Polyester Film Substrates for the Flexible Electronics Industry - An Overview and Where Next

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Established 1st January 2000

50:50 joint venture

DuPont & Teijin

$26 billion sales
58,000 employees

$8 billion sales
19,000 employees
11 manufacturing locations

Sites in Europe, the USA, Japan, China and Indonesia

All the major regions of the world

2500 employees

Global turnover $1.5 billion

Europe contributes over one third of global business

Global volume - almost 250,000 tonnes
Market Areas

- Healthcare
- Alternative Energy
- Durable Media
- Electronics
- Specialist Packaging
- Electrical Insulation
- Capacitors
Polyester Film Technology (1)

• 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)

\[
\begin{align*}
\text{O} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\end{align*}
\]

\[T_m = 255 ^\circ C\]
\[T_g = 78 ^\circ C\]

Teonex®
Polyethylene naphthalate (PEN)

\[
\begin{align*}
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\text{O} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\end{align*}
\]

\[T_m = 263 ^\circ C\]
\[T_g = 120 ^\circ C\]
Polyester Film Technology (2)

- **In-line Heat Stabilisation**
  - Film can relax in TD but not in MD
  - Leads to shrinkage on subsequent processing

- **Off-line Heat Stabilisation**
  - Allows relaxation in MD
  - Minimum shrinkage on both directions

- **Oven**
Heat-Stabilised PEN and PET Films

Upper temperature for processing

Shrinkage in MD after 30 min at 150 °C

Minimal shrinkage at temperatures > $T_g$

CTLE

20 ppm/°C

5 GPa

0.05%

180-220 °C

1 GPa

0.1%

150 °C

4 GPa

25 ppm/°C

120 °C

1 GPa

78 °C

0.7%

1000 ppm

0.7%

1000 ppm

1000 ppm

Moisture pick-up at 200 °C, 40% RH

Haze

Young’s Modulus at 20 °C

Young’s Modulus at 150 °C

Glass transition temperature

ST506 (PET)

Q65FA (PEN)
DTF Film range for Flexible Electronics

• Red denotes new
• Melinex® - A diverse range of heat stabilised PET films
  – Dimensionally stable up to 150°C
  – Thickness 50 micron to 250 micron
  – UV stabilised
  – Range of pretreats for enhanced adhesion to functional coatings
• Tetoron® - Low shrink, planarised PET films
  – Ultrasmooth defect free surface for improved device performance
• Teonex® - Leading range of high performance PEN films
  – Dimensionally stable up to 180-200°C
  – Thickness 25-200 micron
  – Pretreated for enhanced adhesion to functional coatings
  – White film at 75 micron
• Teonex® - Low shrink, planarised PEN films
  – High temperature performance with ultrasmooth defect free surface
  – 50 and 125 micron film
  – Protect film (one or two side) available
Where did it all start?

Foil - the boring bit that no one was taking seriously but the basic building block - essential to get it right!
And now

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

- Organic active matrix backplanes
- Inorganic active matrix backplanes
- OLED displays

Increasing complexity of substrate structure and more demanding property set

Combinations of high performance film eg PEN film and specialty coatings. Plastic film alone can't do it.

“Simple” organic circuitry

Paper, O-PP, PET

Factors Influencing Film Choice - Property Set
Physicalform/manufacturing Route

- Physical form of device and type of usage will influence film choice particularly with respect to thickness
  - Flat but exploiting light weight, ruggedness
  - Conformable, one time fit to uneven surface
  - Flexible
  - Rollable

- Batch, fast sheet and R2R processing

- End device manufacture batch based
  - Fits with existing s/c manufacturing tooling equipment
  - Used to give dimensional reproducibility
  - But brings a different set of technical challenges
    - Bowing
    - Release from carrier

- R2R used for specific steps (eg conductive, barrier etc)
Factors Influencing Film Choice-Substrate Properties

