Encapsulation of Organic Photonic Elements

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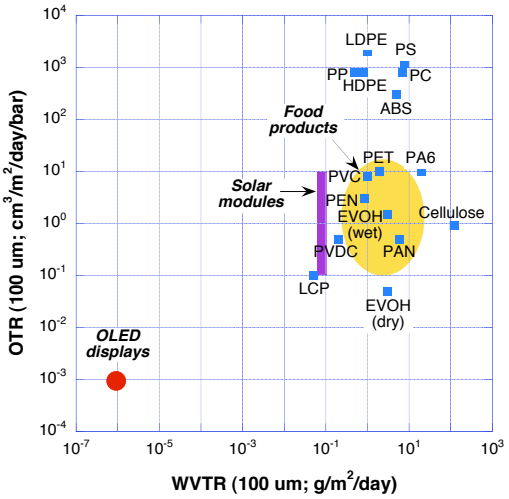
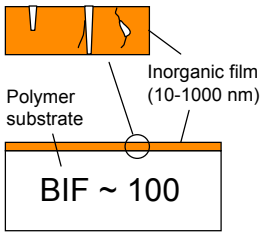
Polymers are (too) permeable

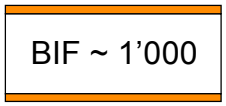


Crank & Park, 'Diffusion in polymers' Academic Press (1968)
Chatam, Surf. Coat. Technol. (1996)
Pauly, in 'Polymer Handbook' Wiley (1999)

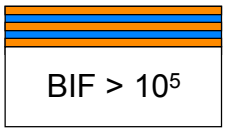
High-Barrier Strategies

Barrier Improvement Factor: BIF = P_s/P



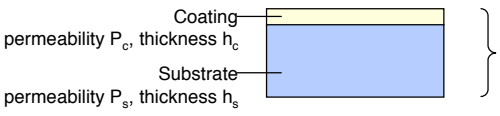


nanolaminates

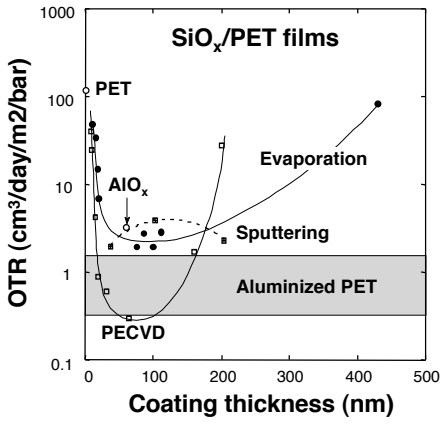


Organic-inorganic hybrids

Nanosized inorganic coatings/polymer composites

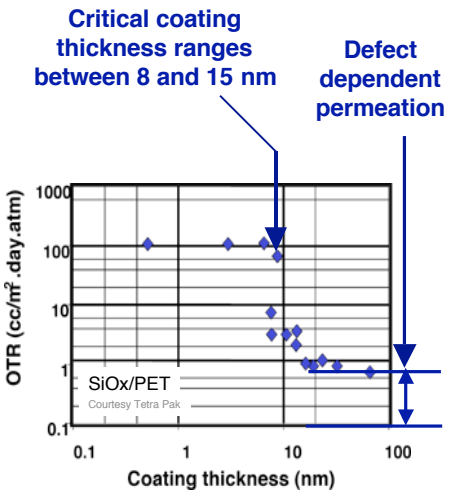


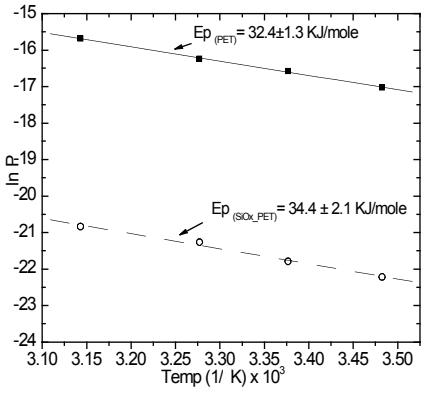
$$\frac{h}{P} = \frac{h_c}{P_c} + \frac{h_s}{P_s}$$



Leterrier, Prog. Mater. Sci (2003)

