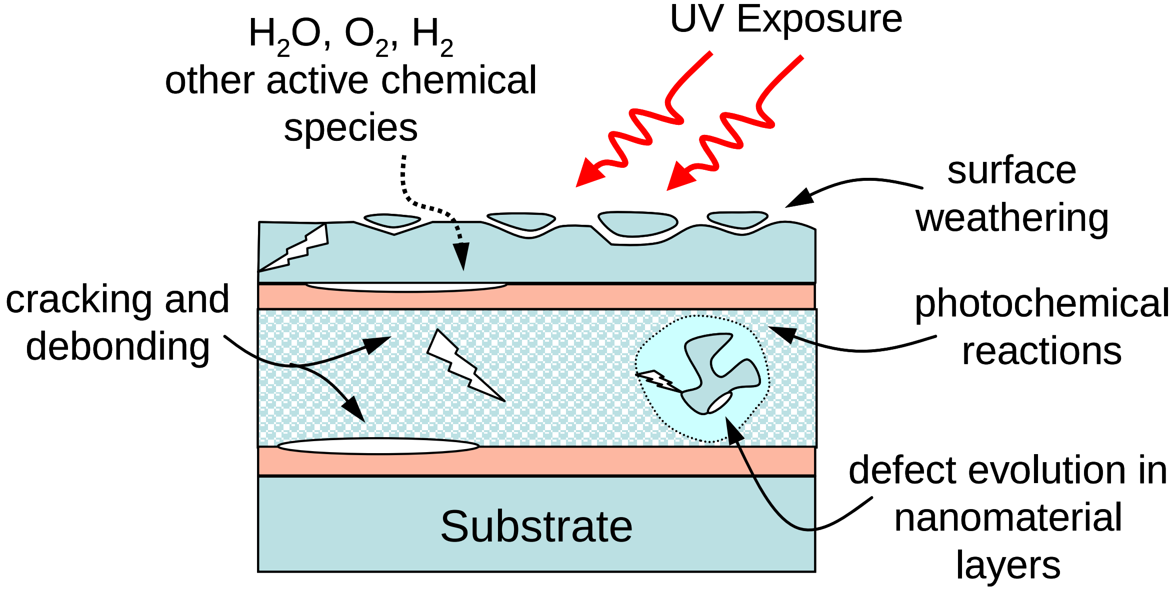
1. Efficiency
2. Reliability
3. Cost

To make a difference…

1. Cost
2. Reliability
3. Efficiency

- Engineer durable solar technologies with robust and predictable lifetimes. Start early in development – avoid roadblocks.
- Leverage from reliability physics in microelectronics – thin-film metrologies, kinetic models, accelerated tests, life prediction.
- Are degradation processes coupled and how?
- Kinetic models for damage evolution - basis for life prediction and accelerated testing (T, environment, stress, solar flux, etc.)
- Effective defensive strategies – e.g. transparent barriers with anti-reflective properties.

Degradation and Reliability of PV Devices and Modules



Severe operating environments.

Exposure to thermal cycling, stress, moisture, chemically active environmental species, and UV.

Uncertain degradation kinetics and reliability models.

Activation Energies for Bond Rupture:

VDW ~ 0.001 - .4 eV/bond

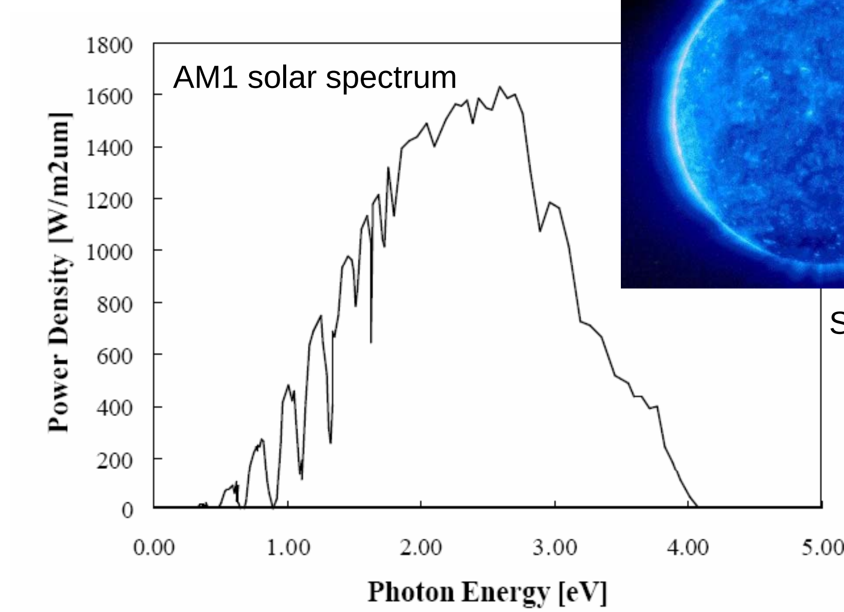
H-bonds ~ .1 - .4 eV/bond

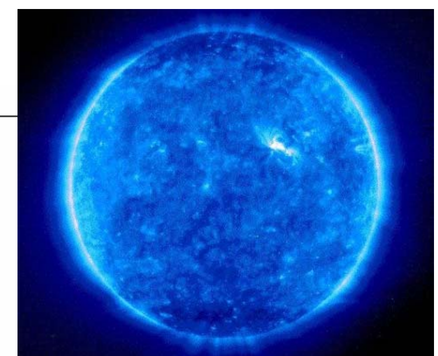
Ester Hydrolysis (100% RH)

E* ~ .81 eV/bond

SiO_2 cracking in water

E* ~ 1.39 eV/bond





Sun in UV

Solar spectrum from B. Van Zeghbroeck, U. Colorado

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Evolution of Defects and Device Reliability

absence of chemically active environmental species, damage propagates if

$$G \geq G_c \left[J/m^2\right]$$

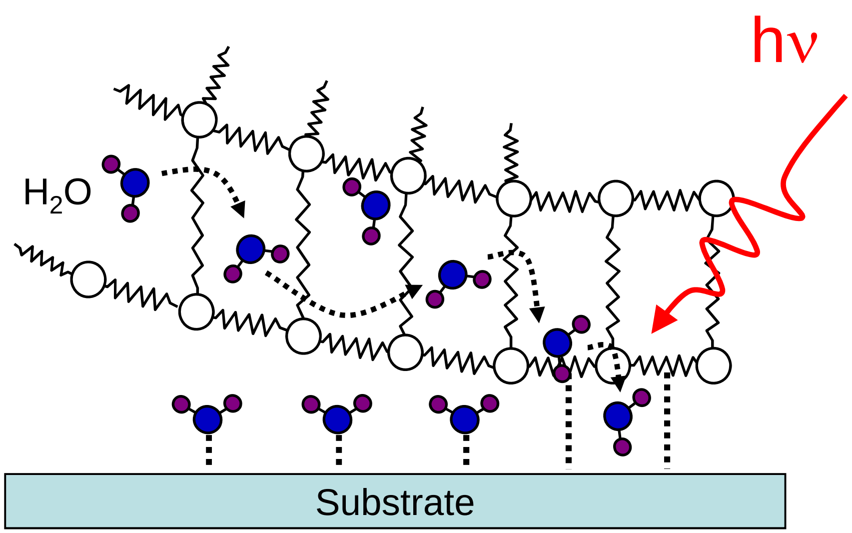
presence of chemical species and photons, damage propagates even if

$$G < G_c \left[J/m^2\right]$$

environment and stress accelerates defect evolution

Role of coupled kinetic parameters:

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



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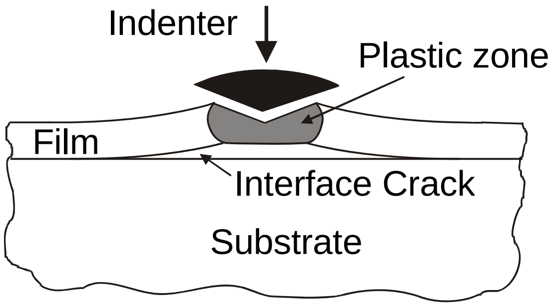
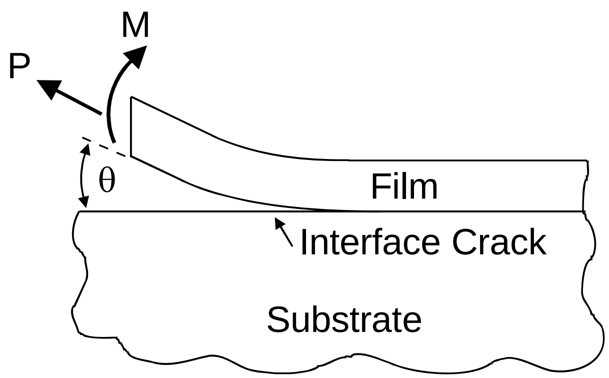
Typical Film Adhesion Tests that Don't Work Well

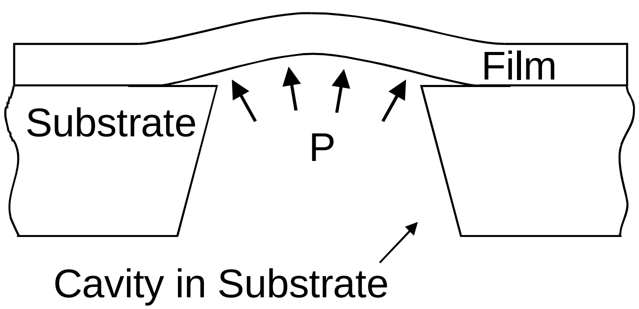
- Indentation/Scratch Test
  - complex stress and deformation fields
  - principally <u>qualitative</u> results
  - (nano) scratch test even less quantitative



