Solar Thermal Absorber Coatings

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- Ongoing development of Thermal Absorber Coating for elevated temperatures
  - Process stability
  - Testing procedure

Outline

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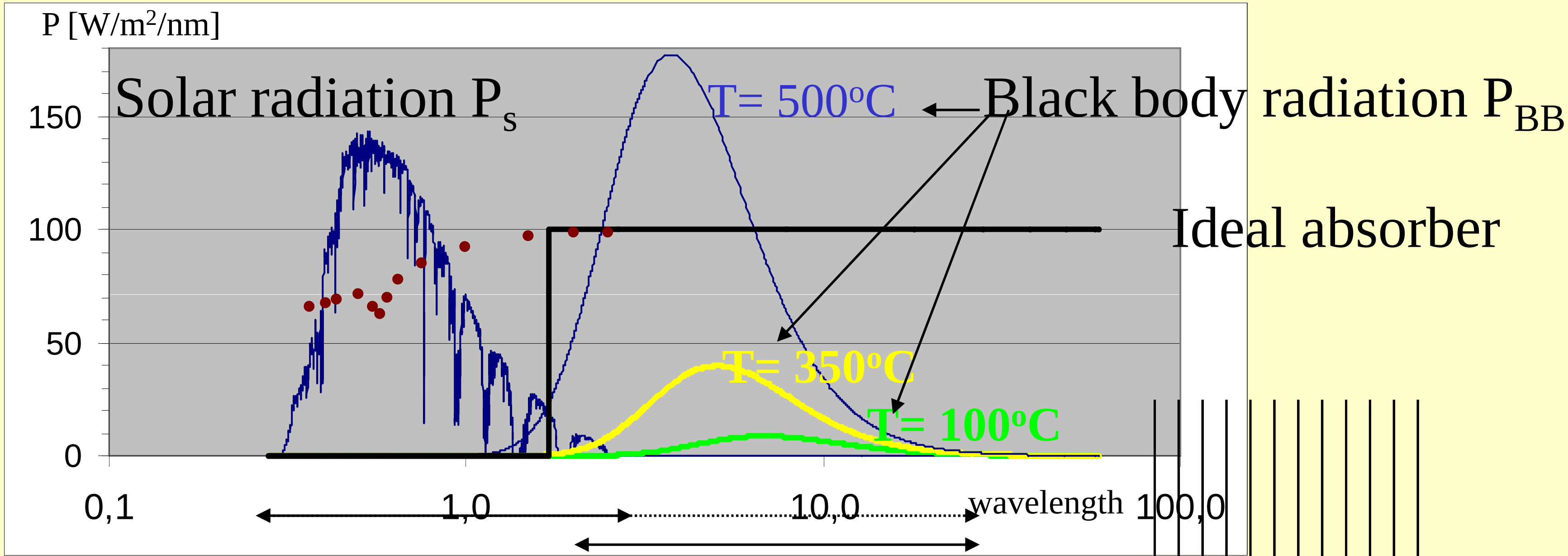
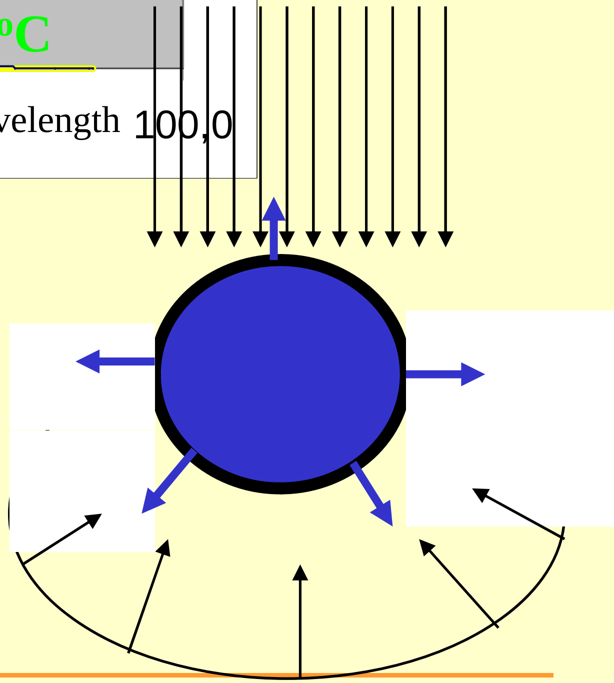
1. Coating properties
2. Existing solutions
    1. Paint
    2. Electrochemical black Cr /Ni
    3. **PVD / PECVD multlilayered coating**
3. Coating development
    1. Process stability
4. Thermal Testing
    1. Degradation mechanism
    2. Flat panel collector
    3. Vacuum tube collector
5. Summary

Goal for coating properties (1)



