DuPont Teijin Films™

Substrates: Polyester Film for the Flexible Electronics Industry

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THE QUEEN'S AWARDS FOR ENTERPRISE: INNOVATION 2011

DuPont Teijin Films:
Winner of new 2009 FLEXI Award for Substrate Developments in Flexible Displays Market
FlexTech Alliance

OSIA
Organic Semiconductor Industry Awards
product of the year
2008

OUTLINE:

- DuPont Teijin Films Overview
- Flexible "Plastic" Substrate Evolution
  - Original Substrate Goals
  - The Ideal Substrate vs. Managing Expectations
- Extending the Range of Existing Polyester Substrates
- Conclusion

Established
1st January
2000

50:50
joint venture

DuPont & Teijin

DUPONT
The miracles of science™

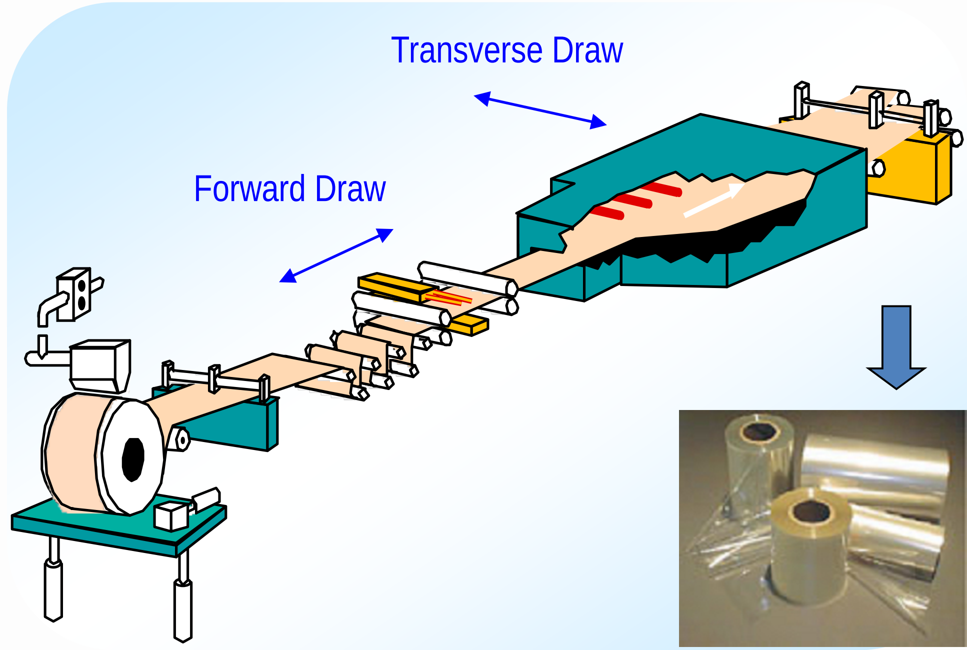
TEIJIN
Human Chemistry, Human Solutions

$26 billion sales
58,000 employees

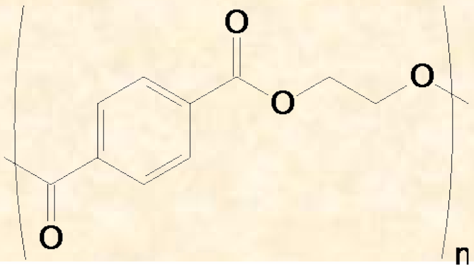
$8 billion sales
19,000 employees

Polyester Film Technology

- PET and PEN polyester films
- Biaxially oriented, semi-crystalline
  - High stiffness
  - Dimensional stability
  - Optical transparency
  - Solvent resistance
  - Thickness = 0.6-500 µm

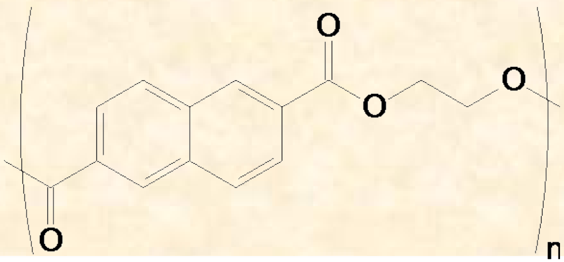


MELINEX®, MYLAR® and Teijin® TETORON®
Polyethylene terephthalate (PET)