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



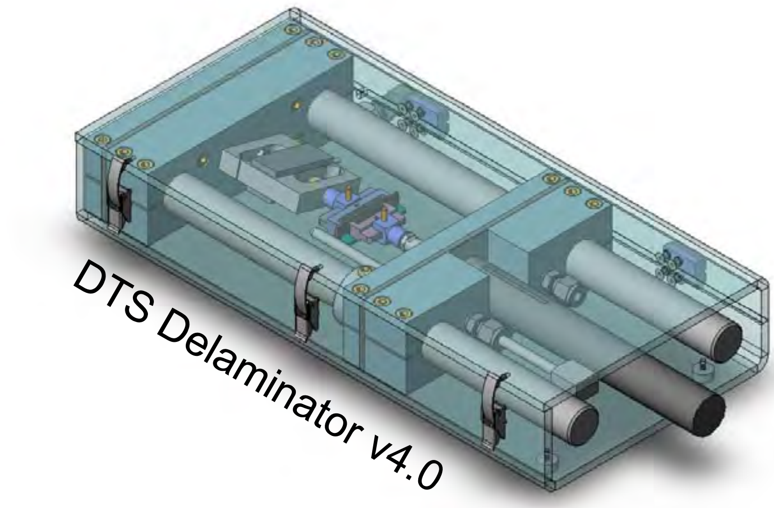
- Blister Test
  - compliant loading system
  - environmental effects
  - etching/machining of cavity difficult

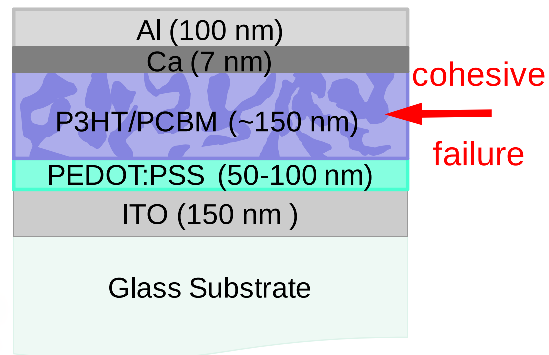


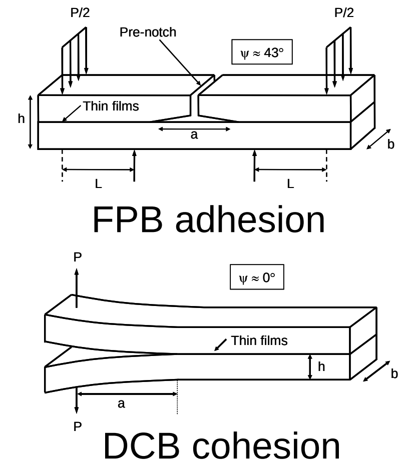
Major limitations: need detailed film properties, film stress relaxation and film plasticity

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

Quantitative Adhesion/Cohesion and Debond Kinetics

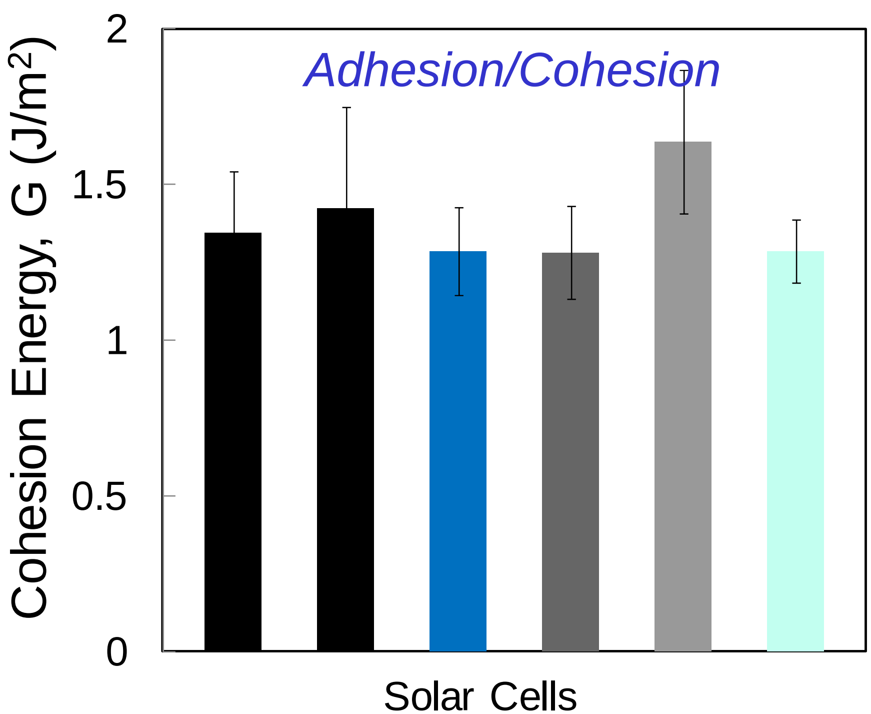


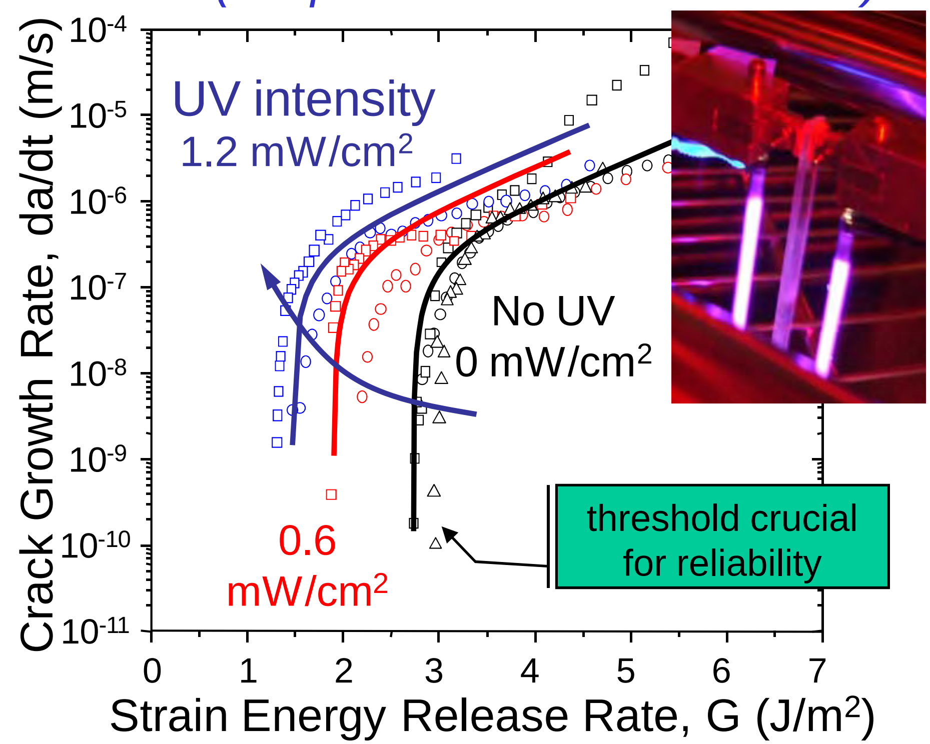




DTS system and support contact dauskardt@stanford.edu

Degradation Kinetics
(temp/environment /UV effects)



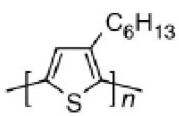


Inherent
Solar Cell Thermomechanical Reliability, G_c

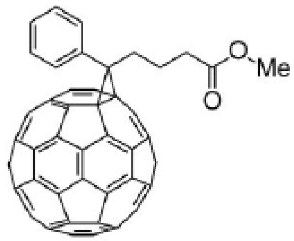
Grad students: Vitali Brand, Jeff Yang and Chris Bruner

Adhesion/Cohesion Sample Preparation

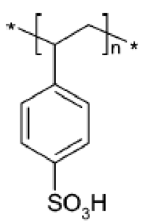
Thin films sandwiched between elastic substrates



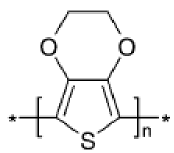
P3HT



PCBM

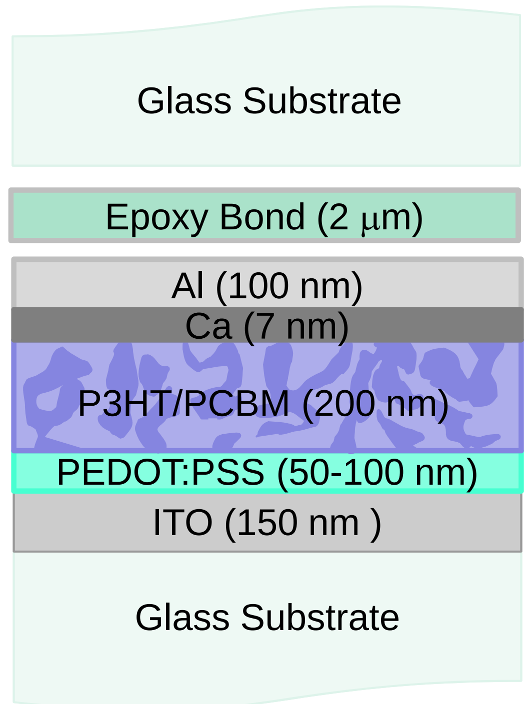


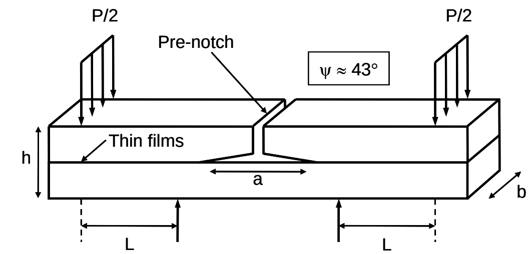
PSS



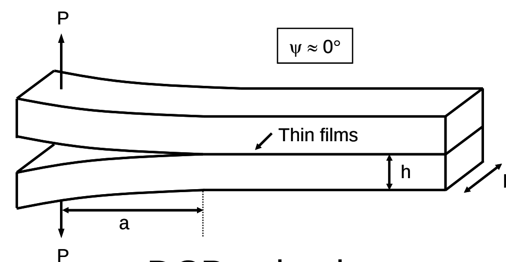
pEDOT

Gunes, et. Al. *Chem. Rev.* 2007.





FPB adhesion



DCB cohesion

Fabricated 4-point bend adhesion and DCB cohesion test structures using standard epoxy bonding techniques.

Similar transparent glass substrates on each side.