Optical (reflection) measurements

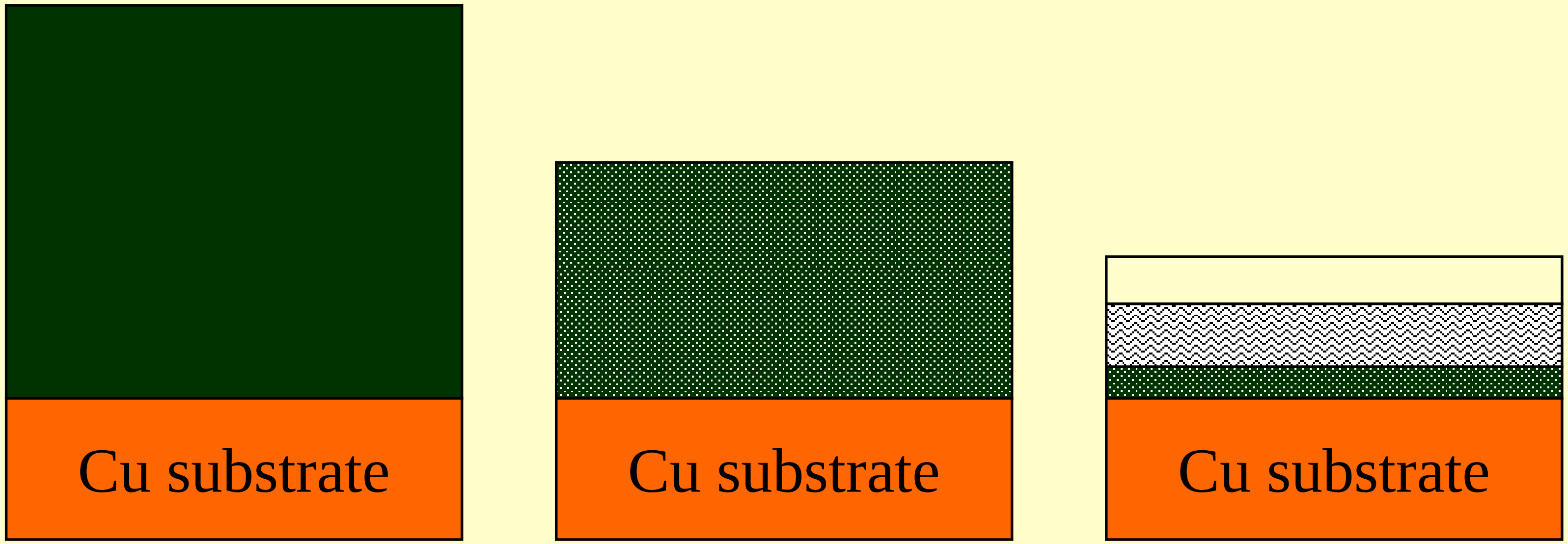
Global emission at working temprature (emissometer)



$$\alpha = \int a(\lambda) p_S(\lambda) d\lambda$$

$$\varepsilon = \int a(\lambda) p_{BB}(\lambda) d\lambda$$

Coating solution (s)



Black paint	Black Cr and Ni (electrochemical)	multi layer (PVD, PECVD)
α= 50 %...93 %	85...95 %	> 95%
ε = 40..80 %	12 %	< 5%

Thermal emission during application

Lisbon: P_s = 2200 kwH / y / m2

Net absorption: P = Pα – Pε

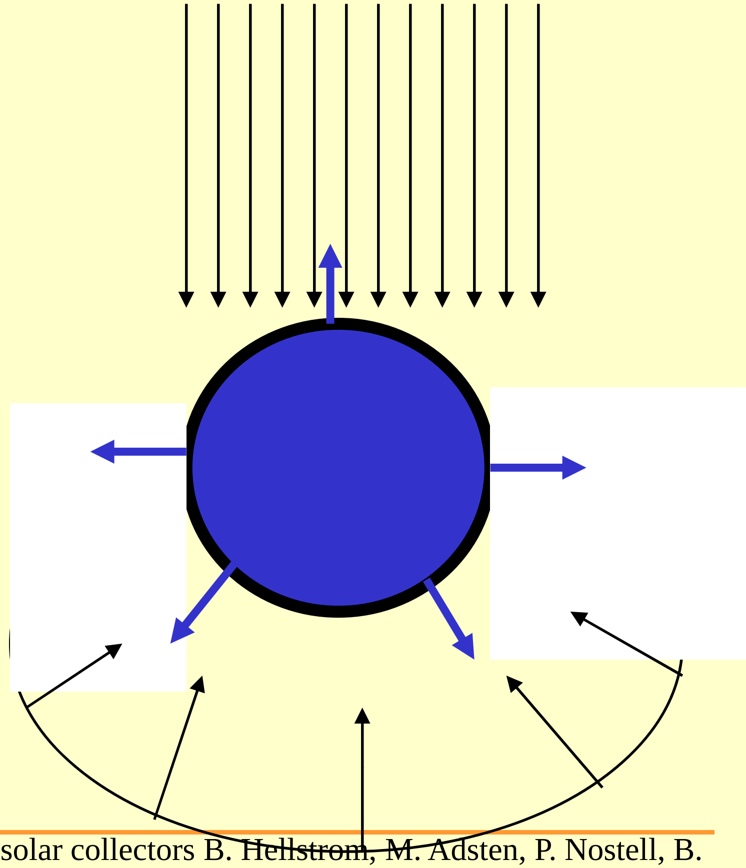
$ = 0.1 € / KwH

α = 0.95

ε= 0.07….0.05

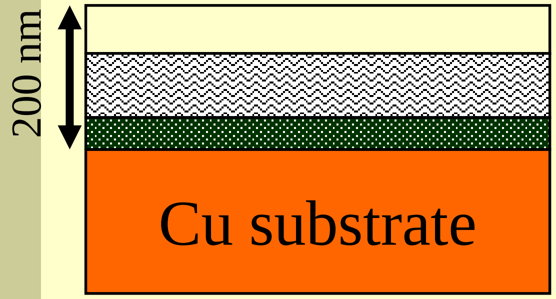
Pe = 98 KWh …70 Kwh

ΔP = 3 € /y



The impact of optical and thermal properties on the performance of flat plate solar collectors B. Hellstrom, M. Adsten, P. Nostell, B. Karlsson, E. Wackelgard, Renewable Energy 28 (2003) 331–344