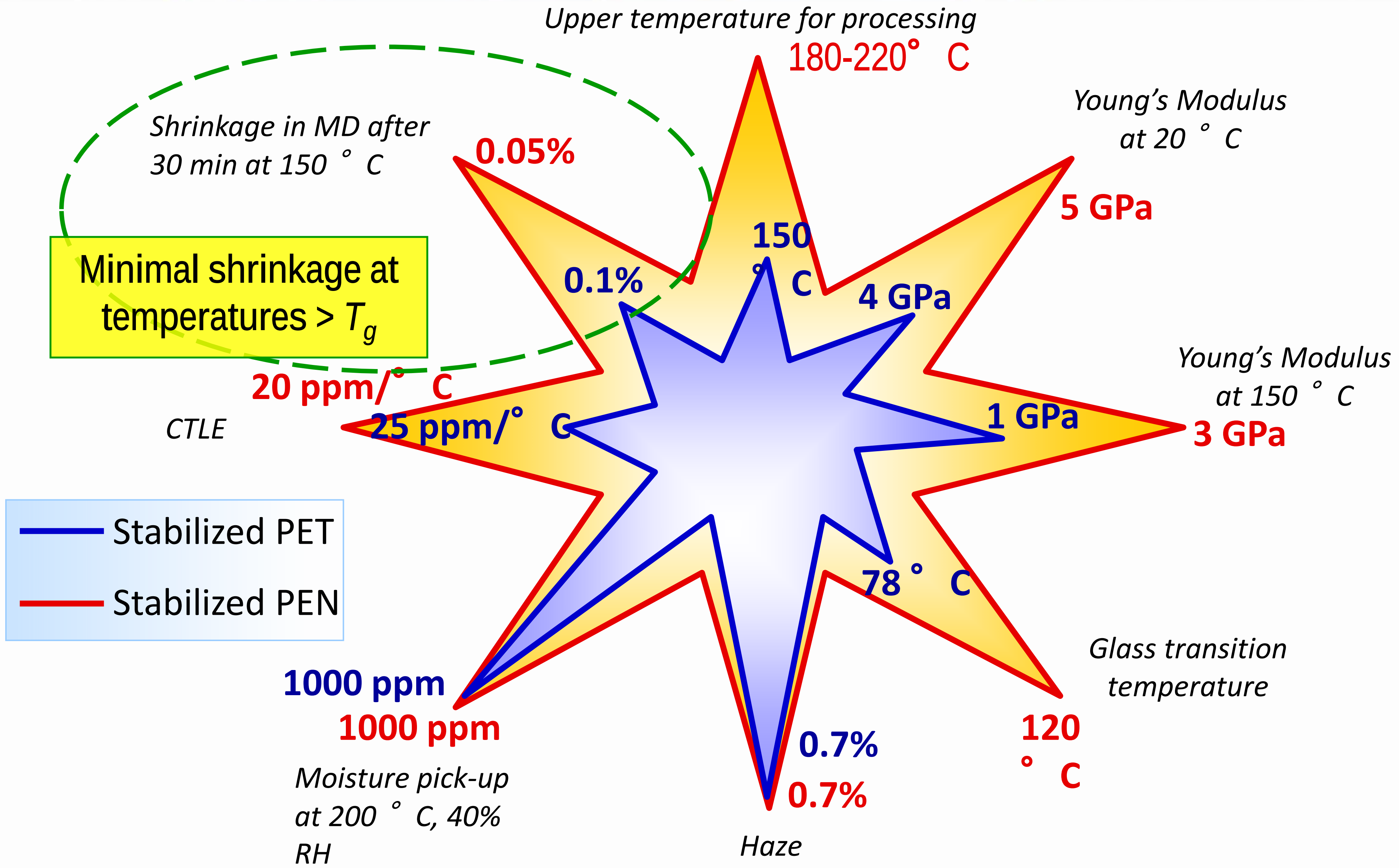


T_m = 255 °C
T_g = 78 °C

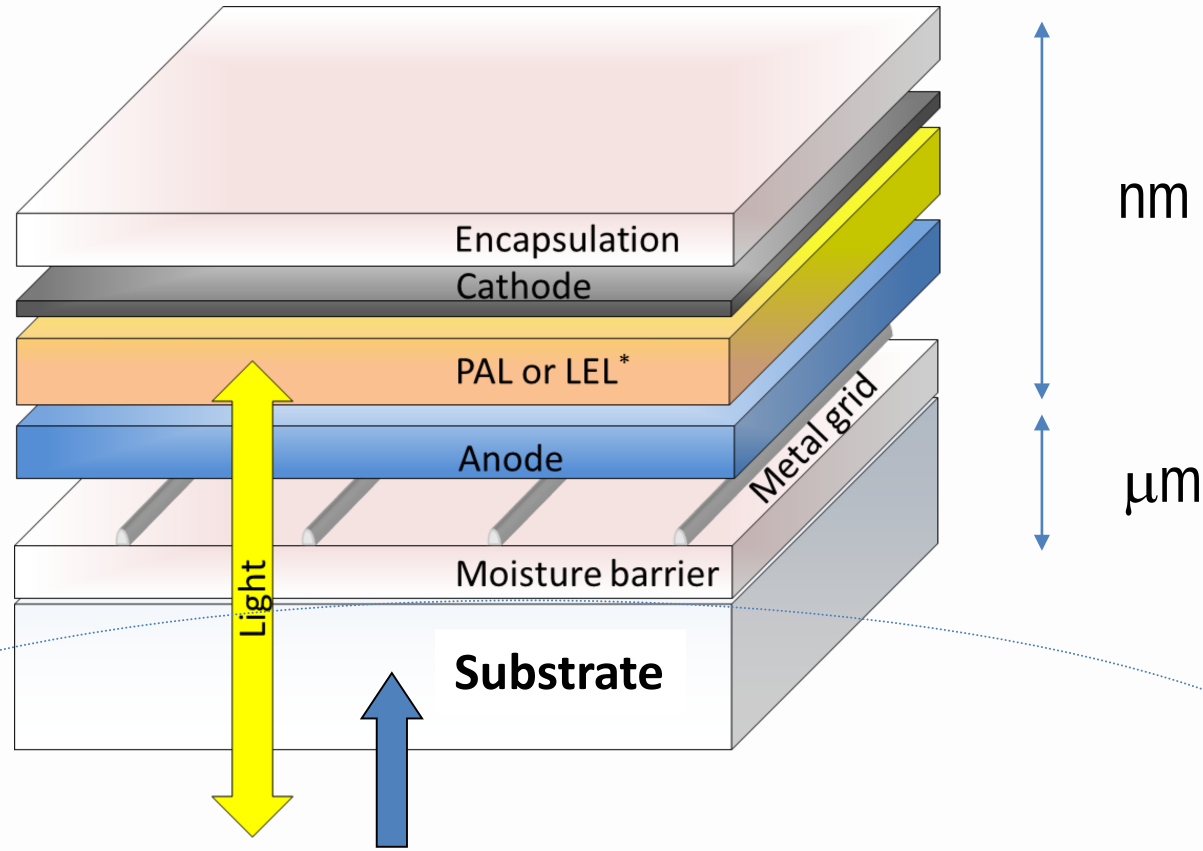
TEONEX®
Polyethylene naphthalate (PEN)



T_m = 263 °C
T_g = 120 °C


Upper temperature for processing
180-220° C
150 ° C
Young's Modulus at 20 ° C
5 GPa
4 GPa
Young's Modulus at 150 ° C
3 GPa
1 GPa
Glass transition temperature
120 ° C
78 ° C
Haze
0.7%
0.7%
Moisture pick-up at 200 ° C, 40% RH
1000 ppm
1000 ppm
CTLE
20 ppm/° C
25 ppm/° C
Shrinkage in MD after 30 min at 150 ° C
0.05%
0.1%
Minimal shrinkage at temperatures > T_g
Stabilized PET
Stabilized PEN

Flexible/Printed Electronics' origin? OLED Displays



Film Substrate – "Boring", yet the basic building block

– Essential to getting it right!

And now?