Defects in vapor-deposited inorganic films on polymers

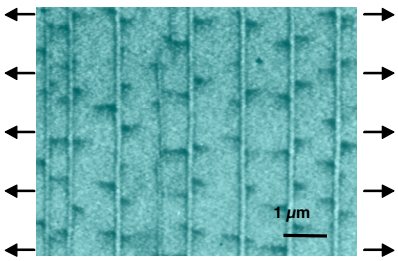


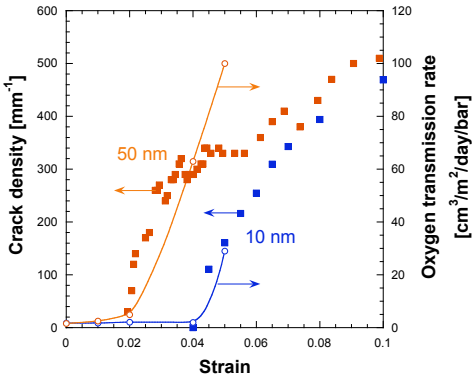


Roberts et al., J. Membrane Sci. (2002)
Rochat, Leterrier, Månson, Fayet, Surf. Coat Technol. (2003, 2006)

Effect of coating defects on failure of barrier

10 nm SiO_x on PET @ 10% strain

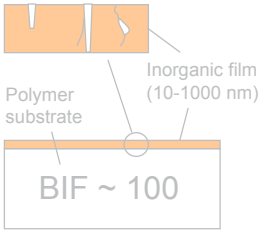




Rochat, Leterrier et al., J. Appl. Phys. (2003)
Singh, Leterrier, Månson, Fayet, Surf. Coat. Technol. (2007)

High-Barrier Strategies

Barrier Improvement Factor: BIF = P_s/P



BIF ~ 100

BIF ~ 1'000

nanolaminates

BIF > 10^5

Organic-inorganic hybrids

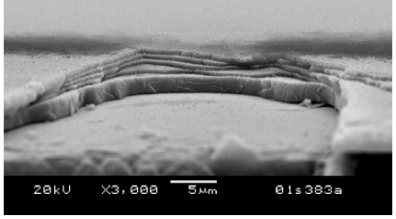
BIF ?

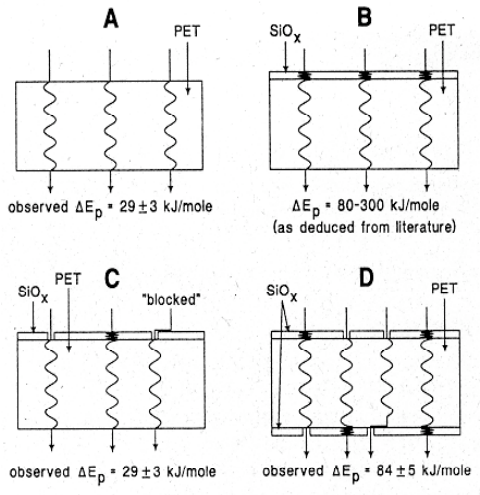
Why nanolaminate structures?

Nanolaminates decouple defect structure

BIF > 10^5

WVTR (20°C) ~ 2·10^{-6} g/m^2/day
(Vitex Systems, CA)

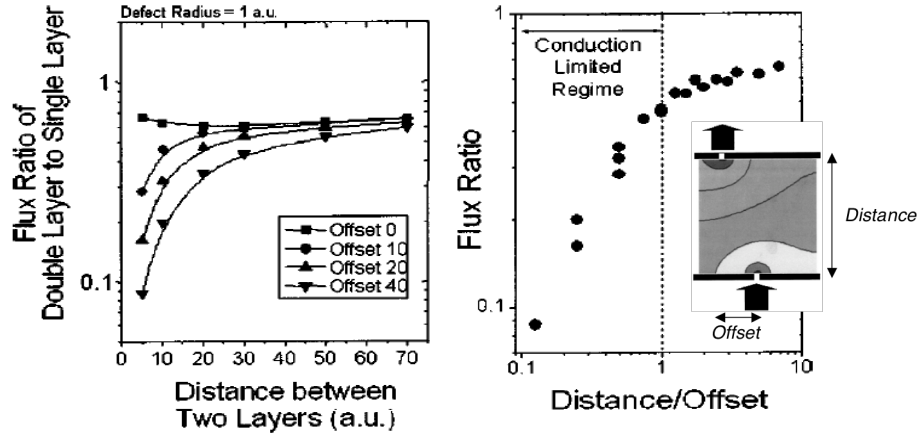




Trophsa & Harvey, J. Phys. Chem. B (1997)