PVD coating solution (s)



multi-layer PVD

layer3	SiO_x	Si_3N_4	a-C:H	Al_2O_3	SnO_2:F
layer2	TiN_xO_y	$TiAlN_xO_y$	a-C:H/Cr	Al	Cr_xO_y
layer1	TiN (1)	TiAlN (2)	CrC (3)	Al_2O_3 (4)	CrN_xO_y (5)
Diff. barrier	TiC				??
α	**95%**	**96 %**	**91...95%**	**90%**	**95%**
ε	**5 %**	**7 %**	**9....5%**	**6 %**	**4...5%**

(1) http://www.tinox.com/

(2) US20070196670 H.C. Barshilia et.al.

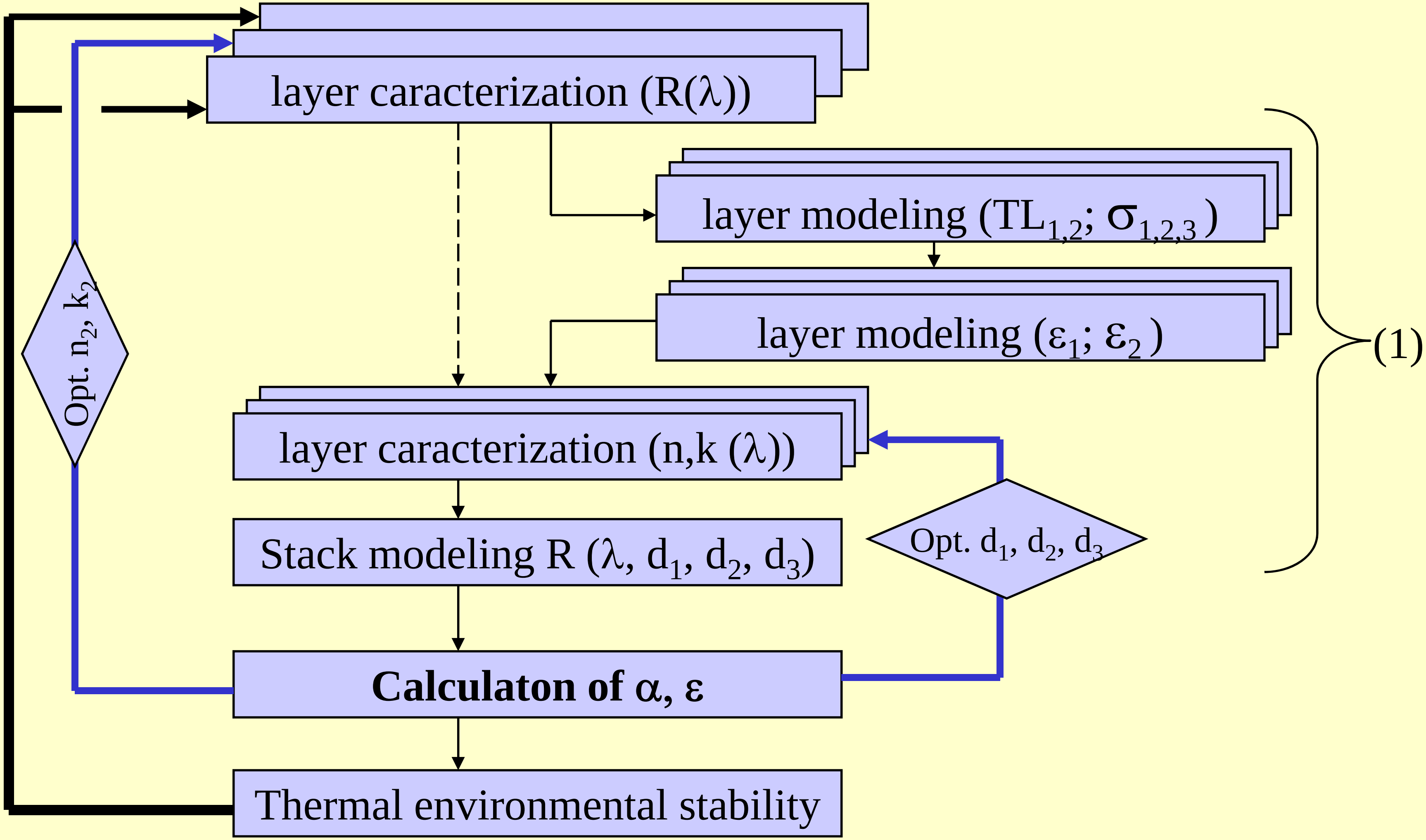
(3) Von Ardenne http://www.ese.iitb.ac.in/activities/ ; Accelerated aging tests of chromium containing amorphous hydrogenated carbon coatings for solar collectors Solar Energy Materials and Solar Cells 54 (1998) 369Ð377R. Gampp P. Oelhafen, P. Gantenbein, S. Brunold, U. Frei

(4) Optical properties and thermal stability of pulsed-sputter-deposited Al_xO_y/Al/Al_xO_y multilayer absorber coatings; Solar Energy Materials and Solar Cells, Volume 93, Issue 3, March 2009, Pages 315-323 H C. Barshilia, Net.al

(5) Von Ardenne http://www.ese.iitb.ac.in/activities/ ;