- A much broader range of applications based on flexible substrates
    - Printed electronics
    - Electrophoretic, electrochromic, electrowetting displays
    - Printed memory; Sensors
    - OLED lighting; Thin film PV/O-PV

Figure: Plastic Logic/Popslate - Always-on 2nd screen display for their Apple iPhone 5 & 5S accessory

But also…

- Use of film in "rigid" devices
  - Touchscreens
  - Light management films

Factors Influencing Film Choice – Property Set

OLED displays

Inorganic active matrix backplanes

Organic active matrix backplanes

“Simple” organic circuitry

Increasing complexity of substrate structure, and more demanding property set

Factors Influencing Film Choice – Property Set

Combinations of high performance Film; Plastic film alone cant do it

OLED displays

Inorganic active matrix backplanes

Organic active matrix backplanes

Paper, O-PP, PET

“Simple” organic circuitry

Increasing complexity of substrate structure, and more demanding property set

Physical Form/Manufacturing Route

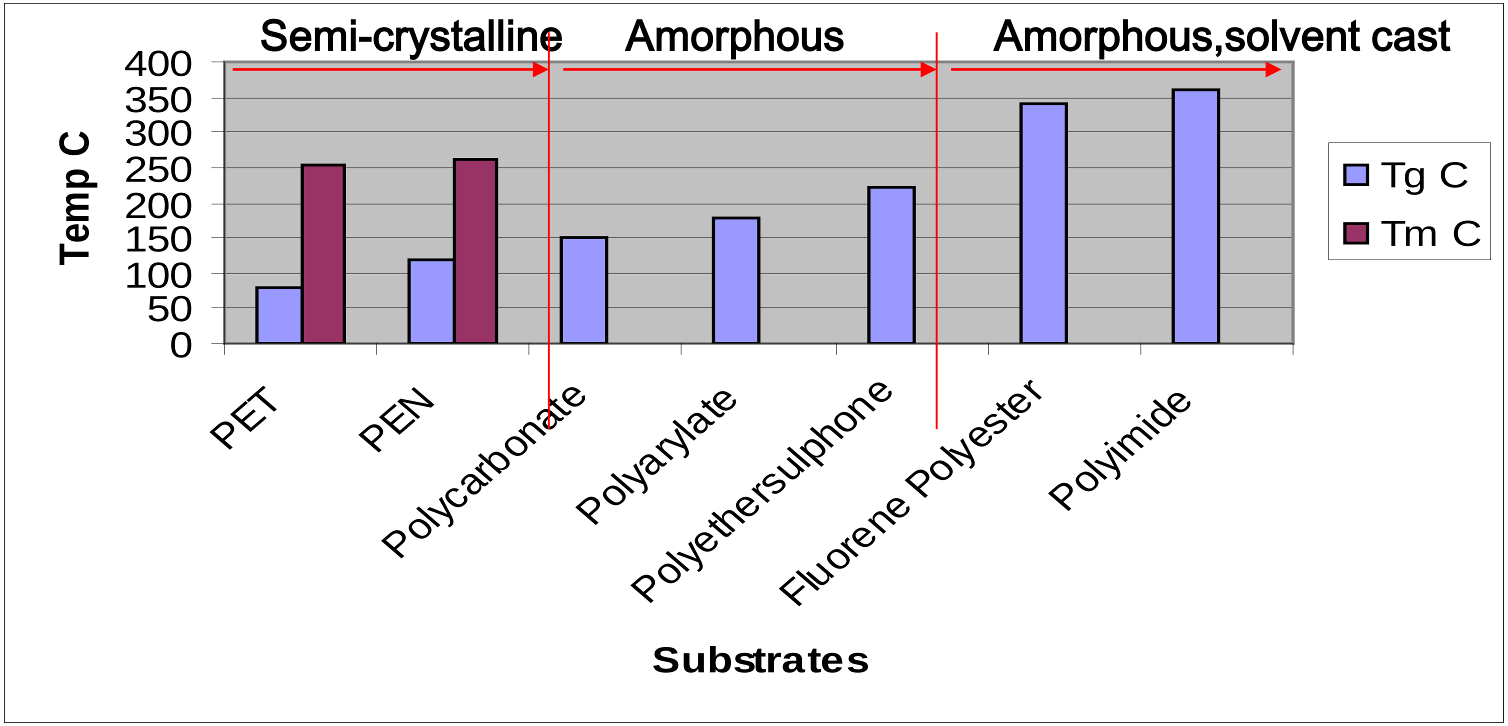
(Red Denotes Newer Trend)

- Physical form of device and type of usage will influence film choice particularly with respect to thickness
  - Flexible, Rollable
  - Flat but exploiting light weight, ruggedness
  - Conformable, one time fit to uneven surface
- Batch, fast sheet and R2R processing
- End device manufacture batch based
  - Fits with existing semiconductor manufacturing equipment
  - Used to give dimensional reproducibility
  - But brings a different set of technical challenges
    - Bowing
    - Release from carrier
- R2R used for specific steps (e.g. conductive, barrier etc)

Factors Influencing Film Choice:

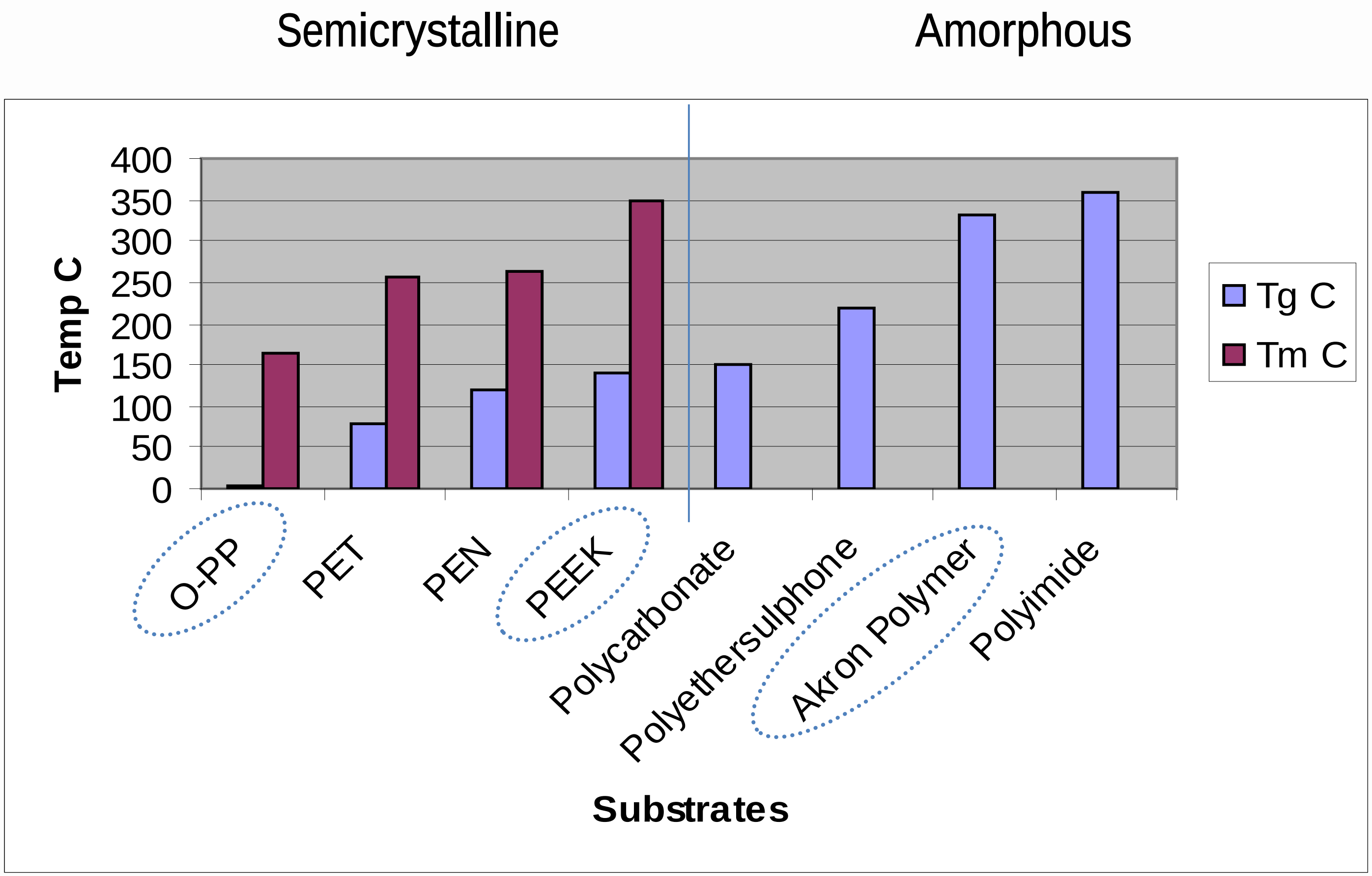
Substrate Properties

Films grouped by thermal properties



MacDonald W A, Rollins K, MacKerron D, Eveson R, Rakos K, Adam R, Looney M K, and Hashimoto K, J of SID, 2007, 15/12, 1075-1083

Current Situation



Existing Materials

	Substrate						
Property	Biaxially oriented heat stabilised PET	Biaxially oriented heat stabilised PEN	Biaxially oriented PEEK	PC	PES	Akron APS	Polyimide
CTE (-55 to 85 ºC) ppm/ºC	√√	√√	√√	√	√	√	√√
%Transmission (400-700 nm)	√√	√√	√√	√√√	√√	√√	X
Water absorption %	√√	√√	√√	√	X	√	X
Young's modulus (Gpa)	√√	√√	√√	√	√	√	√
Tensile strength (Mpa)	√√	√√	√√	√	√	√	√
Solvent resistance	√√	√√	√√	X	X	X	√√
Upper Operating Temp	√	√√	√√√	√	√√	√√√	√√√
Availability at commercial scale	√√√	√√√	√	√√√	√√√	√	√√√

"New" Plastic Substrates – A Personal View

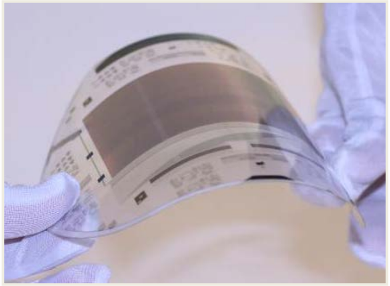
- The Holy Grail – water white, low CTE, low shrinkage, stability at >300C
- The likelihood is that a new material will be based on "exotic" raw materials – cost pressures
- Possibly will involve
  - New monomer synthesis – new plant?
  - Polymer synthesis – new polymer plant?
  - Film on existing film line or new film line?
  - Heat stabilisation?
- The entry cost to scale up a new material to commercial scale film involving some or all of above is likely to be prohibitively expensive
- Points towards making the most of existing commercially available materials

Existing Plastic Materials

- Films sourced "off the shelf" for device use are unlikely to be optimised for device manufacture.
- The quality required for commercial display manufacture can only be achieved when the film is being manufactured at volume on commercial scale lines
- Material supplier commitment to flexible electronic market is essential to optimising the film
- Once a device manufacturer focuses on a particular material set and/or process they will attempt to adapt their processing technology to make it work
- Win-Win is if both substrate supplier and device fabricator work together to match film capability to process capability

Example – Inorganic Active Matrix Backplanes

- Progress achieved by The Flexible Electronics and Display Center (FEDC) at Arizona State University, pushing PEN to its processing limits
  - Developed bond-debond system optimised for PEN processing
  - Bow and Warp of rigid carrier, adhesive and PEN are targeted to be below 125um and have been held to <60um
  - Runout or layer to layer alignment tolerances are being held to less than 0.5um for a 9 layer process of conductors, semiconductors and insulators
  - Have shown the ability to increase area from 150mm round carriers to 370mmX470mm and currently routinely process both sizes without any yield loss due to Bond Failure or Bow Warp regardless of size of carrier used.