Modeling of gas transport

Barrier improvement obtained when adding a second inorganic layer



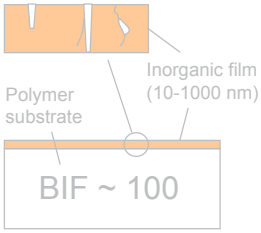
Trophsa & Harvey, J. Phys. Chem. B (1997)
Schaepkens et al., J. Vac. Sci. Technol (2004)

Nanolaminate encapsulation

Producer	Encapsulation Structure	Number of layers	W V T R (g.m^{-2}.day)	Crack Onset Strain (%)
Vitex (Barix)	$[acrylate/Al_2O_3]_n$	10	~ 1×10^{-6}	0.8
Philips (NONON)	$[SiN_x/SiO_x]_n$	'12' + topcoat	3.6×10^{-6}	1.0
GE (graded UHB)	$[SiN_x/SiO_x]_n$	'5'	8.6×10^{-6}	-
Applied Materials	$(SiN/lacquer)_2$	4	~ 1×10^{-5}	1.0

High-Barrier Strategies

Barrier Improvement Factor: BIF = P_s/P



BIF ~ 100

BIF ~ 1'000

nanolaminates

BIF > 10^5

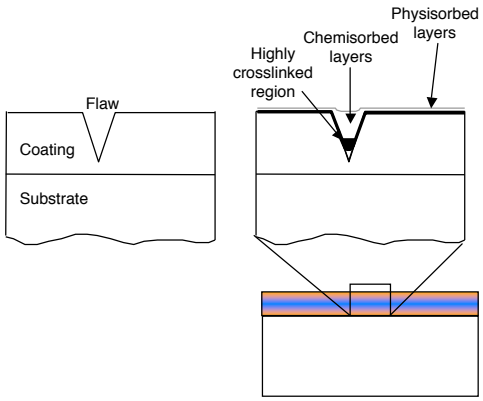
Organic-inorganic hybrids

BIF ?

Why organic-inorganic hybrids?

Organo-silanes reduce the severity of superficial defects ('Griffith flaws')

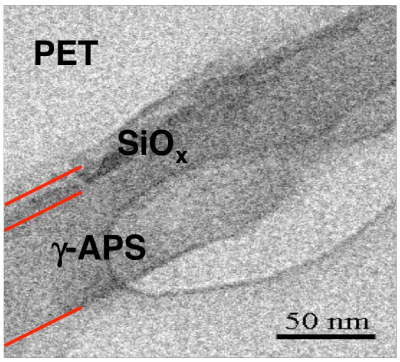
R—Si—(OR')$_3$



Pluddemann, Silane Coupling Agents, Plenum Press (1990)
Zinck et al., J. Mater. Sci. (1999).
Haas et al., Surf. Coat. Technol. (1999)
Bouchet et al., Surf. Coat Technol. (2005)

Processing of organosilane-silica hybrids

SiO_x 12 nm PECVD from O_2 diluted HMDSO on 12 μm thick PET web
OTR ~ 2.1 $cm^3/m^2/day/bar$
COS ~ 3.5%



NH_2 ⟋⟍ $Si(OC_2H_5)_3$

Gamma-aminopropyltriethoxysilane (γ-APS, Silquest A-1100™)

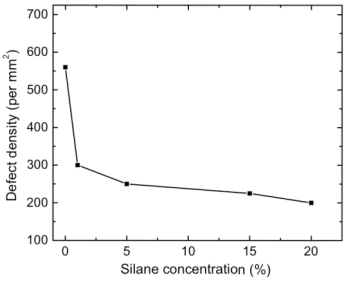
1 - 20 %wt γ-APS/ethanol
pH=11.4 and pH=8 (acetic acid)

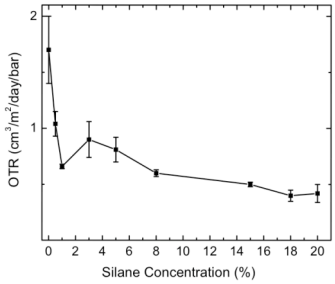
Spin coating on SiO_x/PET films
1000 rpm, 20 s

oligomerization: 12 h at 60°C
10 - 500 nm thick silane films

Magni et al, *J. Phys. D (2001)*
Bouchet, Leterrier et al., Surf. Coat. Technol. (2005, 2007)

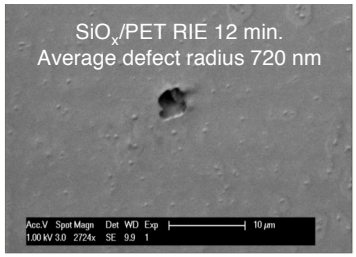
Defect analysis in organosilane-silica hybrids