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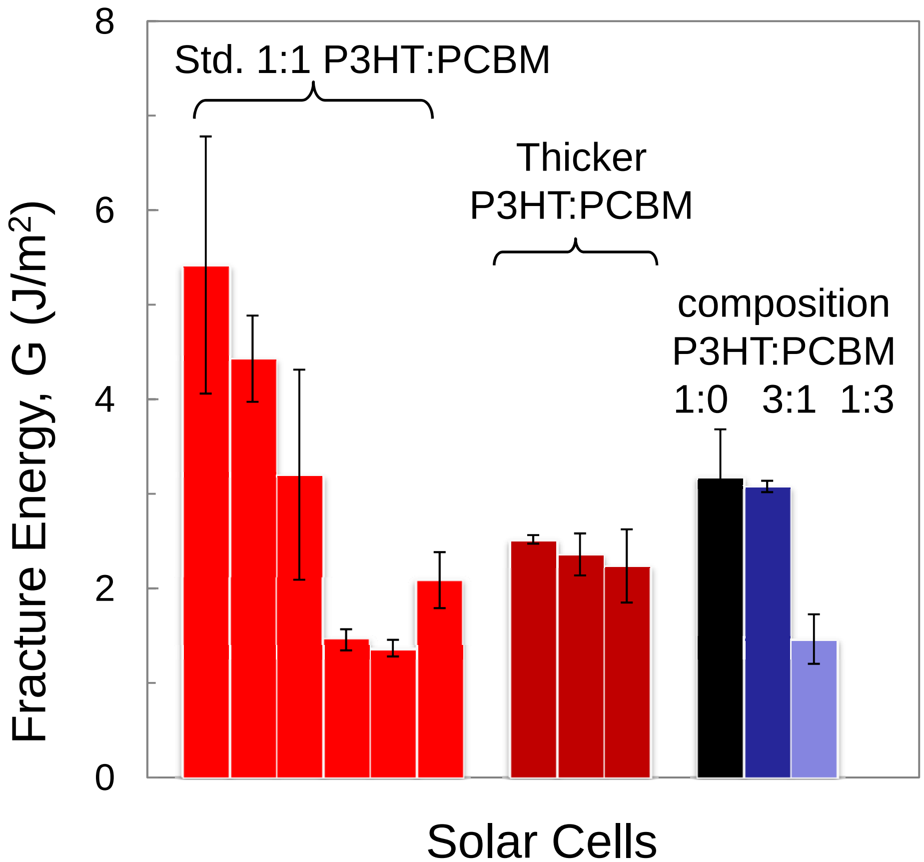
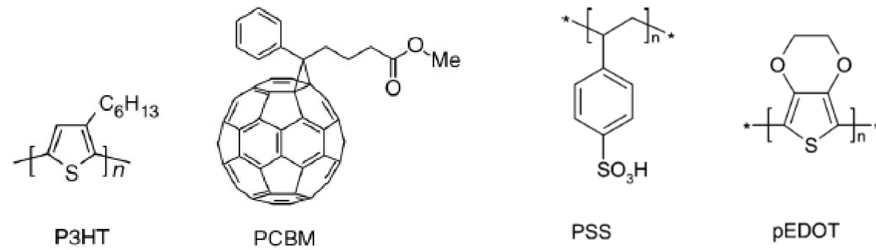
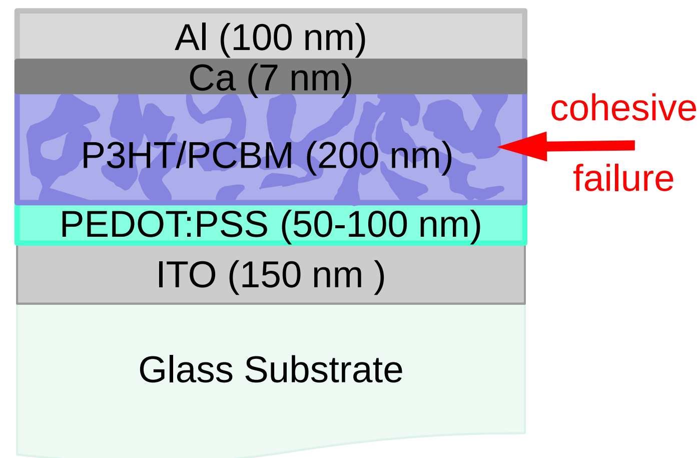
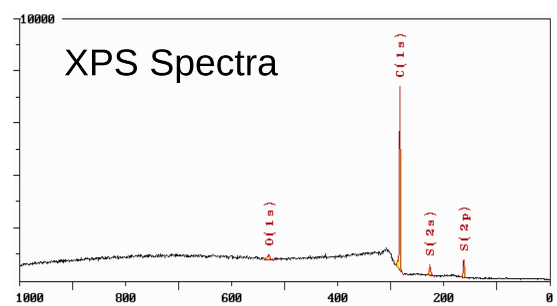
Adhesion/Cohesion of P3HT/PCBM Structures







- XPS reveals similar debond path for DCB and 4-pt bend samples
- C ~ 92%, S ~ 6%, O ~ 2%
- Suggests cohesive failure in PCBM:P3HT layer



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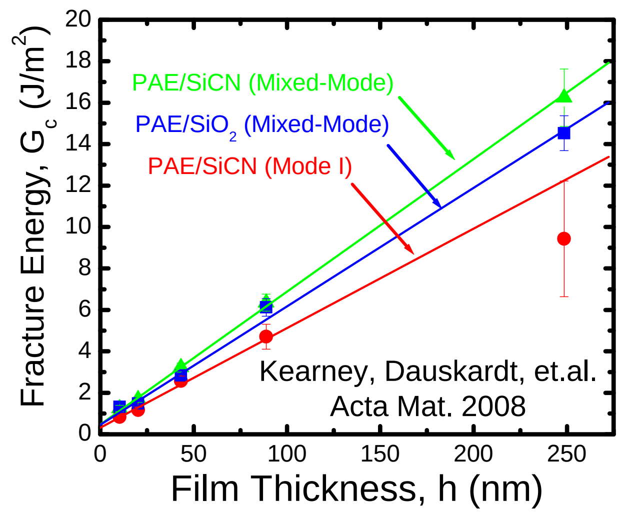
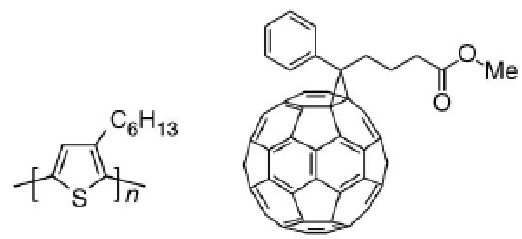
Factors Effecting Cohesion of P3HT/PCBM Layers

- Heterojunction layer thickness
  - cohesion in polymer layers is sensitive to layer thickness
  - plastic energy dissipation in organic layers



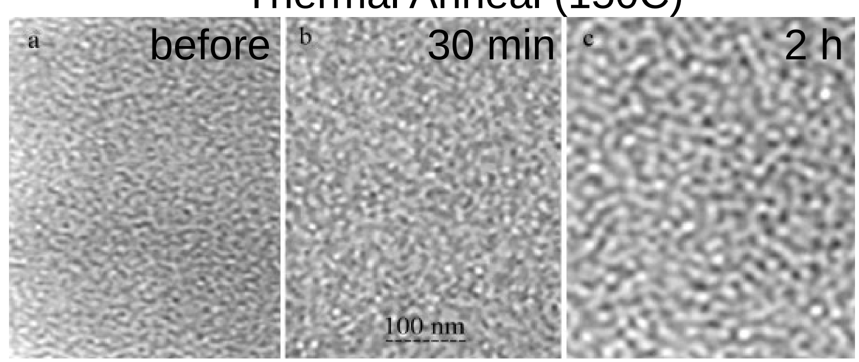
- Composition of the heterojunction layer
  - limited bonding to fullerene – expect low cohesion
  - preliminary measurements indicate higher ratios of P3HT to PCBM make stronger active layer



P3HT PCBM

- Annealing
  - morphology of the P3HT:PCBM film changes with annealing, expect effect morphology on cohesion

Thermal Anneal (150C)



TEM of P3HT:PCBM film
Heeger, et. Al. Adv. Func. Mat. 2005.

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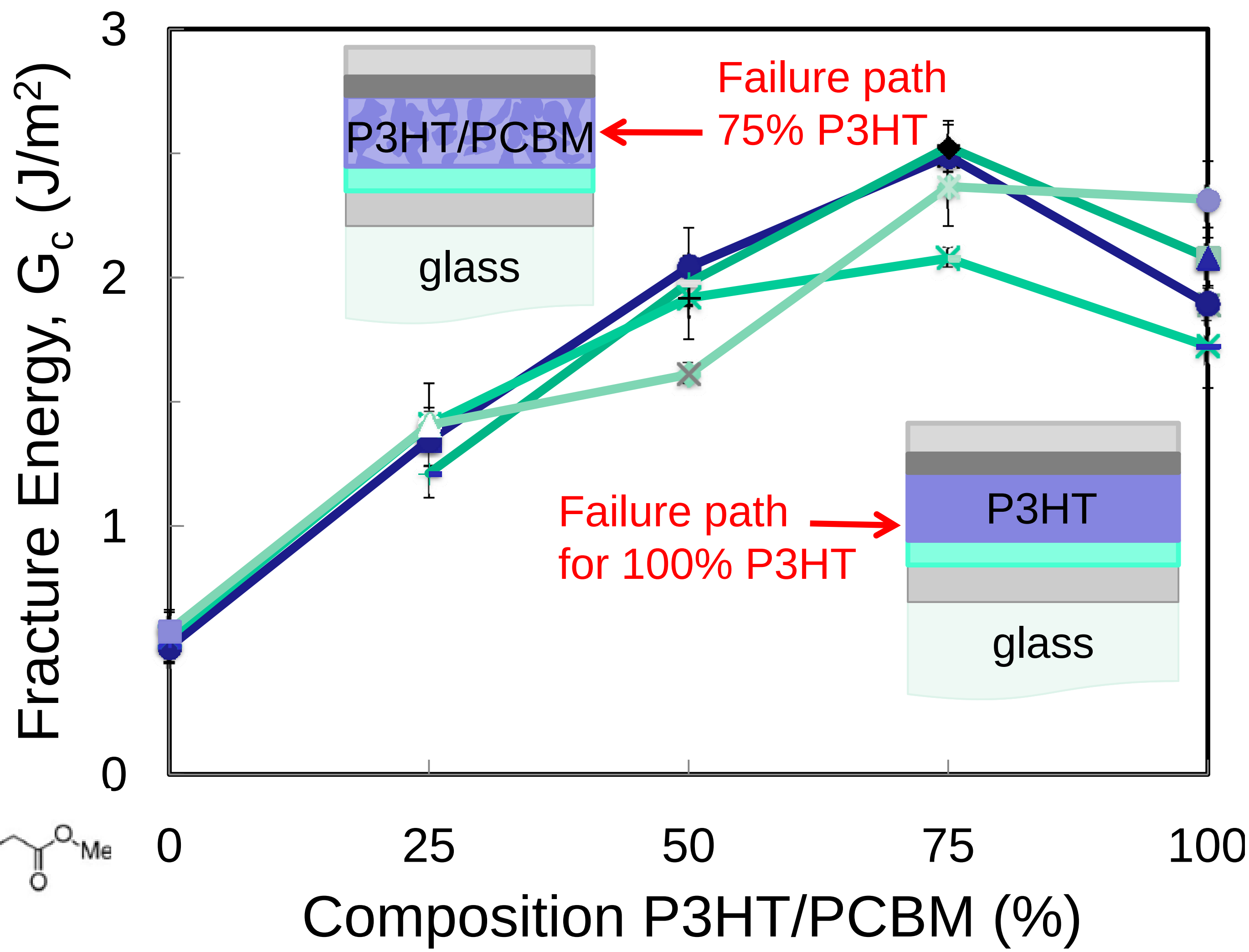
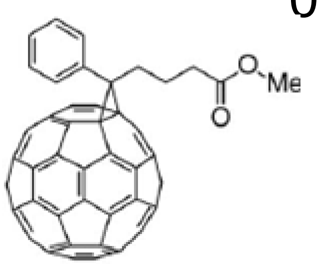
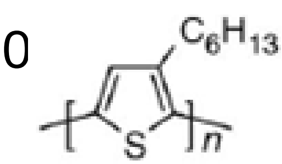
Effect of Composition of BHJ on Cohesion