Fully Processed PEN after De-bond & before Display Build

370mmX470mm PEN after De-bond

Alternative Materials

- Stainless Steel
  - Finding application in flexible PV
  - Little activity in other flexible device areas
- Flexible Glass
  - Recently re-emerged
  - Solves the part of the barrier problem (edge seal, etc. remain issue)
  - Thinner /lighter weight alternative to rigid display glass?
  - Challenges
    - R2R processing and handling
    - Availability
    - Quality at commercial scale
    - Durability
    - Cost

The Flexible Substrate Design Challenge

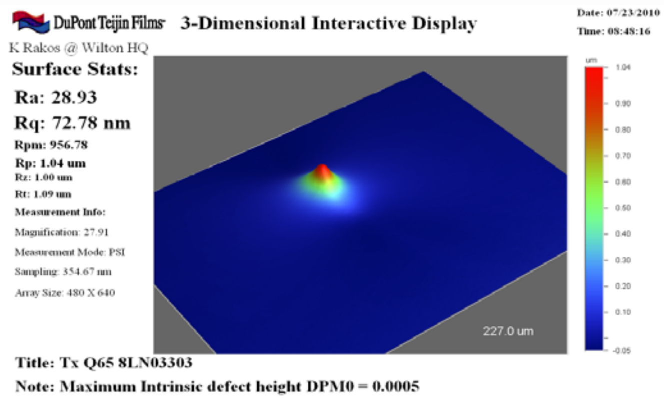
- Flexible, transparent, high barrier
  - For OLED, target water transmission rates of $<10^{-6}$ g/m^2/day and oxygen transmission rates of $<10^{-5}$ mL/m^2/day (today: 10^{-3} g/m^2/day)
- Dimensional reproducibility (multi layer registration e.g. TFT)
  - Achieved via a combination of low shrink films, control of environment and control of process
- Surface quality
  - External debris rather than internal contamination is the real issue
  - Planarized film options offer one route to smooth surface
- Transparent
  - Low Bloom, Refractive Index Matched Films are Commercial

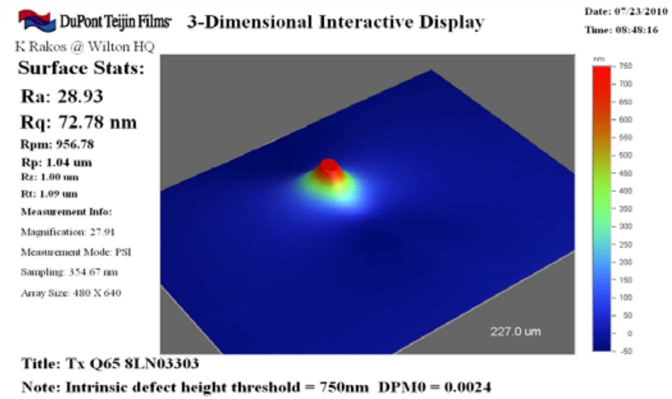
Key Substrate Properties

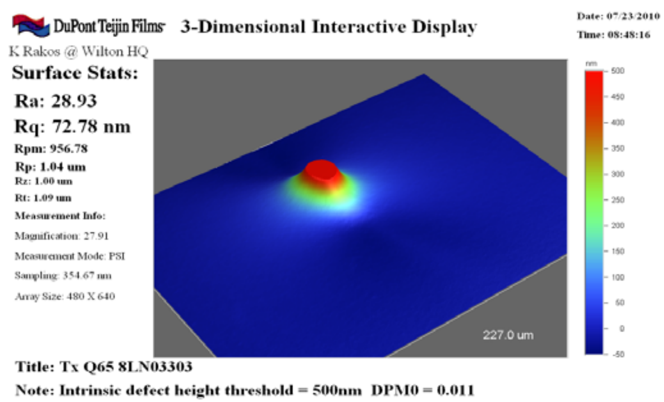
- Perfection is not possible and not required, but
  - We need to understand which defects are critical, where they arise, and target elimination
  - Rapid surface analysis remains an issue - The Large Area Metrology 'LAM' tool - fast measurement of film surfaces (14" x 14")
- Two major EU Funded programs targeting surface quality
  - HighQSurf (finished)
  - Clean4Yield (ongoing)
- Recognition that the provision of defect free film surfaces for device manufacture would remove a key technology road block to commercialization

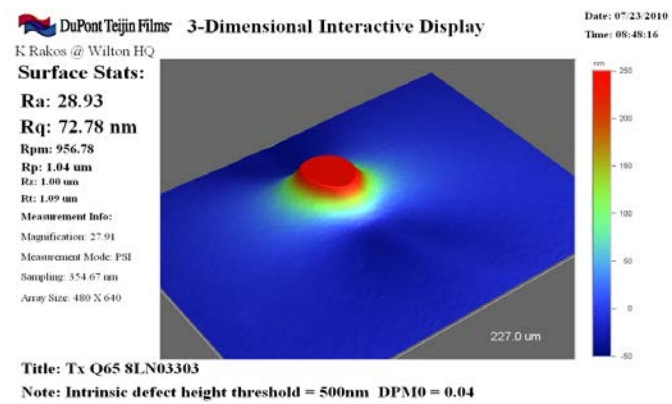
Large Area Metrology (LAM) Surface Analysis

TEONEX® Q65FA, non pretreated, 'raw surface' 200um



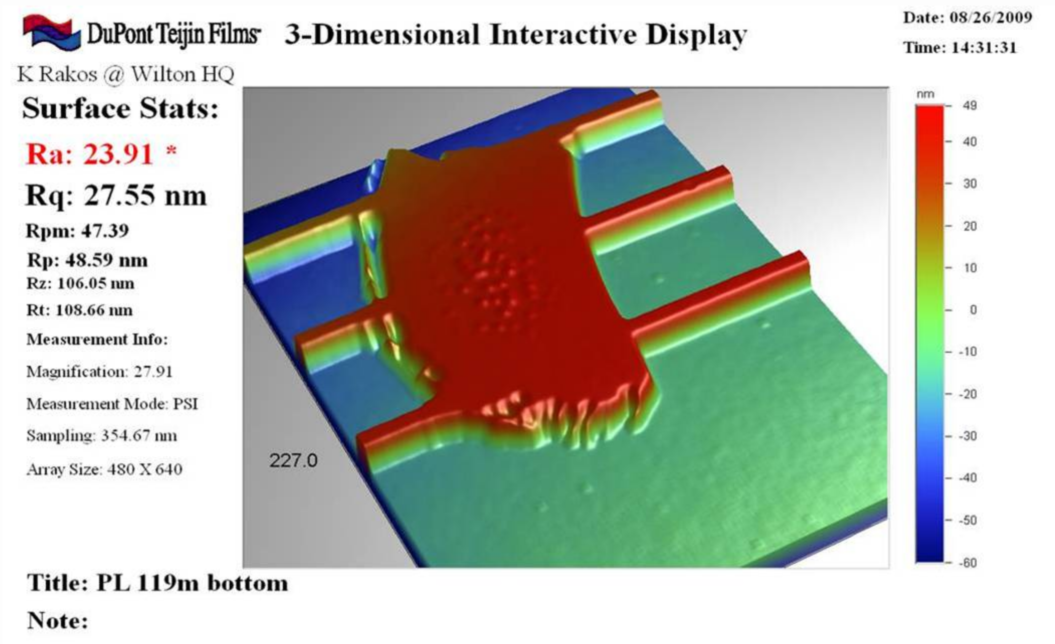






(Defect area for a given height threshold as a fraction of total sample – measured area = DPMO (ppm)

Large Area Metrology Image Of Short Circuit Caused By Surface Debris



- Mask-lines 320mm length, 10 microns width, 40 microns spacing
- Used to study defect density and identify debris with potential to cause shorts
- Majority of breakages were found to be extrinsic

Where does external debris arise?