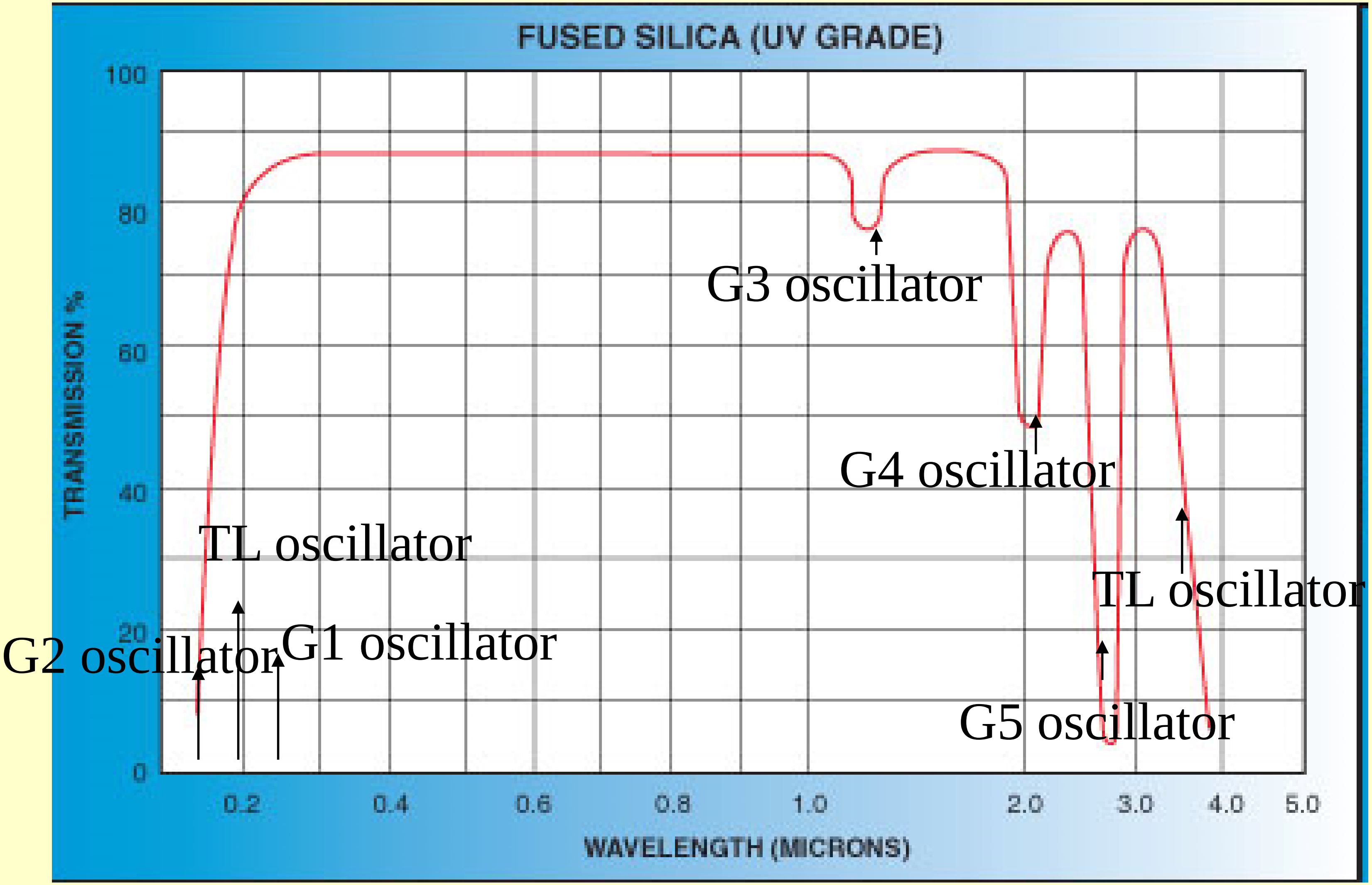
(6) www.alanod-solar.com , www.bluetec-germany.com