PCBM



P3HT

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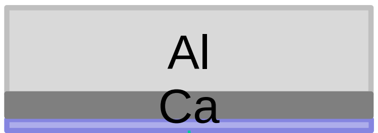
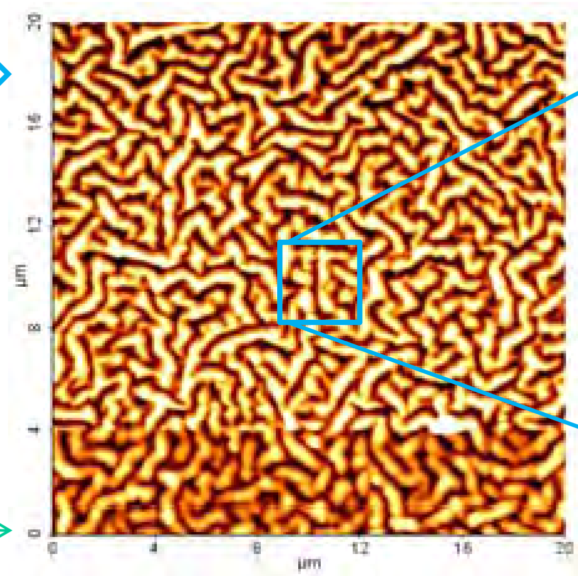
Cohesion increases with P3HT due to increased network formation

AFM of Failure Path Near Ca Interface

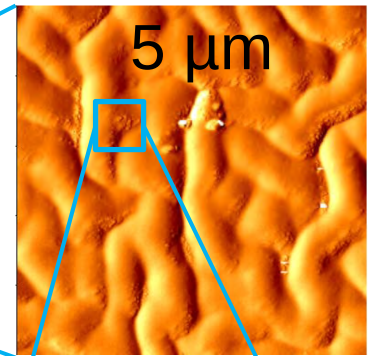
Topography

R_a = 20 nm
R_q = 24 nm

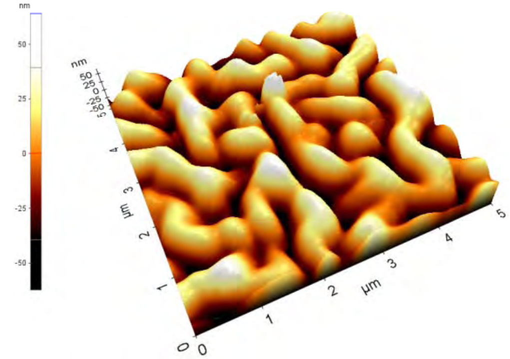


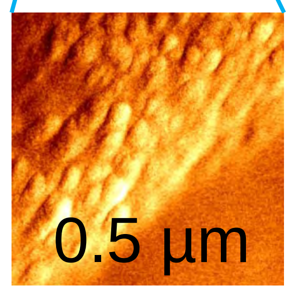


Phase



Topography

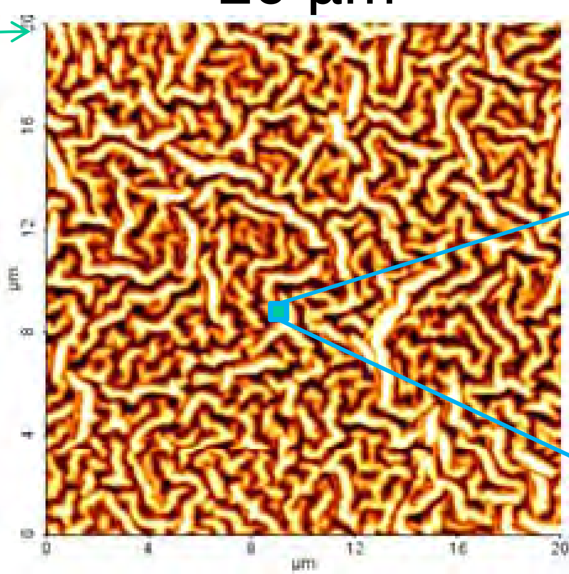




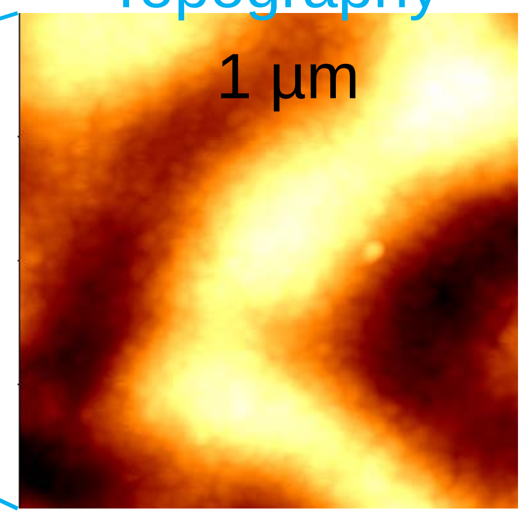
Annealing effects during Al vapor deposition is a possibility

cohesive surfaces

20 µm



Topography



R_a = 25 nm
R_q = 30 nm

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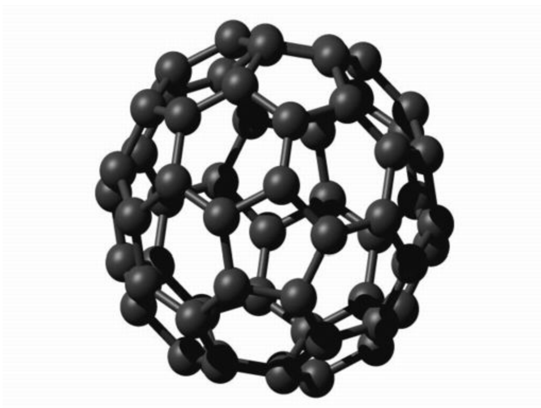
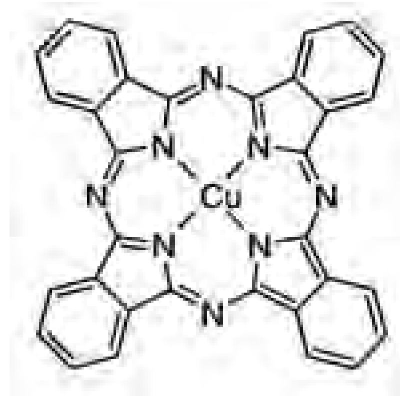
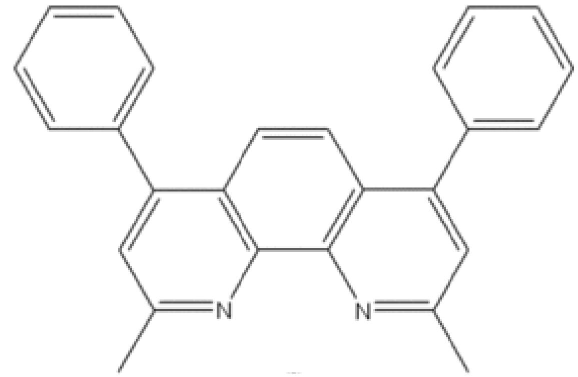
Small Molecule Solar Cell Thin Films