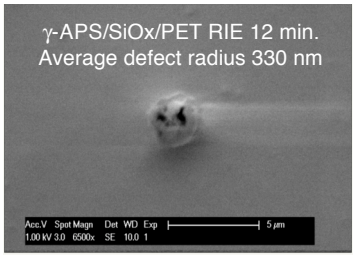




Singh, Leterrier et al., Surf. Coat. Technol. (2007)

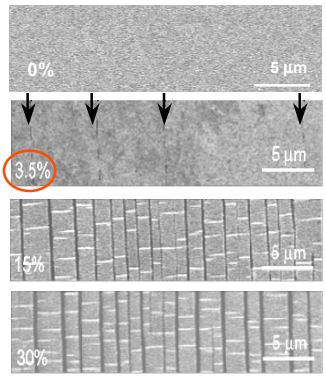
Amino-silane treatment reduces the size and population of macro-defects





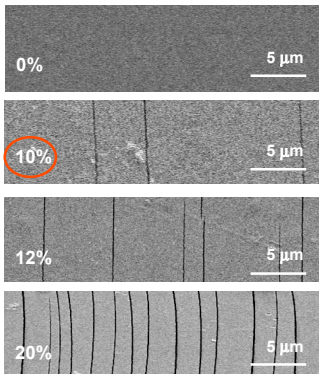
Mechanical integrity of organosilane-silica hybrids

10 nm SiO_x/PET reference



Crack onset strain 3.5%

γ-APS/SiO_x/PET

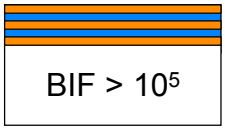


Crack onset strain > 6%

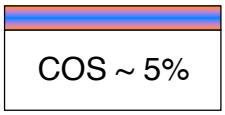
Rochat et al. *Thin Solid Films* (2003)

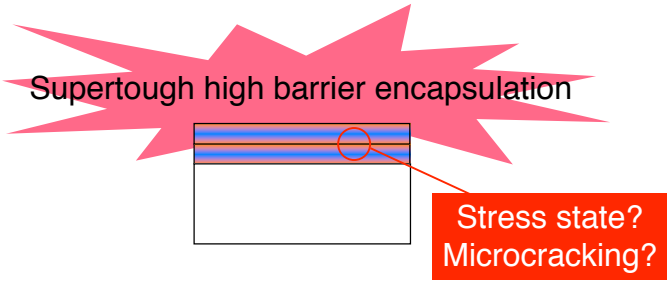
Supertough high barrier encapsulation

nanolaminates

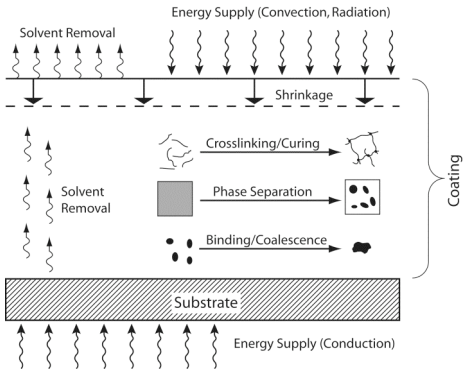


Organic-inorganic hybrids





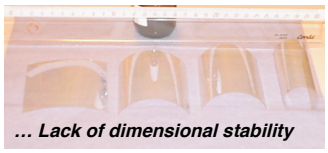
Origin of stress in polymer coatings



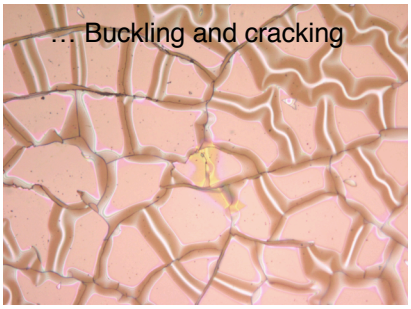
$$\sigma(t) = 2\int_0^t G(t)\frac{\partial c}{\partial t}dt + 2\int_{T_c}^{T_f} G(\alpha_s + \frac{\partial c}{\partial T})dT$$

Cure shrinkage stress

Thermal stress *(small for UV-curable polymers)*



… Lack of dimensional stability



… Buckling and cracking

Lange, Månson et al., Polymer (1995, 1997); Payne (1998)