Coating Development

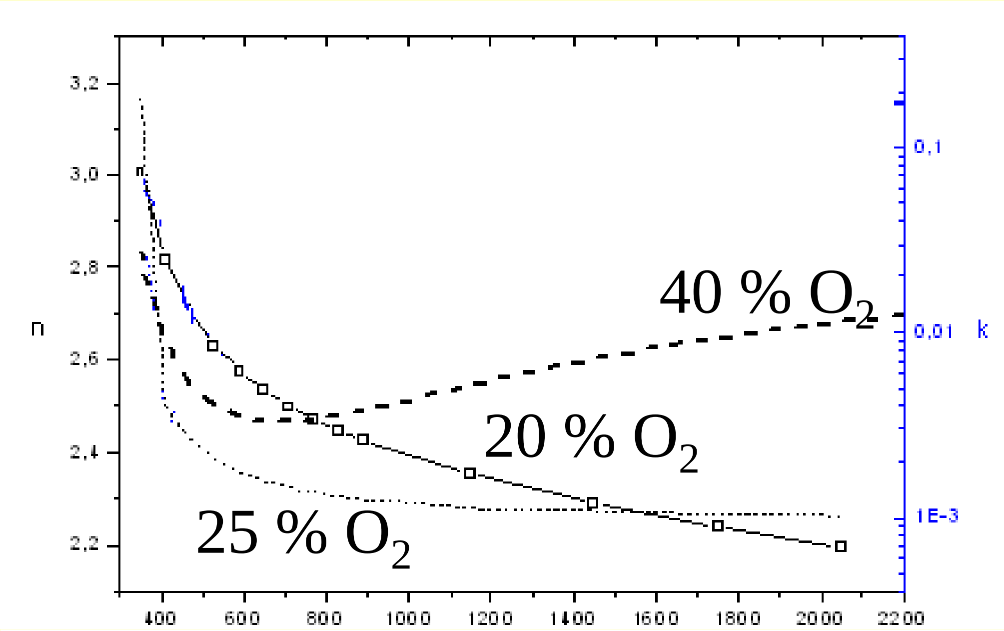


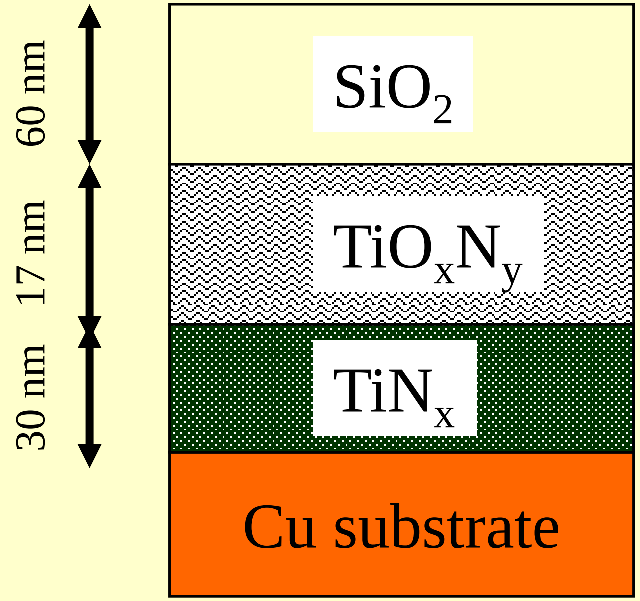
(1) JOURNAL OF APPLIED PHYSICS **106**, 073110 2009, E. Malainho, M. I. Vasilevskiy, P. Alpuim, and S. A. Filonovich

Optical Development (1)



Coating Development (1): TiO_xN_Y composition





multi-layer PVD

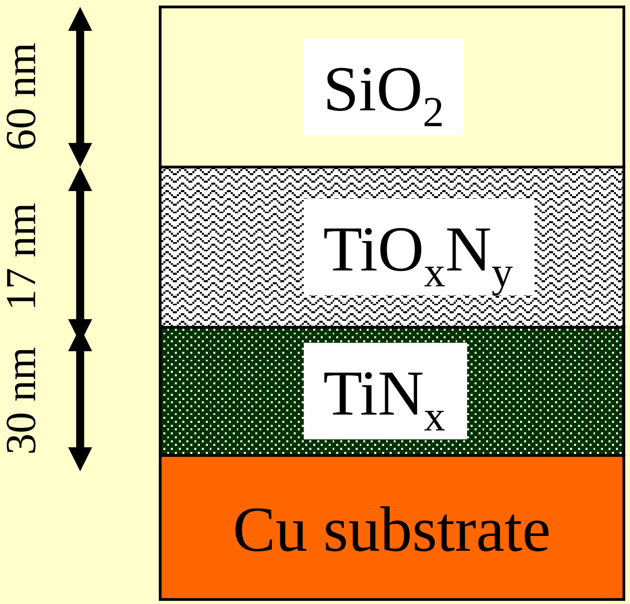
$$Ti + a\ N_2 + b\ O_2 \rightarrow TiO_xN_y$$

N_2 flow constant

O_2 quantity controlled by plasma emission PE

PE_{O_2}	n_{500nm}		α	ε
20 %	2.7		94 %	6 %
25 % →	**2.4**		**93 %**	**7 %**

Coating Development (2)