C60

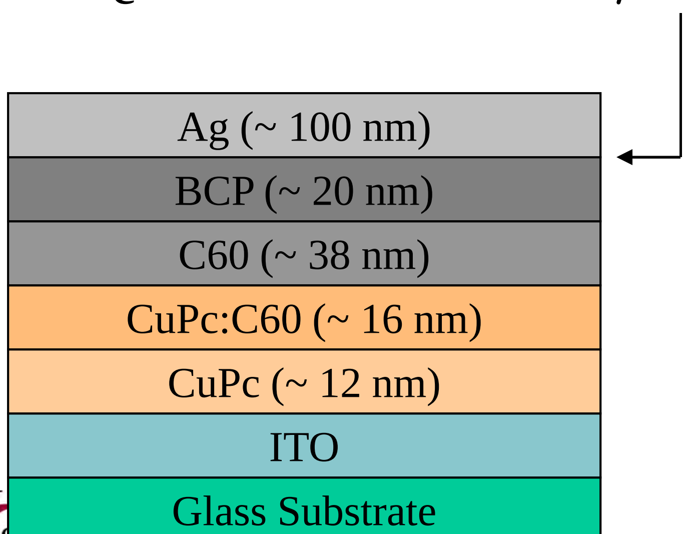


CuPc

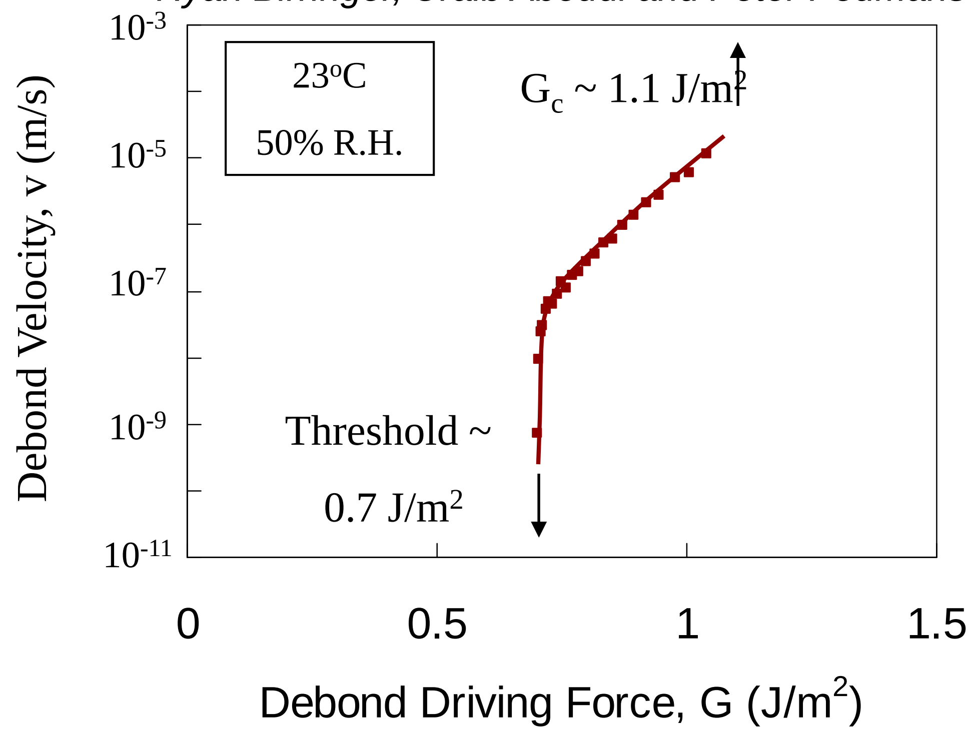


BCP

$$G_c = 1.1 \pm 0.4 \ \ J/m^2$$



Ryan Birringer, Uraib Aboudi and Peter Peumans



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Molecular Bond Rupture Kinetics (Barrier Films)

Grad student: Fernando Novoa and Monika Kummel

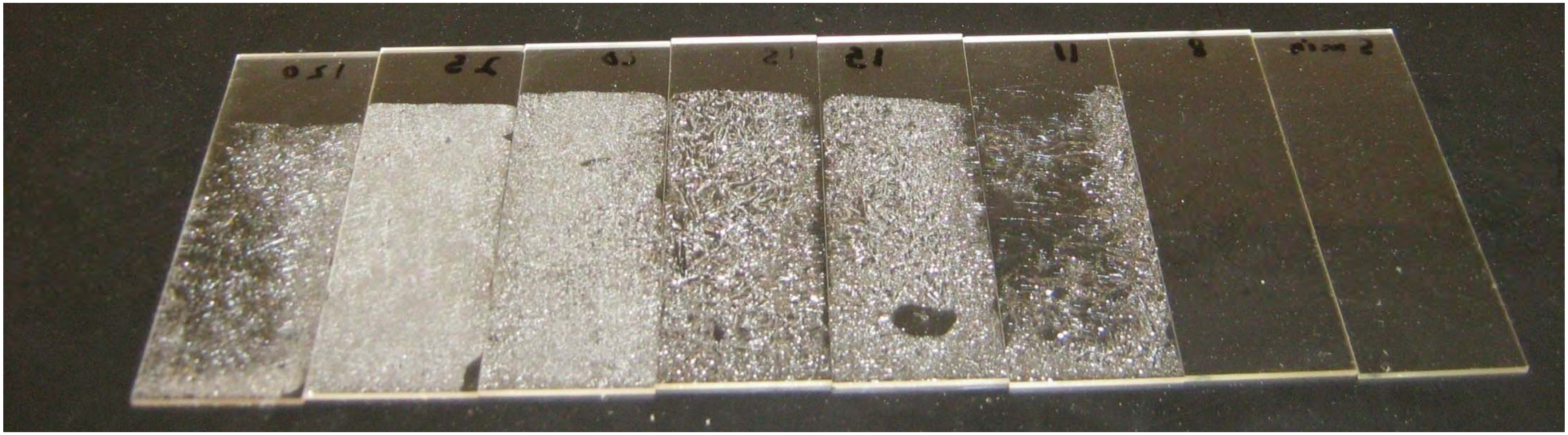
$$G \quad < \quad G_c \left[J / m^2 \right]$$

environment and stress <u>accelerates</u> defect evolution

Weathering Test of Polysiloxane Barrier

UV exposure: 28 mW/cm^2 at 6 mm UV-257nm

120 min…………….15 min……………………5 min



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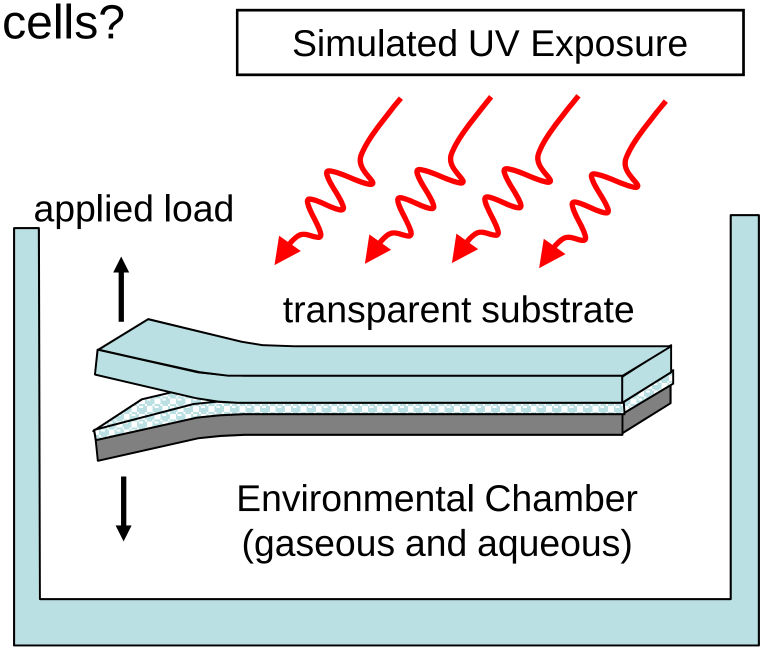
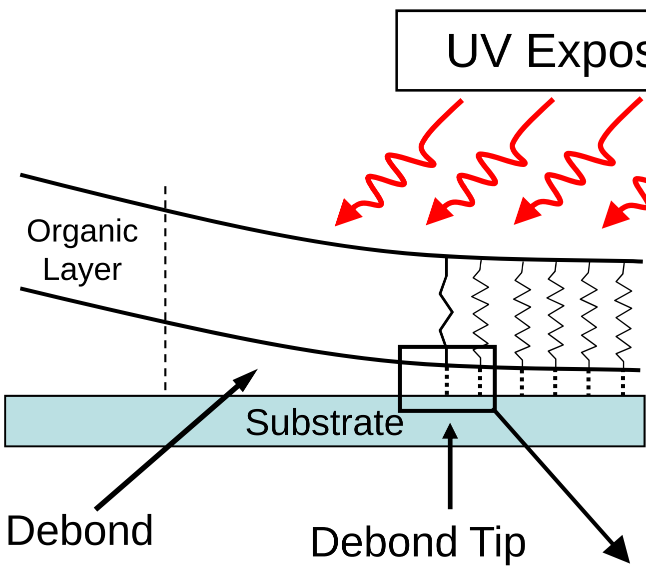
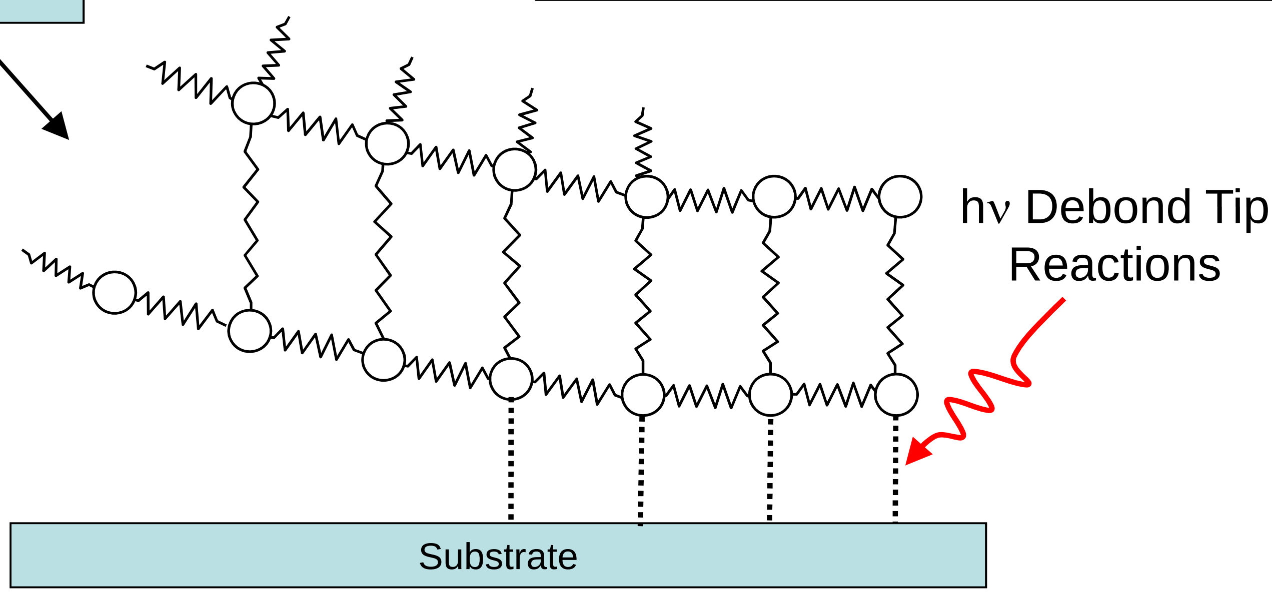
Environment and Stress Accelerates Damage

Does UV exposure accelerate decohesion in solar cells?