### Films grouped by thermal properties

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Semi-crystalline</th>
<th>Amorphous</th>
<th>Amorphous, solvent cast</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET</td>
<td>0</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>PEN</td>
<td>50</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>100</td>
<td>200</td>
<td>300</td>
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<td>Polyarylate</td>
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<td>225</td>
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<tr>
<td>Polyethersulphone</td>
<td>200</td>
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<td>Fluorene Polyester</td>
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<td>300</td>
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<tr>
<td>Polyester</td>
<td>300</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td>Polyimide</td>
<td>350</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

**Factors Influencing Film Choice**

- **Substrate Properties**

**“New” Plastic Substrates - A Personal View**

- The Holy Grail - water white, low CTE, low shrinkage, high temp stability (>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 Materials - A Personal View

• 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.
## Existing Materials - A Personal View

<table>
<thead>
<tr>
<th>Property</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biaxially oriented heat stabilised PET</td>
<td><img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Green" /></td>
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<tr>
<td>Biaxially oriented heat stabilised PEN</td>
<td><img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Green" /></td>
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<tr>
<td>Biaxially oriented PEEK</td>
<td><img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Green" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /> <img src="#" alt="Yellow" /></td>
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<td>Akron APS</td>
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<tr>
<td>Polyimide</td>
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</tr>
</tbody>
</table>

### CTE (-55 to 85 °C) ppm/°C
- **Green** = Present
- **Yellow** = Not Present

### %Transmission (400-700 nm)
- **Green** = Present
- **Red** = Not Present

### Water absorption %
- **Green** = Present
- **Red** = Not Present

### Young's modulus (Gpa)
- **Green** = Present
- **Yellow** = Not Present

### Tensile strength (Mpa)
- **Green** = Present
- **Yellow** = Not Present

### Solvent resistance
- **Green** = Present
- **Red** = Not Present

### Upper Operating Temp
- **Green** = Present

### Availability at commercial scale
- **Green** = Present

---

*Note: The chart above represents the materials and their properties with the following symbols:*
Example-excellent progress achieved by The Flexible Electronics and Display Center (FEDC) at Arizona State University, pushing Teonex® Q65FA to its processing limits in manufacturing inorganic active matrix backplanes

- With Henkel developed bond-debond system optimised for Teonex® Q65FA
- 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.
FEDC recent announcements

• FEDC and PARC-world's largest flexible X-ray detector prototype using advanced thin film transistors (TFTs). Measuring 7.9 diagonal inches, the TFT and PIN diode processing was carried out on the 470mm by 370 mm Gen II line at the FEDC.

• The Flexible Display Center (FDC) - successfully manufactured the world's largest flexible color organic light emitting display (OLED) prototype using advanced mixed oxide thin film transistors (TFTs). Measuring 7.4 diagonal inches.
• Two approaches to flexible TFT arrays

**Traditional TFT** *(high temp)*
- Familiar TFT array process

<table>
<thead>
<tr>
<th>TFT process</th>
<th>a-Si</th>
<th>LTPS</th>
<th>Oxide</th>
<th>OTFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature <em>(°C)</em></td>
<td>300</td>
<td>550</td>
<td>~300</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

**Organic TFT (low temp)**
- Emerging OTFT array process
- Standard engineering plastics
- High yield demount technology

OTFT enables low-processing manufacturing temperatures (80°) – benefiting yields:
- reduced distortion and substrate strain
- reduced bow to facilitate processing
- improved materials compatibility, including PET

Shrinkage leads to panel bow

Slide courtesy of Plastic Logic
Alternative Approaches

- Electronics on Plastic by Laser Release (EPLaR)
- Alternative approach- PI spin coated on to glass, fabricate TFT on glass then remove
- Technology developed by Philips, adopted by Prime View International
- TFT manufacture becomes independent of film used in manufacture of device

9.7” EPLaR display
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
    - Cost
10 years ago, focus on flexible OLED—we highlighted

- Flexible – but what does this mean?
- “Managed” dimensional and humidity stability
- Excellent optical properties
- Cleanliness – internal and external
- Surface topography
- $\text{O}_2$ and $\text{H}_2\text{O}$ barrier
- Robust to processing – TFT arrays, solder processes, processing chemicals, roll to roll processing
- Cost!
Key Substrate Properties Now