multi-layer PVD

Oxide layer thickness

d_1	d_2	d_3	α	ε
30	17	60	94 %	6 %
30	17	**50** →	89 %	**7 %**

TiN_x composition

$Ti + a\ N_2 \rightarrow TiN_x$

PE_{N_2}	n		α	ε
90 %	3.1		94 %	6 %
80 % →	2.8	→	86 %	7 %

N_2 quantity controlled by plasma emission PE

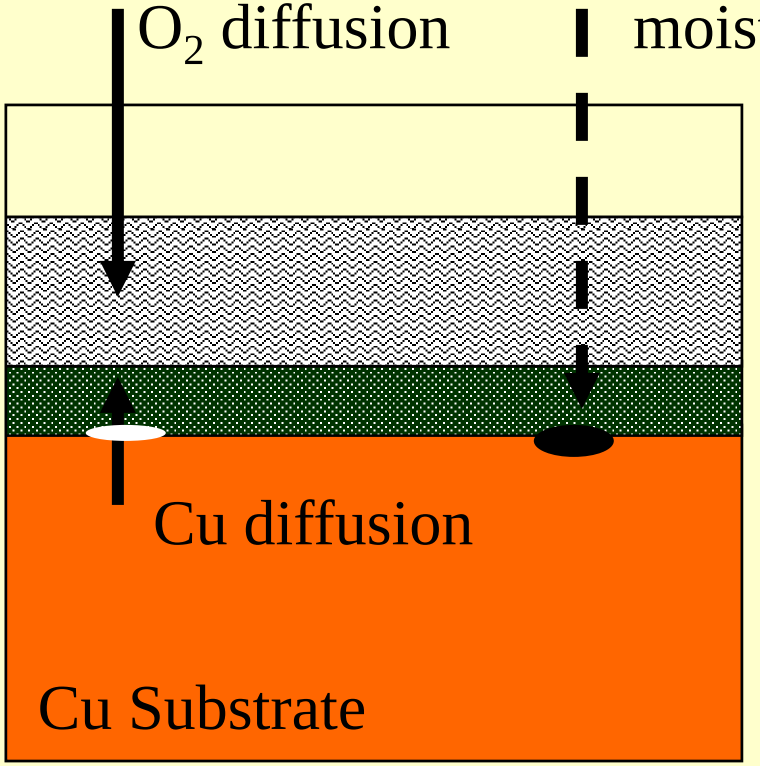
Degradation mechanism

Long term stability at operation temperature:

PC =
$-\Delta\alpha + 0.25\,\Delta\varepsilon < 0.05$

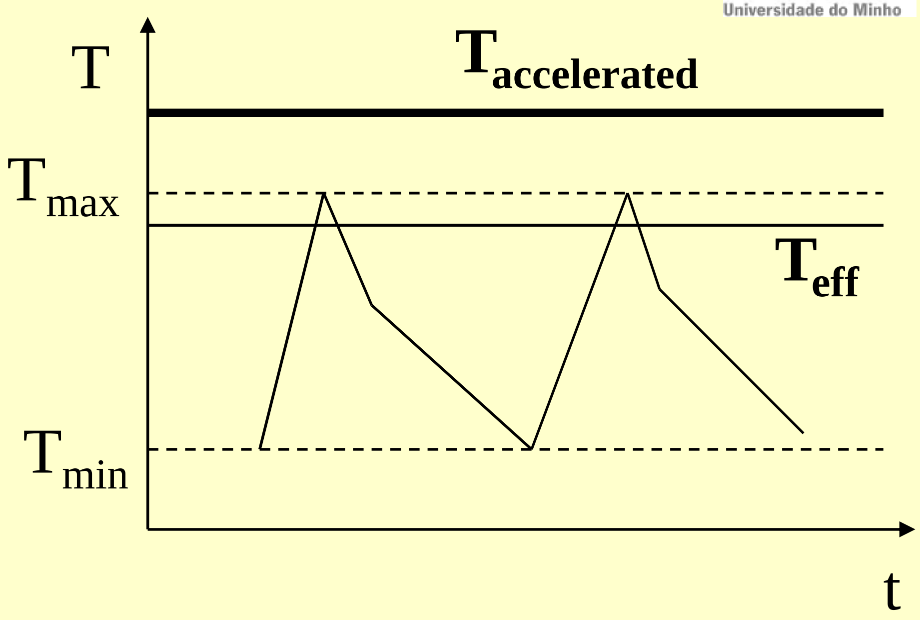
no spallation

Thermal expansion during thermal cycling



multi layer PVD

Accelerated tests (effective temperature)



$$t_{lifetime} = 25y$$

$$e^{\frac{-E_a}{RT_{eff}}} = \int_{T\min}^{T\max} e^{\frac{-E_a}{RT}} f(T)dT$$

$$t_{accelerated} = 25ye^{\frac{-E_a}{R}\left(\frac{1}{T_{eff}} - \frac{1}{T_{accelerated}}\right)}$$

Advanced procedure for the assessment of the lifetime of solar absorber coatings M. Koehl, M. Heck, S. Brunold, U. Frei, B. Carlsson, K. Moeller Solar Energy Materials & Solar Cells 84 (2004) 275–289

Accelerated testing (1)

Long term stability
at low operation temperature ($T_{typical}$ < 100°C) flatpanel collector:

PC =
$-\Delta\alpha + 0.25\,\Delta\varepsilon < 0.05$

Test procedure (ISO/CD 12592.2):
($T_{stagnation}$ = 203°C, α= 95 %, ε = 5 %)

1. Adhesion Test:
Tape test > 0.15 MPa
2. Thermal testing
T= 278°C, t = 36 ,75, 150, 300, 600h
T= 308°C, t = 141, 342 h
3. Humidity testing (w/ condensation)
T=40°C ; RH = 95 %, t = 80, 150, 300 and 600 h
T=60°C ; RH = 95 %, t = 85 h
4. Additional testing (microclimate)

Carlsson, B., Moller, K., Kohl, M., Frei, U. and Brunold, S. Qualification test procedure for solar absorber surface durability. *Sol. Energy Mater. Sol. Cells* **61,** 255-275.

Accelerated testing (2)

Long term stability

at high operation temperature ($T_{stagnation}$ > 350ºC) vacuum tube collector:

$PC = -\Delta\alpha + 0.25\,\Delta\varepsilon < 0.05$

Test procedure:

($T_{stagnation}$ = 350ºC, t = 25 000 h (25 y)