What are the kinetics?







Activation Energies:

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H-bonds ~ .1 - .4 eV/bond

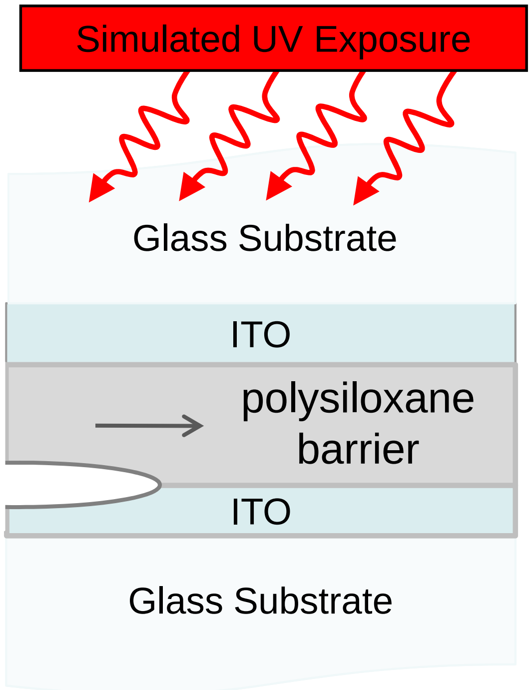
Ester Hydrolysis (100% RH)

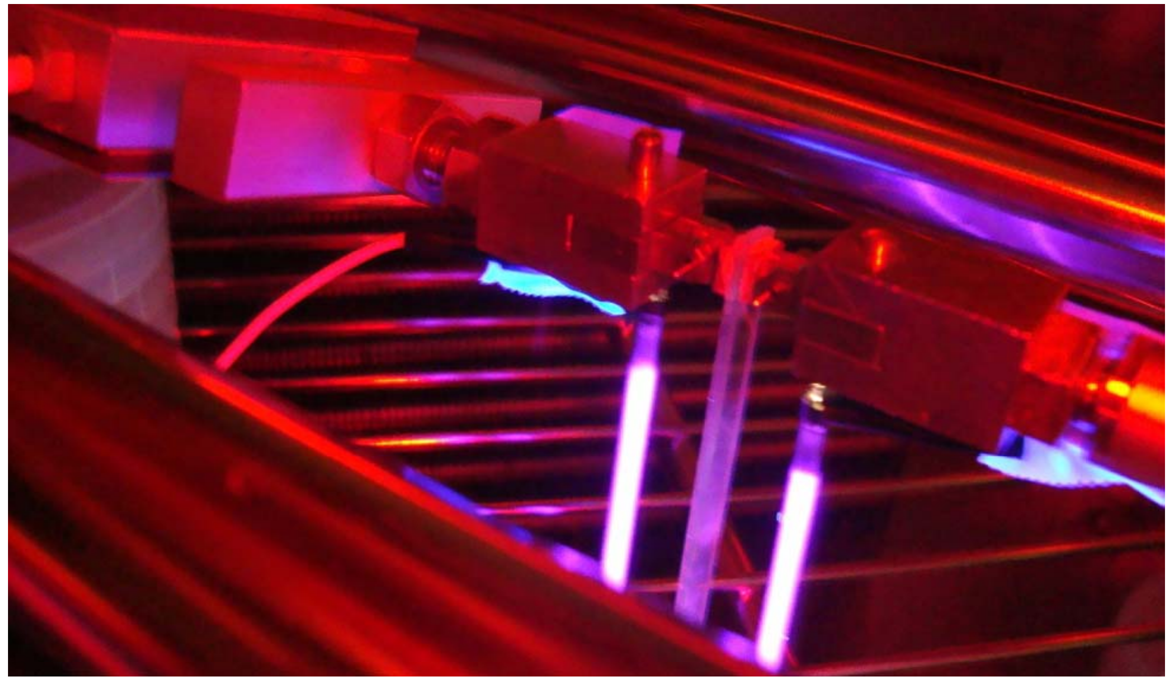
E* ~ .81 eV/bond

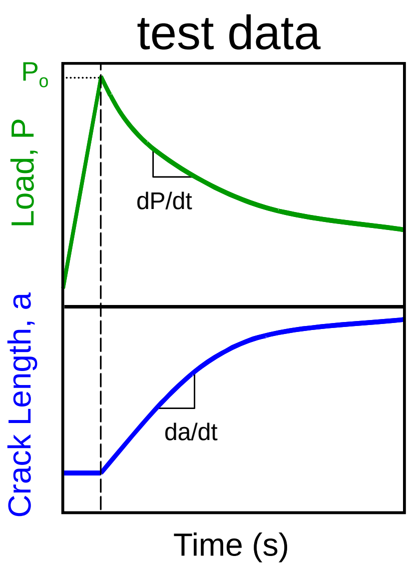
SiO_2 cracking in water

E* ~ 1.39 eV/bond

Assessing UV and Environment on Debonding Kinetics







DTS Delaminator v4.0
automated load relaxation debond growth analysis

compliance analysis

sensitivity to < 10^{-10} m/s

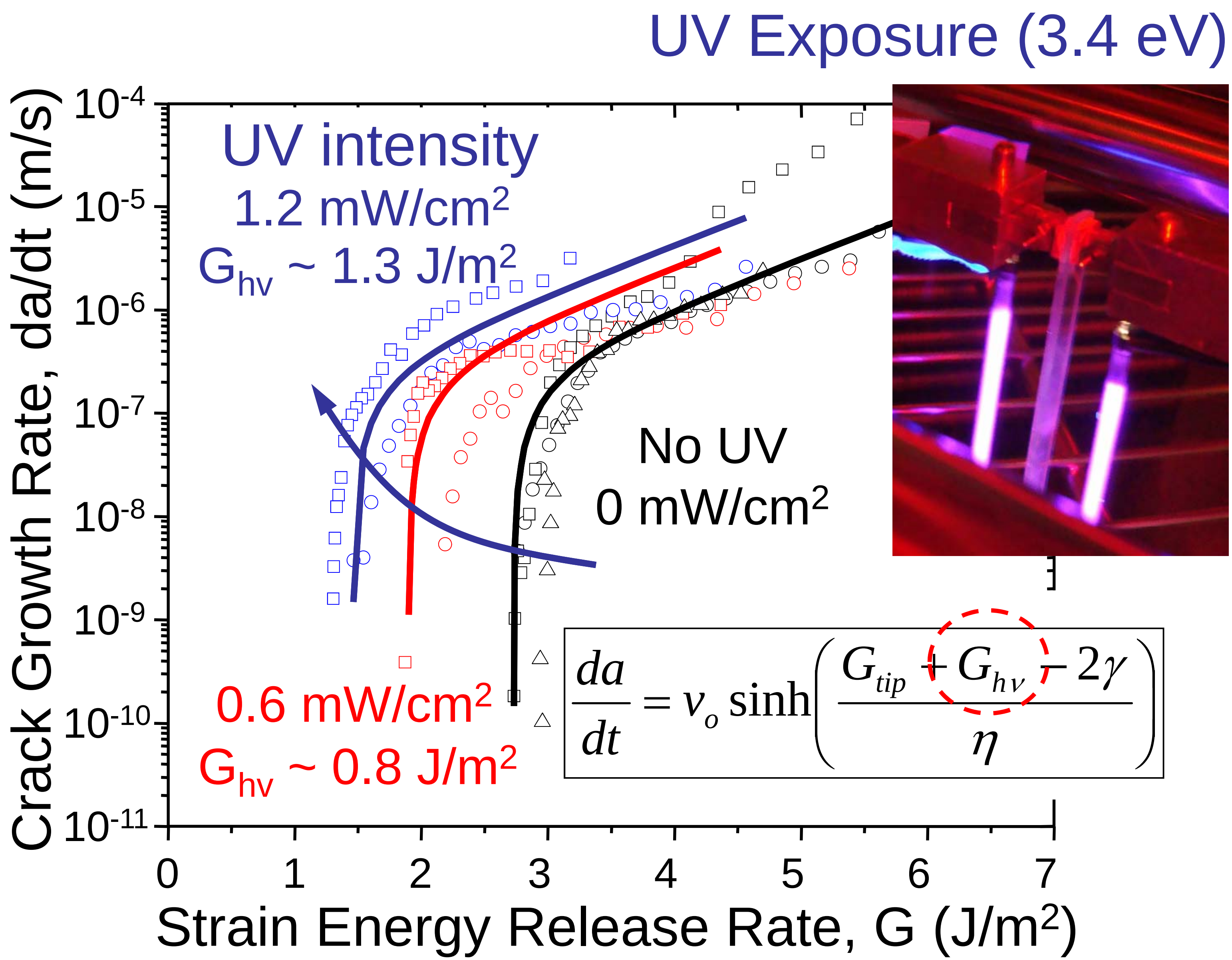
Debonding Kinetics

explore role of:

- UV flux
- humidity, O_2, OH, …
- temperature
- mechanical loading

DTS system and support contact dauskardt@stanford.edu

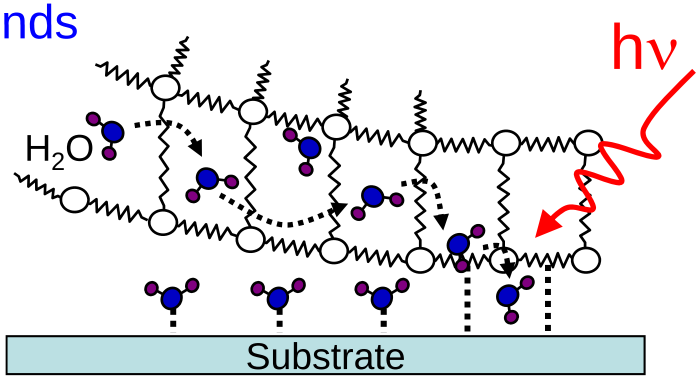
UV Effects on Molecular Bond Rupture



Modeling Bond Rupture Kinetics

- Interaction of moisture with strained debond tip bonds

$$nH_2O + B(\text{debond tip}) \xrightarrow{h\nu} B^*(\text{activated complex})$$