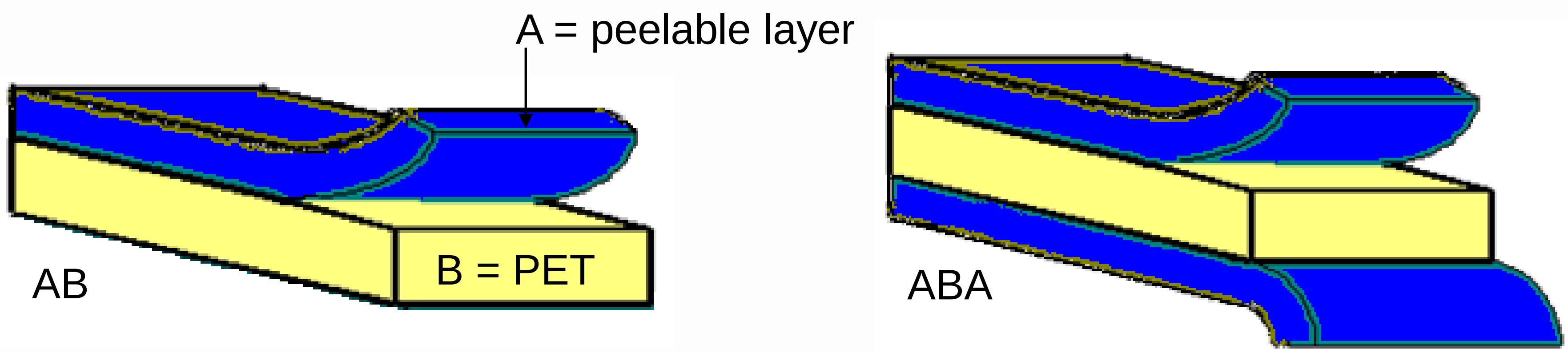
- Major audit of film entering customers clean room
  - Particles found on the film surfaces were identified with human, packaging and process interactions.
  - There is a clear link between individual substrate processing and handling steps which plays a major part in ensuring the delivery of defect free devices.
- Some interactions are inevitable
  - Packaging of films; Transport through processing equipment
- Protect films protect surface but must be clean and must not leave residue on surface; Static control is essential
- Final “just in time” cleaning is an essential process step in the production of defect free flexible electronic devices

HiQSurf-Protecting/Cleaning Surface-strategies

- Address hygiene issues associated with the packaging, transport and handling of the film
- Exploit contact and non contact methods of cleaning to make best use of the cleaning capability of both types
- The “Nanocleen” cleaning roller (from Teknek) launched to produce the most efficient removal of both large and small particles (nanoparticles) from flexible substrate

“On-Demand” Clean Film

- Is there an alternative way to make high quality, perfectly clean surfaces ?
- Coextrusion technology may provide the answer
- Concept
  - Coextrude a sacrificial protect film with the PET
- PET surface is an internal layer, only exposed to air after peel
  - Intrinsically clean
- Peelable layer absorbs damage from subsequent web transport handling, leaving PET surface unaffected



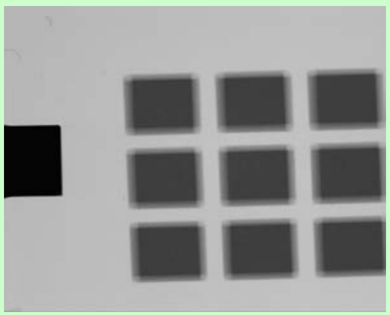
"On-Demand" Clean Film

PEELABLE POLYMER	SURFACE IMAGE OF PET after peel
Polymer A	
Polymer B	
Polymer C	
Polymer D	

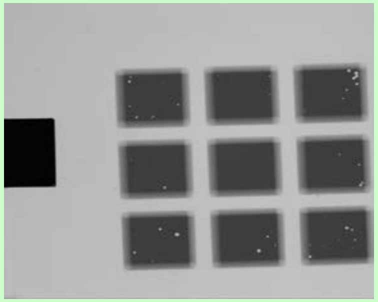
- Requires a coextrusion layer which ;
  - Peels off easily from PET biaxial film
  - Leaves PET with same or better surface microroughness than mono PET
  - Leaves PET with reduced surface defects compared to mono PET
  - Leaves no chemical residue left on PET
- Examples in table show how different polymers can impact on above

“On-Demand” Clean Film affect on Barrier

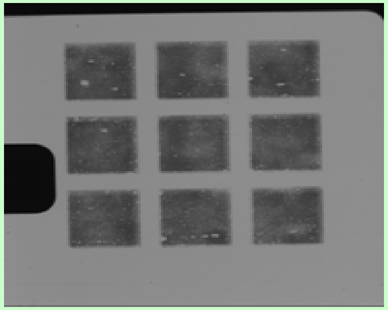
- Ca test results on barrier film – 20C and 50% relative humidity
- Reduced decay of Ca on barrier films deposited on On-Demand Clean film