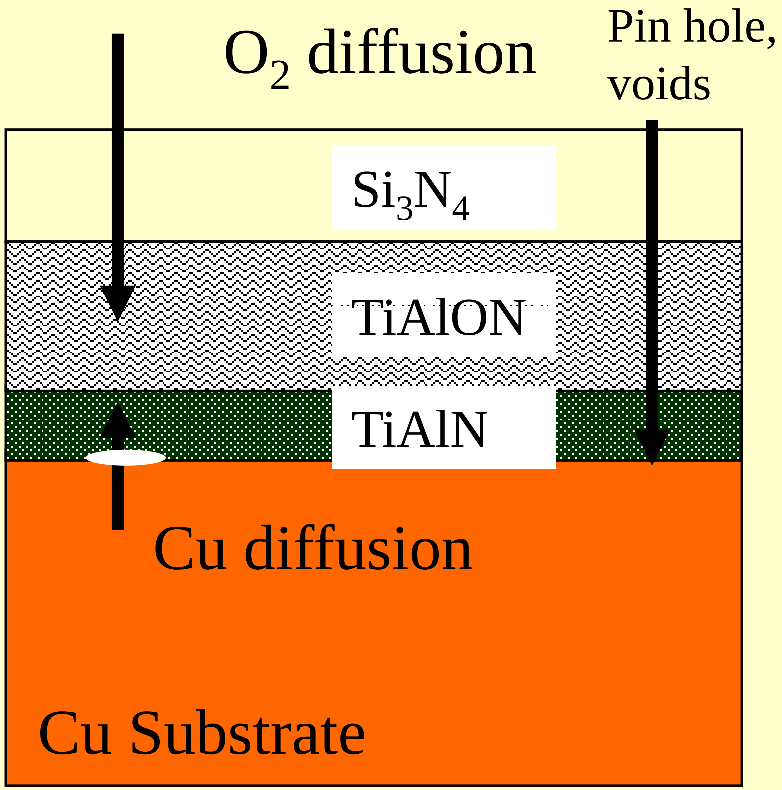
α= 95 %, ε = 5 %, E_A = 190 KJ/mol for Oxidation)

1. Adhesion Test:

Tape test > 0.15 MPa

2. Thermal testing

T= 440ºC, t = 600 h + T= 483ºC, t = 85 h



multi layer PVD

Accelerated tests: diffusion mechanism

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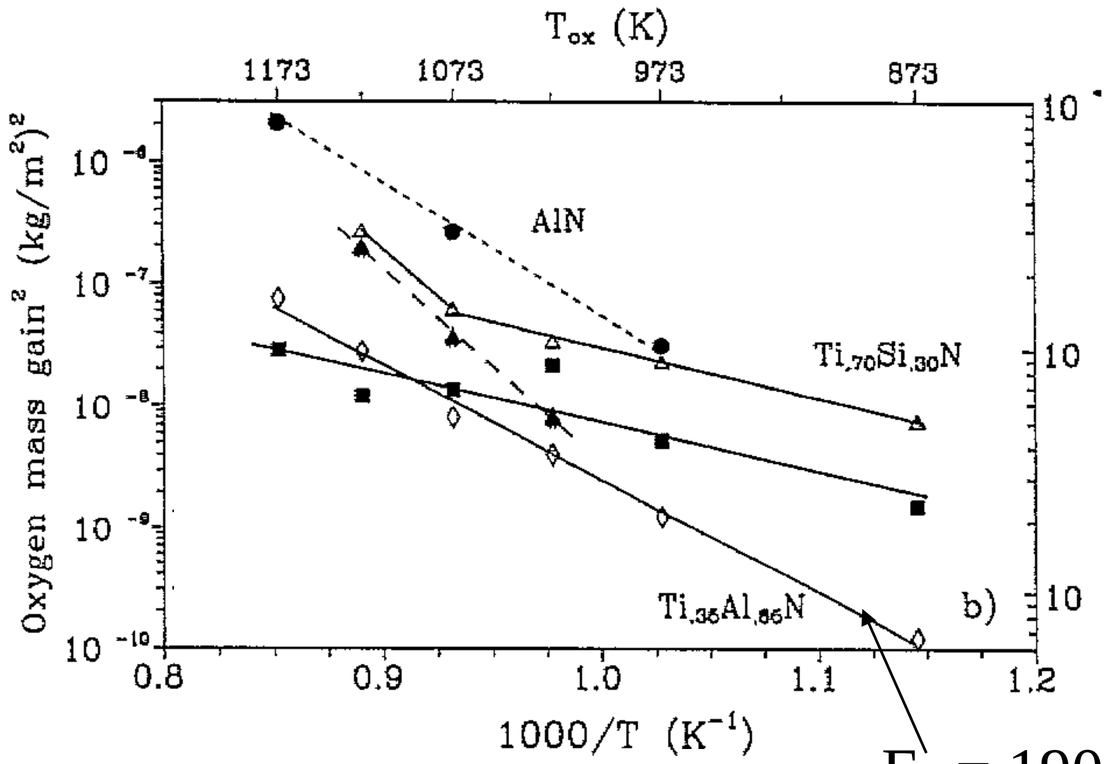
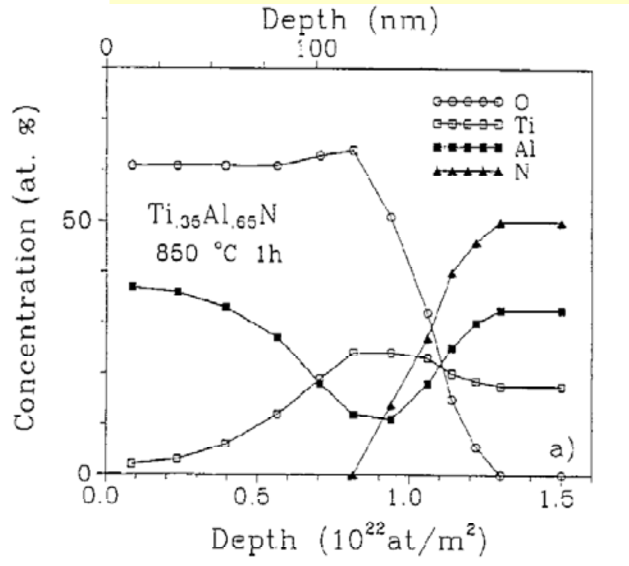
Long term stability

at high operation temperature ($T_{stagnation\ T} > 350^oC$) vacuum tube collector:

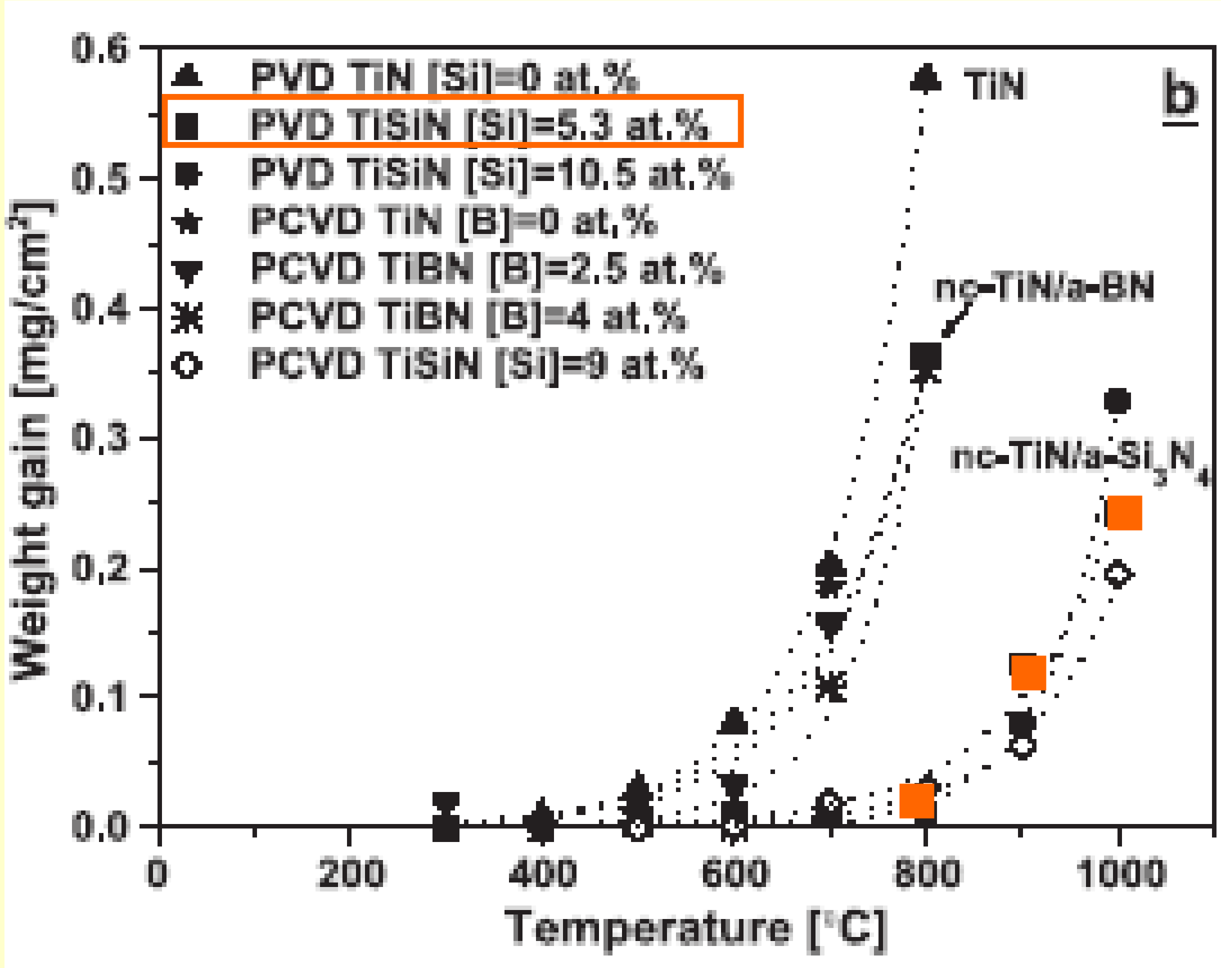
PC = $-\Delta\alpha + 0.25\,\Delta\varepsilon < 0.05$





E_a = 190 KJ/mol

Growth of oxide layer



$$\Delta m[\frac{mg}{cm^2}] = \sqrt{k^* t}$$

$$k^* = k_o^* \exp(-\frac{E}{RT})$$

➔ T = 600^0C

t = 30 000 h

<u>Δd < 15 nm</u>

Novel thermodynamically stable and oxidation resistant superhard coating materials

S. Vepfek *, M. Haussmann, S. Reiprich, Li Shizhi', J. Dian Surface and Coatings Technology 86-87 (1996) 394--401

Summary

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- Numerous optical solutions for a high performance ($\alpha >$ 95 %, $\varepsilon <$ 5 %) absorber coating
  - main characteristics: 3 layer PVD coating

- Elevated temperature degradation controlled by diffusion processes
  - All layers must be stable at application temperature (stagnation temperature)
  - At least one layer must be dense to protect the Cu substrate against oxidation/corrosion. Most manufacturers use a coating technology which intrinsically produces a dense layer (e.g. PECVD or natural oxide growth top layer)

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