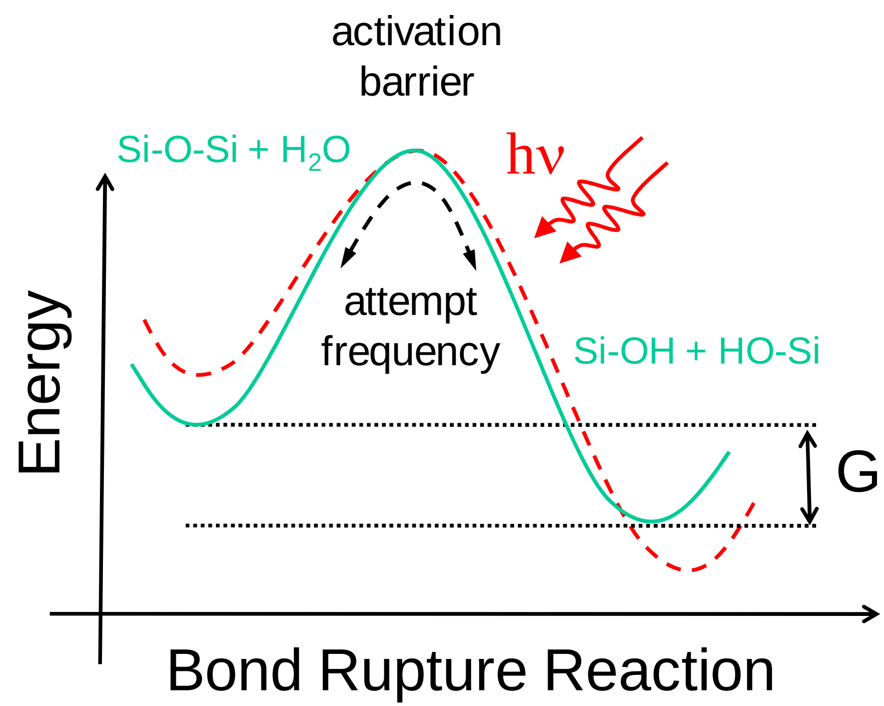
- Atomistic bond rupture models:

$$rate = f_o\left[\exp\left(\frac{-U_+^*}{kT}\right) - \exp\left(\frac{-U_-^*}{kT}\right)\right]$$

- Damage growth rate:

$$\frac{da}{dt} = v_o \sinh\left(\frac{G_{tip} + G_{h\nu} + 2\gamma}{\eta}\right)$$