- Flexible, transparent, high barrier
  - 10 years ago for OLED probably the key substrate property
  - Water vapour transmission rates of $<10^{-6}$ g/m²/day and oxygen transmission rates of $<10^{-5}$ mL/m²/day
  - Significant progress with commercial products available - $10^{-3}$ g/m²/day
  - Higher performance barrier films under development
  - Challenge remains to get to desired barrier levels at acceptable price points

- Game Changers
  - R2R ALD
  - Atmospheric
  - Lamination
Key Substrate Properties Now

- Dimensional reproducibility (multi layer registration eg TFT)
  - Largely controlled by a combination of optimisation of film properties (low shrink), use of a rigid carrier and process technology that allows for dimensional change
  - Once a certain level of dimensional change is achieved, consistent dimensional reproducibility is more important than ever lower dimensional change
  - Demonstrated on DTF materials
  - Achieved via a combination of low shrink films, control of environment and control of process
Unstabilised PET vs. Heat Stabilised PEN: TD

non-subtracted data
Key Substrate Properties

- **Surface quality**
  - External debris rather than internal contamination is the real issue
  - Ra etc over small areas can be misleading. Need to look at surface analysis over display size area
  - DTFs planarised film options offer one route to smooth surface
Example of dust on surface of film

Film with planarising coating
Effectiveness of planariser

Effectiveness of Planariser on Intrisic Surface Roughness.

Total sampling area 5cm x 5 cm

Surface Peak Count

Surface Peak Height 'nm'

TEONEX Q65 'raw'

TEONEX Q65 'planarised'

PLANARISER EFFECT
Effectiveness of Planariser

A factor of 50 reduction in occupied surface area of peaks greater than 200nm in height for planarised PEN film compared to standard PEN film.

**Intrinsic Surface Defect rate Six Sigma DPMO 'ppm' for both 'raw' and 'planarised' Teonex® Q65**

![Graph showing the comparison between planarised and raw films with a 50% reduction in occupied surface area of peaks greater than 200nm in height for planarised PEN film compared to standard PEN film.](image-url)
Key Substrate Properties

- Perfection is not possible and not required, but
  - we need to understand which defects are critical
  - where they arise
  - and to target elimination of them
  - achievable target
  - rapid surface analysis remains an issue

- Two major EU Funded programmes 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 commercialisation
The Large Area Metrology ‘LAM’ tool - the first of its type.
- The tool delivers fast measurement of film surfaces (14x14”)
- High magnification measurements delivering close to absolute true surface peak heights and therefore analysis of slopes etc much more meaningful to device failure
- Able to distinguish between internal and external debris
Results 3, iii): Example of how DPMO value for a given height threshold is calculated.

(Defect area for a given height threshold as a fraction of total sample – measured area = DPMO (ppm)
WYKO – LAM surface analysis: Teonex Q65FA, (non pretreated, ‘raw surface’) 200µm gauge ex Roll No. 8LN03303.

Summarising the films surface quality w.r.t Intrinsic defect propensity

**Intrinsic defects in terms of DPMO (ppm) > given height threshold (nm)**

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

• The Large Area Metrology ‘LAM’ tool - the first of its type.
  – The tool delivers fast measurement of film surfaces (14x14”)
  – High magnification measurements delivering close to absolute true surface peak heights and therefore analysis of slopes etc much more meaningful to device failure
  – Able to distinguish between internal and external debris

• Used to identify defects critical to device manufacture, determine impact of the different process steps on debris generation and effectiveness of removal strategies

• Used with project partner (Plastic Logic) to identify defects with potential to cause shorts etc and attempt to work back through film handling to identify where defect was introduced
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
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
HiQSurf - Protecting/Cleaning Surface - Strategies

• Protect films protect surface
  – but protect films must be clean and mustn't 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.
• Considerable scope to provide film fit for purpose

• Adopting and exploiting strategies have taken Plastic Logic to the point where they are achieving yields on PET similar to yields achieved on glass