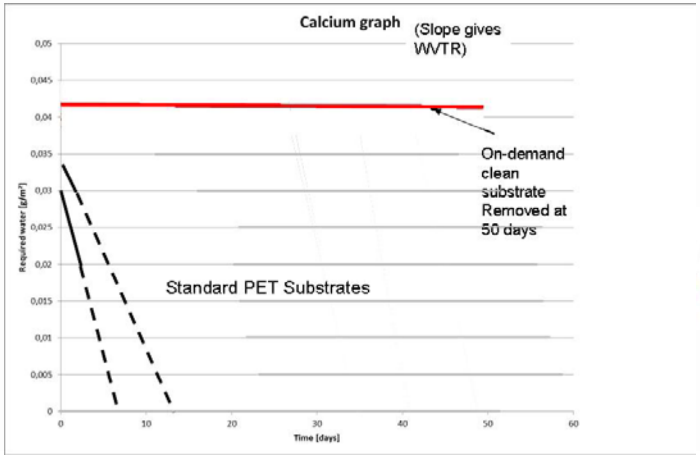
Start



“On Demand” PET after 26 days



Regular PET after 3 days



Results courtesy of Dr. Sandeep Unnikrishnan
TNO-Holst Centre

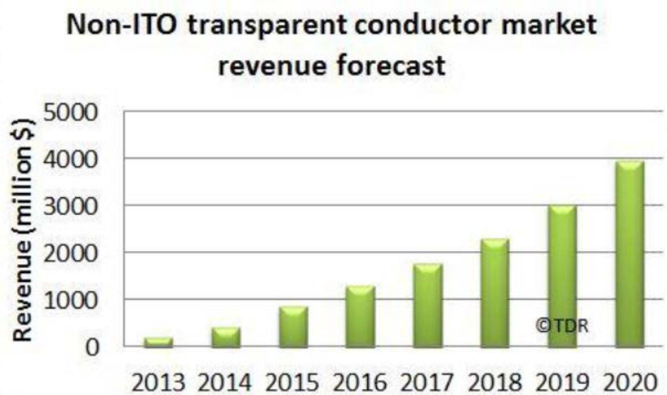
CLEAN 4 YIELD
DETECTION • CLEANING • PREVENTION • REPAIR

Optical Effects – Displays

- Touch Screen Market growth
- Many designs use PET film as the transparent conductor substrate
  - Requires PET film optimization
  - Mainly, Haze & Iridescence
- Manufacturing processes expose PET film to very high temperatures for extended periods
  - Heat stabilized film satisfies the shrinkage requirement
  - But, PET will "haze-up" under these conditions

ITO-replacement Market Forecast

- Touch Display Research forecasts that non-ITO transparent conductor market revenue will increase from $206 million in 2013 to $4 billion in 2020.

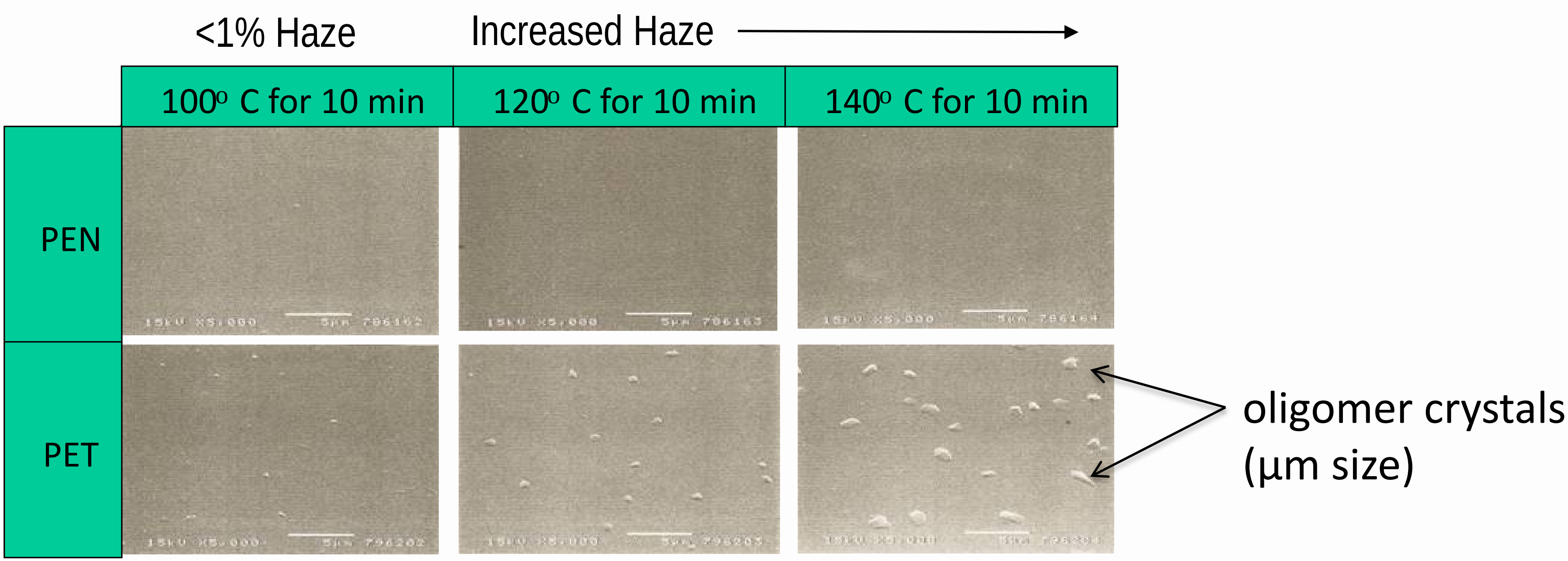


Source: Touch Display Research "ITO replacement" report, May 2013

TOUCH DISPLAY RESEARCH

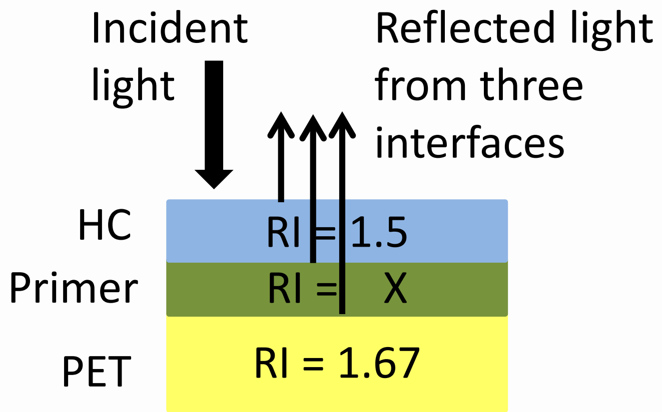
Haze – "Bloom" of Cyclic Oligomers

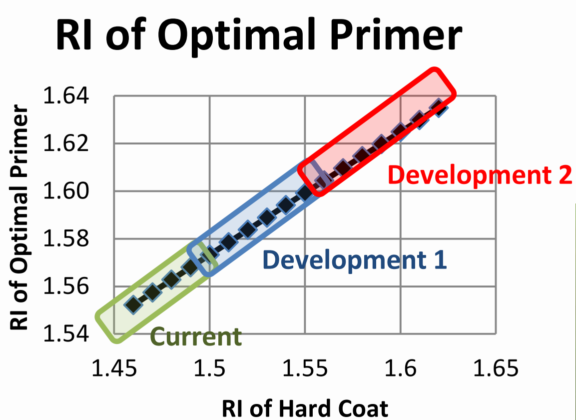
- PET films held at temperatures above 100C film starts become hazy
  - Due to migration of cyclic oligomers to the surface
- Can be controlled by coatings (block formation) and raw material selection