$$v_o = \frac{2 f_o}{Nw}\exp\left(\frac{-u_1}{kT}\right)$$



Bond Rupture Parameters

N - bonds per unit area

u_o - work of rupture

2γ - N u_o

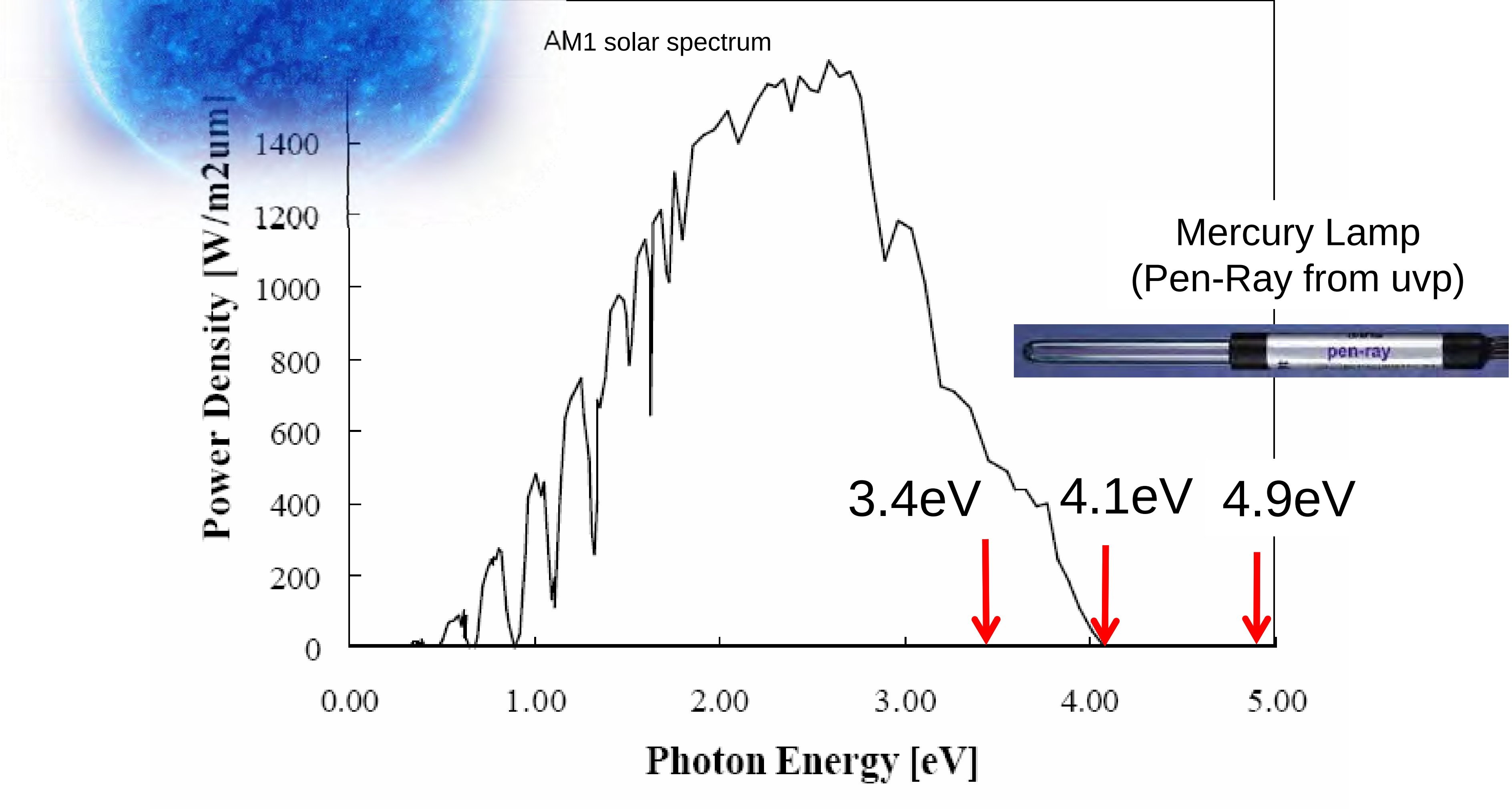
w - crack width

f_o - attempt frequency

u_1 - energy barrier

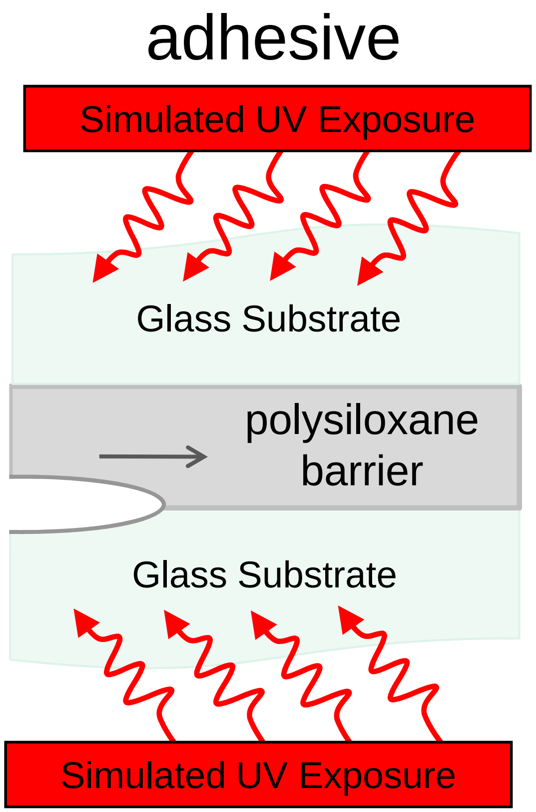
η - 2NkT

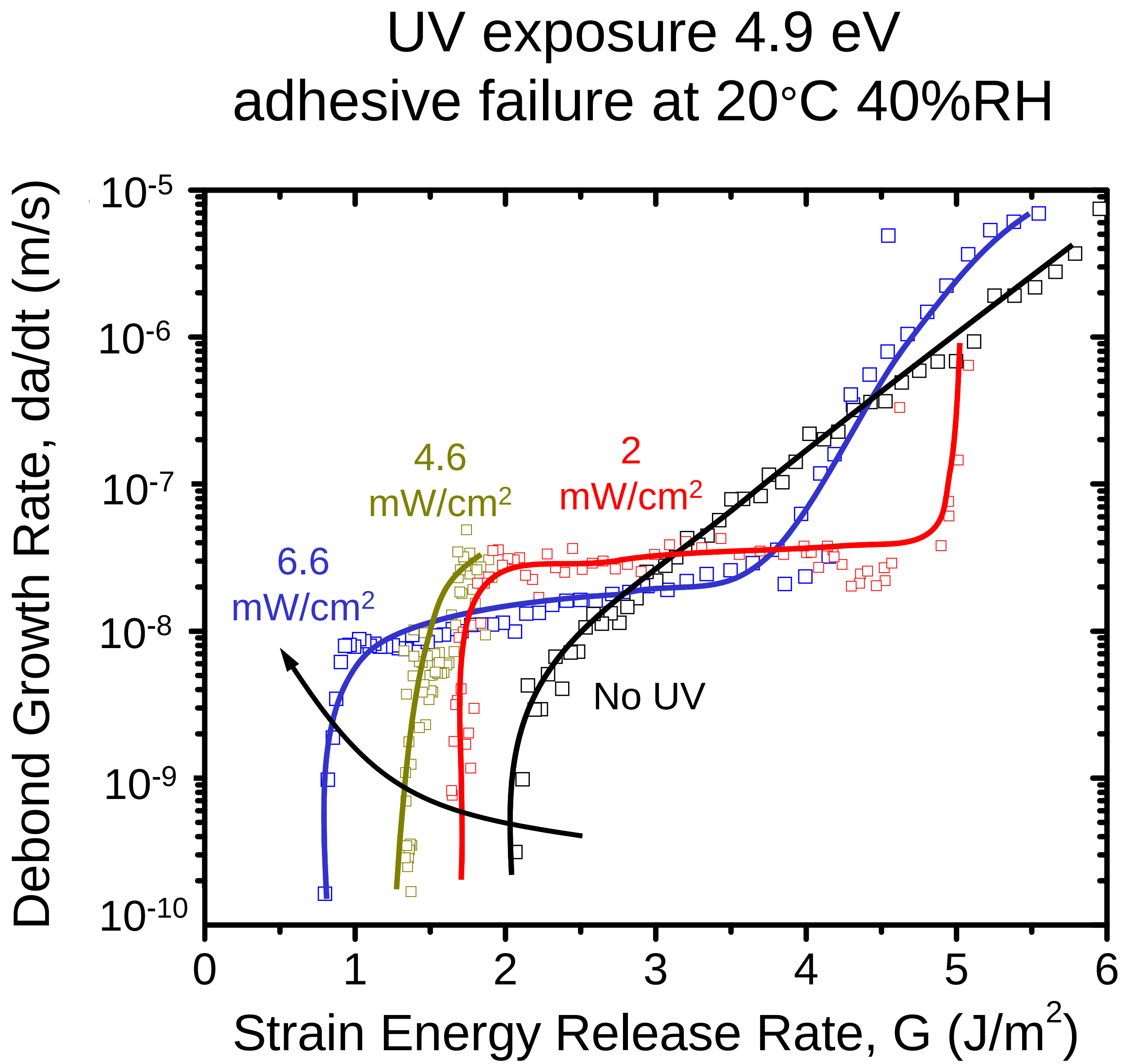
UV Sources



Solar spectrum from B. Van Zeghbroeck, U. Colorado

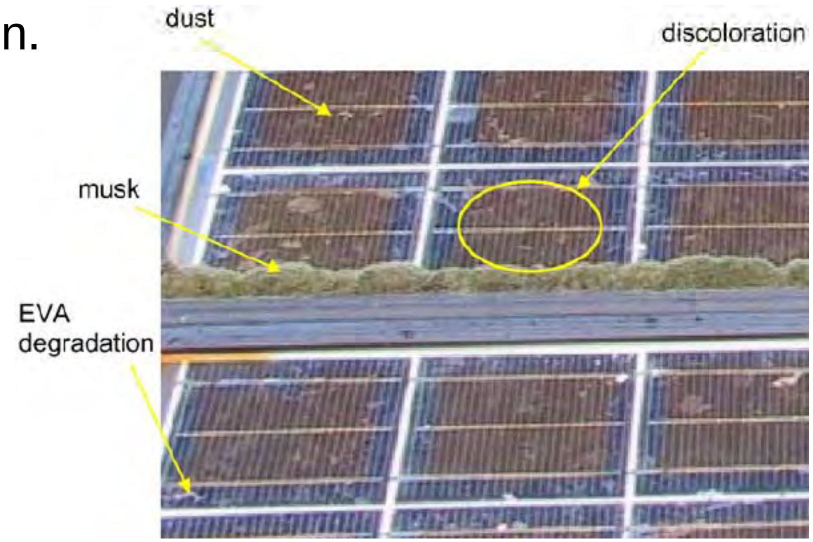
UV Effects on Molecular Bond Rupture





Delamination of EVA-TPE Lamination

- Poly-ethylene vinyl acetate (EVA) copolymer extensively used by solar module manufacturers, particularly for laminating c-Si photovoltaic modules.
- Good optical properties and high adhesive contact with glass cover and Si cells.
- Inexpensive and relatively easy fabrication.



Parreta Antonio, et al., Solar Energy Materials & Solar Cells, 2005

- Delamination can occur between EVA and the front surface of the solar cells.
- More frequent and in hot and humid climates.
- Exposure to atmospheric water and/or ultraviolet radiation leads to EVA decomposition to produce acetic acid, lowering the pH and increasing corrosion.
- EVA Tg ~ -15°C so lower temperatures may result in "ductile-to-brittle" transition in adhesive/cohesive properties.

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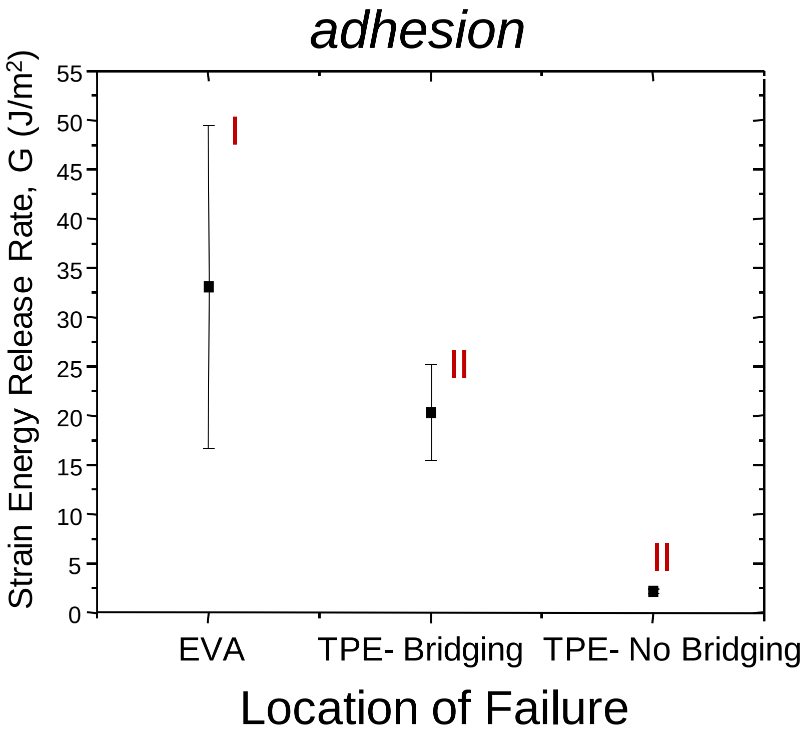
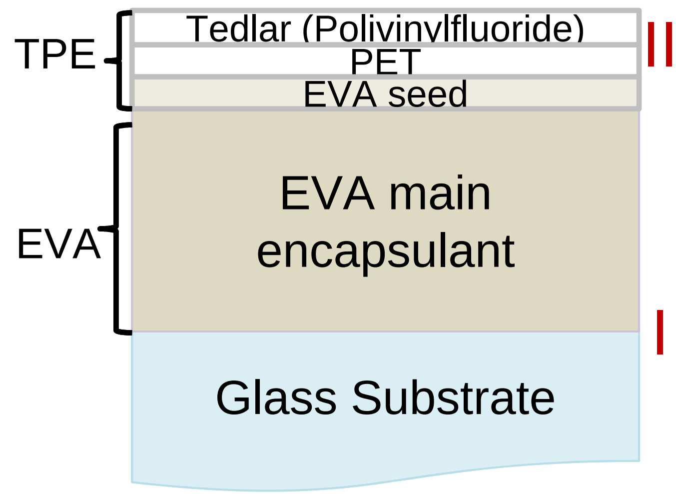
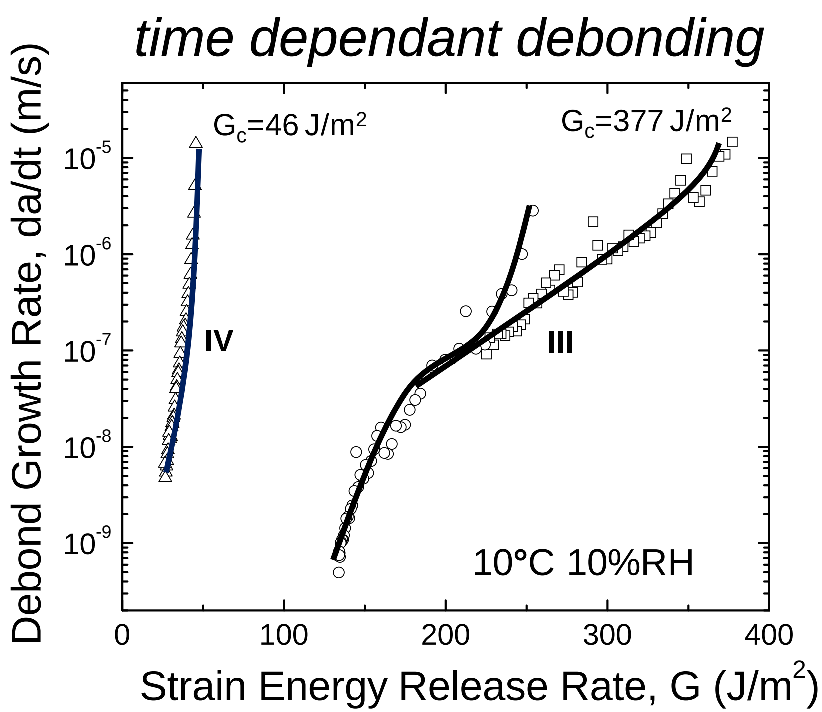
Delamination of EVA-TPE Lamination







Interface "I" located between EVA and Glass
Interface "II" inside the TPE multilayer

STANFORD MATERIALS SCIENCE AND ENGINEERING

Summary for PV Durability and Reliability

We want to engineer durable PV devices and modules with robust and predictable lifetimes.

- Leverage from reliability physics in microelectronics – mechanisms, kinetic models, accelerated tests and life prediction
- Develop metrologies to quantitatively characterize thermo-mechanical properties (e.g. adhesion, cohesion), photochemical and environmental degradation processes
- Are degradation processes coupled and how?
- Kinetic models of damage evolution - basis for life prediction and accelerated testing (effect of operating temperature, environment, mechanical stress, solar flux, etc.)
- Effective transparent barriers with anti-reflective properties and low cost.