• For DTF an ongoing story-Clean4Yield

• Cleaning/handling regimes are specific to a given process and need careful consideration
“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

```
A = peelable layer

AB

B = PET

ABA
```
"On-Demand" Clean Film

- Require 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

<table>
<thead>
<tr>
<th>PEELABLE POLYMER</th>
<th>SURFACE IMAGE OF PET after peel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer A</td>
<td></td>
</tr>
<tr>
<td>Polymer B</td>
<td></td>
</tr>
<tr>
<td>Polymer C</td>
<td></td>
</tr>
<tr>
<td>Polymer D</td>
<td></td>
</tr>
</tbody>
</table>

- Examples in table show how different polymers can impact on above
Impact of “On-Demand” Clean Film on Barrier

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

Results courtesy of Dr. Sandeep Unnikrishnan, TNO-Holst Centre
Ca-Test Graph

- Results expressed as water required to degrade the thickness of calcium in the sample
- Barrier on “On-Demand” Clean film outperforms barrier on “standard” PET

Results courtesy of Dr. Sandeep Unnikrishnan, TNO-Holst Centre
Adhesive Coated Film

- Most TFT processing is still carried out on a rigid carrier.
- Film needs to adhere to carrier during processing but should be easily detached at end of processing without:
  - Damaging TFT array
  - Remaining on TFT array
Adhesive Coated Film

- DTF have the capability to develop adhesive coated films to meet these requirement
  - Switchable at room temperature
  - Peel strength (“post-it” note type peel strength)
  - Remains on carrier and can be removed allowing reuse of carrier

- Available as development quantity rolls (contact DTF for more information)
Films for Touchscreen

- Rapid Touch Screen Market growth
- Requires continued optimization for PET

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
Films for Touchscreen

- Projected Capacitive Touch is the primary driver for growth
  - Many designs use PET film as the transparent conductor substrate
  - 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
Polyhedral or hexagonal platelike oligomer crystals form, a few microns in size
Soluble in solvents (e.g. MEK)
Cyclic trimer Tm 318°C present at ca 1.1 to 1.4wt%

Other cyclics present but in lower amounts. Trimer is low strain relative to other cyclics.
Traditional Strategy

- Traditional strategy used is to coat the surface with a coating that acts as a barrier to oligomers migrating to surface

- ITO blocks to an extent but blooming becomes more of an issue with other approaches to conductive films eg printed silver grids etc
- Presence of planarising coatings significantly reduces bloom
- Coatings acting as a barrier

Non planarised PET: 30mins / 120 C
Planarised PET: 30mins / 120 C
New Developments

- Inherently low bloom film has been developed
- New development grade, 1% haze on ageing at 150°C /30 mins
- Now in qualification with customers
- Able to tailor with respect to surface treatments for specific applications
- DTF is investigating further strategies to minimise the impact of blooming on subsequent processing
• Controlling refraction and reflection effects in optical stacks
An example: Reduced iridescence in hard coats

• 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

• Through optical modelling we can model the effect and design the stack to minimize fringing
  – Monitor the effect of changing specific layer parameters, e.g. refractive index and thickness
  – Look for ‘fringing’ in visible spectrum as an indication of rainbow effect
Modeling the transmission spectrum shows the fringing effect.

Substrate refractive index is cycled between 1.67 and 1.51 to show effect on fringing (right). Fringing occurs at higher RI values.

**Hard Coat (RI=1.5)**

**Substrate (RI varied)**
In the real world, it’s a bit more complex

<table>
<thead>
<tr>
<th>Layer</th>
<th>Refractive Index</th>
</tr>
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<tbody>
<tr>
<td>Hard Coat (RI=1.5)</td>
<td></td>
</tr>
<tr>
<td>Adhesion Primer (RI = X)</td>
<td></td>
</tr>
<tr>
<td>PET Film (RI=1.67)</td>
<td></td>
</tr>
</tbody>
</table>

Note: most top layers require an adhesion priming layer

- Manipulation and control of the adhesion primer can optically bridge the gap from substrate to top layer
DTF primer technology can reduce hard coat fringing

Transmission spectra of new trial films + hardcoat, compared to standard film control

ACTUAL DATA
Visual proof of the new film’s effect

New Product

Standard PET

Competitor X

Competitor Y

Each sample is hard coated PET and photographed under a monochromatic light source.