Iridescence – Refractive Index

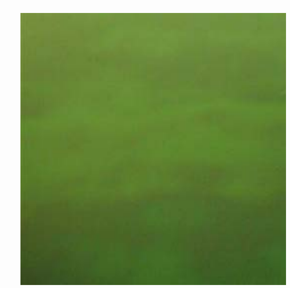
- Controlling refraction and reflection effects in optical stacks
- Typically, hard coated PET films exhibit iridescence or rainbow which is objectionable in display and touch applications
- Rainbow results from interference fringes stemming from reflections in the optical stack





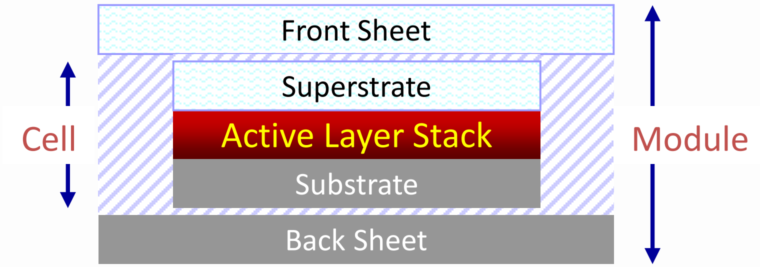
New Product

Standard PET



Competitor X

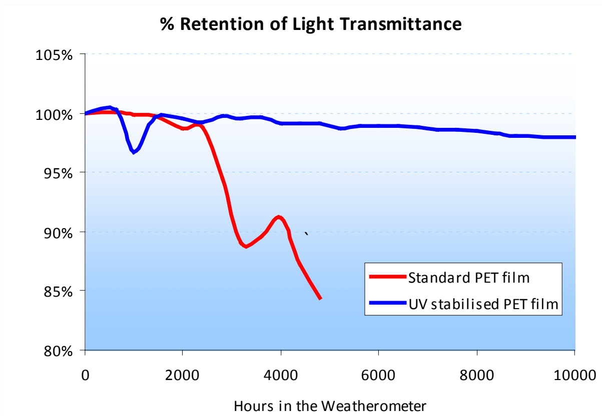
Photovoltaics

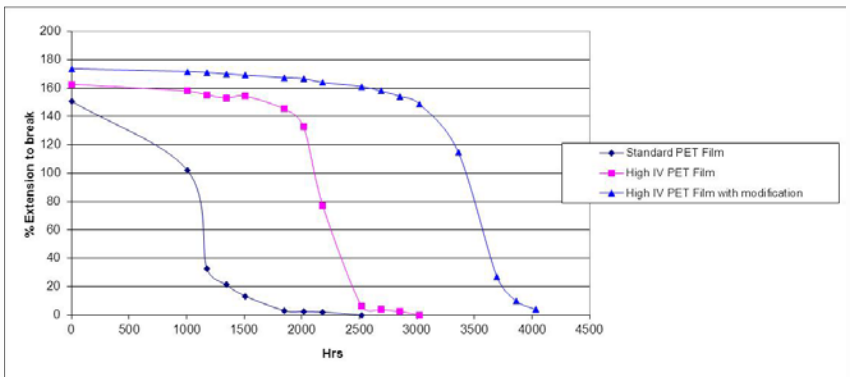


➔ A complex film development agenda!!

- Lifetime perception: "Polyester films degrade rapidly under UV light exposure and Polyester films hydrolyse rapidly"
  - Polyester films can be modified to have improved resistance to UV light
  - Polyester films can be modified to pass the standard "Damp Heat" test

10,000 hours in Weather-Ometer®





Damp Heat Test End Capped PET

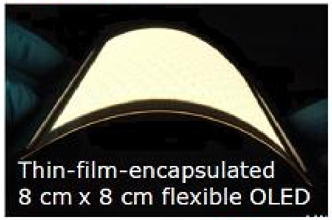
Other Polyester Film Substrate Possibilities

- Thermo-form and In Mold Electronics
  - 3-D surfaces for Capacitive Touch Switch
- Light Outcoupling Films
  - European FP7 program “FLEX-o-FAB” 2012-2015 for OLED Lighting

SEVENTH FRAMEWORK PROGRAMME

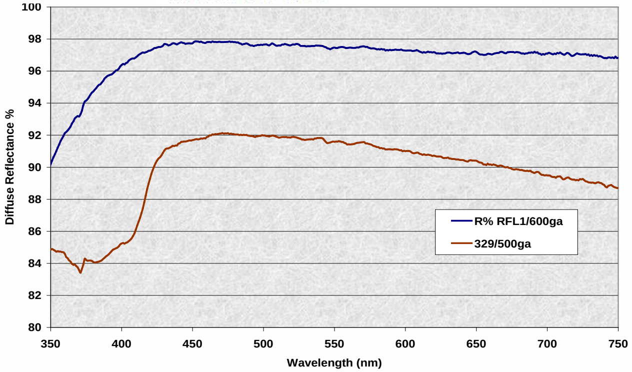
FLEX O FAB

Integration of optical outcoupling



Efficacy increased **30 lm/W -> 42 lm/W** by using barrier foil with integrated outcoupling enhancement

- White Reflector Films
  - LCD Backlights, LED / OLED Lighting



Summary - Trends in PET substrate industry

- Multiple applications, but a shared set of needs
  - Thinner, Conformable, Light Efficiency
  - Weatherable films – UV and hydrolysis resistance
- More focus on commercially available films as the industry matures
- Barrier structures
- Glass /plastic hybrids
- High temperature? Organic low temp vs inorganic high temp
- Pressure on cost

DuPont Teijin Films™

Thank you !!

Questions ??

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