Towards low stress encapsulation

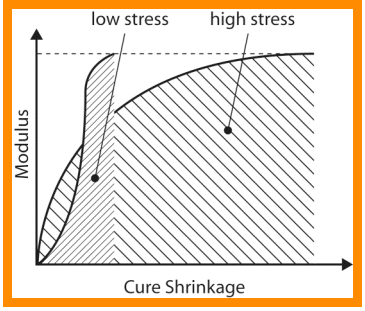
- Tailored process temperature cycles
- 'Low profile' additives
- Radiation curing

…

- Hyperbranched polymers

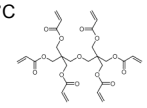
A low-stress material combines:

- **reduced shrinkage**
  ⇒ radiation curing
- **retarded modulus build-up**
  ⇒ hyperbranched polymers

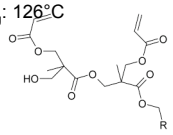


Low Stress UV Curable Hyperbranched Polymer Nanocomposites

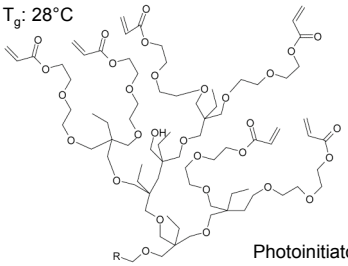
a) Di-Pentaerythritol Hexaacrylate (DPHA)
T_g: 68°C



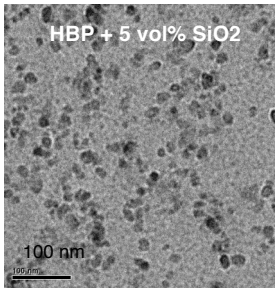
b) Segment of Acrylated Boltorn H20
T_g: 126°C

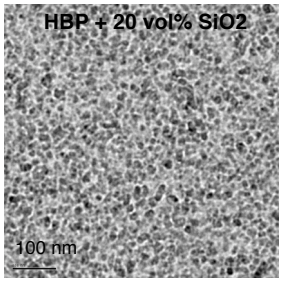


c) Segment of Acrylated Polyether HBP
T_g: 28°C



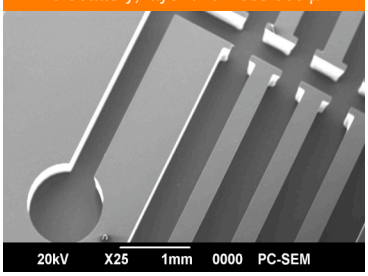
Photoinitiators:
1-Hydroxy-cyclohexyl-phenyl-ketone
1:1 blend of 1-Hydroxy-cyclohexyl-phenyl-ketone and benzophenone



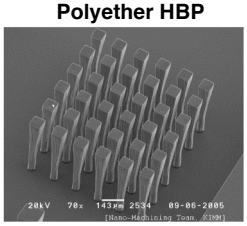


Low Stress UV Curable Hyperbranched Polymer Nanocomposites

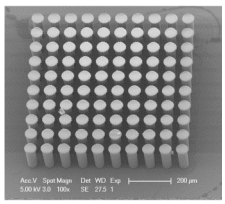
Microbattery, layer thickness 500 µm



Polyether HBP



SU8



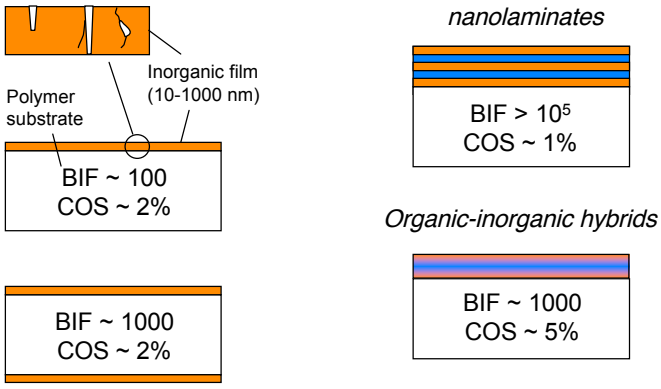
FOM = (L x AR) / (Stress x Fab_Time)

Resist	Layer thickness, L (µm)	Aspect ratio, AR	Residual stress (MPa)	Fabrication time (h)	FOM
Polyether HBP	850	7.7	2.4	0.5	5454
Polyester HBP	500	3.3	4.5	0.5	733
SU-8	250	11	25	3	37

Jin Y.-H., J. Micromech. Microeng., **17**, 1147-1153 (2007).
Schmidt et al., J. Micromech. Microeng. **18**, 045022 (2008).

High-Barrier Strategies

Barrier Improvement Factor: BIF = P_s/P



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