Low bloom films with RI matched coatings—contact Scott Gordon (scott.e.gordon@dupont.com).
LIGHT OUTCOUPLING FILMS

- DTF have developed a range of volume scattering films which when applied as an overlaminate to a **rigid glass OLED**, will outcouple light trapped in the “glass” of the structure.
- Outcoupling efficiency (emission enhancement) shown to be dependent on lamp design.
- Best cases: enhancement close to that of microlens array systems (MLAF) but also
- Stable Colour Point as function of viewing angle
- Additional benefits from DTF toolbox surface modification (hardcoats, surface texture, offstate appearance)

Near Lambertian Emission, colour point constant over similar viewing angle range. 

Data courtesy of Holst Centre TIP1 Programme
Flexible OLED lamps are typically built on polymeric substrates:
- Additional outcoupling functions “built-in” to polyester substrate
- Sheet to sheet fabrication processes are routinely performed on PEN film and adhesive precoated PEN film
- Roll to Roll processes will also use polyester film, with integrated outcoupling function
- European funded FP7 programme “FLEX-o-FAB” 2012-2015;
- DTF is combining its experience in optical outcoupling and clean substrate technology with other participants to develop a cost-effective R2R process route to flexible OLED lighting on PET film.
Reflective Film - Melinex® RFL

- 97% diffuse reflectance
- Primarily used as reflector in LCD backlit units
- Available in 150 micron
- Excellent whiteness
- High area yield

### Optical Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Test Method</th>
</tr>
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<tbody>
<tr>
<td>Diffuse reflectance @ 550nm</td>
<td>97.5%</td>
<td>%</td>
<td>ASTM E1175-87</td>
</tr>
<tr>
<td>Gloss 65 degrees</td>
<td>50</td>
<td></td>
<td>ASTM D1003</td>
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<tr>
<td>Total Light Transmission</td>
<td>2.5%</td>
<td>%</td>
<td>ASTM D1003</td>
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<tr>
<td>Whiteness</td>
<td>110</td>
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<td>ASTM E313-79</td>
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### Physical Properties

<table>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>Density</td>
<td>1.25 g/cc</td>
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</tr>
<tr>
<td>Tensile Strength MD</td>
<td>11,500 PSI</td>
<td></td>
<td>ASTM D882A</td>
</tr>
<tr>
<td>Tensile Strength TD</td>
<td>12,500 PSI</td>
<td></td>
<td>ASTM D882A</td>
</tr>
<tr>
<td>Elongation at break MD</td>
<td>80%</td>
<td></td>
<td>ASTM D882A</td>
</tr>
<tr>
<td>Elongation at break TD</td>
<td>65%</td>
<td></td>
<td>ASTM D882A</td>
</tr>
</tbody>
</table>

### Thermal Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage MD (120°C/30min)</td>
<td>1.7%</td>
<td>%</td>
<td>Unstrained 120°C/30min</td>
</tr>
<tr>
<td>Shrinkage TD (120°C/30min)</td>
<td>1.2%</td>
<td>%</td>
<td>Unstrained 120°C/30min</td>
</tr>
</tbody>
</table>
Anatomy of a PV Module

- PV cell
- PV module with connections
- Anatomy of a module
Substrates for PV Cells – Gen. 2 & 3

Gen I
- c-Si

Gen II
- CdTe
- CIGS
- a-Si
- DSSC
- OPV

Gen III

Thin Films

Encapsulation

Encapsulation / Cell

A complex film development agenda!!
Functionalities

- Dimensional Stability
- Surface Quality
- Barrier
- Heat Stability
- Weatherability
- Conductivity
- Light Management
- Adhesion
Mechanism

- **Degradation mode**
  - PET film photodegradation is confined at the surface (microcracks)
  - Crack nucleation propagates into the relatively, intact underlying material leading to a catastrophic failure

- **Degradation mechanism**
  - Photodegradation of PET films reported to be $O_2$-dependent: proceeding at a significant rate on the surface facing the UV source, at a decreased rate on the rear surface, and at a negligible rate inside
  - UV light is filtered through the film
Photooxidation-Colour

First step is peroxidation on DEG unit

See
1. Edge M et al, Polymer, 36, 227, 1995
2. Edge M et al, Polym Deg and Stab, 53, 141, 1996
Photooxidation-Colour Continued

Further oxidation

Thermal degradation leading to fragmentation

Heat leads to further conjugation/more species

more intense colour
Photooxidation Chain Breakdown

Chain fragmentation
Lower mol wt
Embrittlement
Upon UV light-induced degradation:

- **Yellowness increases**
  - formation of new light-absorbing chemical species
- **Haze increases (clear films)**
  - bulk + surface scattering
- **Gloss decreases**
  - surface roughens
- **Light transmittance decreases**
  - more absorption and scattering
- **Mechanical properties i.e. %ETB, UTS decrease**
  - chains break down
Weatherability – UV Resistance

• Lifetime perception: “Polyester films degrade rapidly under UV light exposure” → In reality, only non-UV stabilised films will!

• Polyester films can be modified to have improved resistance to UV light

• Typical results from Weather-Ometer® ageing of a DTF UV stabilised film
  1) Mechanical properties:

Method: ASTM 4892-2
Weatherability – UV Resistance

• Typical results from Weather-Ometer® ageing of a DTF UV stabilised film

  2) Optical properties:

  - % Retention of Light Transmittance
  - % Increase of Yellowness Index

• 10,000 hours in Weather-Ometer® – Equivalent irradiation = 5 (Florida) to 11 years (Northern Europe)
  This is not a lifetime guarantee
Hydrolysis of PET

NB Chain breaking only - no colour formation
Strategies for Improving Hydrolysis Resistance

- Raising Mol Wt of film
- Control of crystallinity through film process control
- Control of polymer chemistry
Weatherability – Hydrolysis Resistance

• Lifetime perception: “Polyester films hydrolyse rapidly”
  → This is very slow under normal atmospheric (T,P) conditions!

• Polyester films can be modified to pass the standard “Damp Heat” test –
  Retention of 10% ETB after 1000 h at 85 °C / 85% RH

• Some industry interest in higher performance PET films for extended testing times (2000+ hours in Damp Heat test)

→ DTF's filled Melinex® 238
  at 50 µm reaches 2000 h at
  85 °C / 85% RH
→ DTF can also apply this technology to optically clear films
• DHT approaching 4000 hours
Weatherable Films

• DTF through control of film process, chemistry and structure continues to further increase the lifetime of polyester films to photodegradation and hydrolysis
Key Project Objectives:

- Printed OPV with high efficiency architectures such as tandem cells and dedicated light management structures
- High performance photo active and passive (barrier) materials including process controlled morphology
- Solutions for cost effective flexible substrates, diffusion barriers and conductors
- Deep understanding of the device physics, elucidation of degradation mechanisms and estimate of the environmental impact of the main materials and processes

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http://sunflower-fp7.eu/
Trends in substrate industry

- Thinner
- Conformable
- Pressure on cost
- Barrier structures based on lamination-a route to low cost barrier?
- Glass /plastic hybrids?
- Light efficiency
- Multiple applications but a shared set of needs
  - Convergence of film requirements
- More focus on commercially available films as industry matures
- High temperature? Organic low temp vs inorganic high temp
- Weatherable films-UV and hydrolysis resistance
Conclusion

• The understanding of film requirement for flexible device application has moved a long way over the last decade
• DTF has demonstrated commitment to the flexible device community
• DTF continues to innovate to address the needs of the end users to provide a tailored film product
• Polyester film is being used in a much broader range of applications than originally envisaged

Touch Devices

(Emerging) Flexible Devices
Image courtesy of FDC