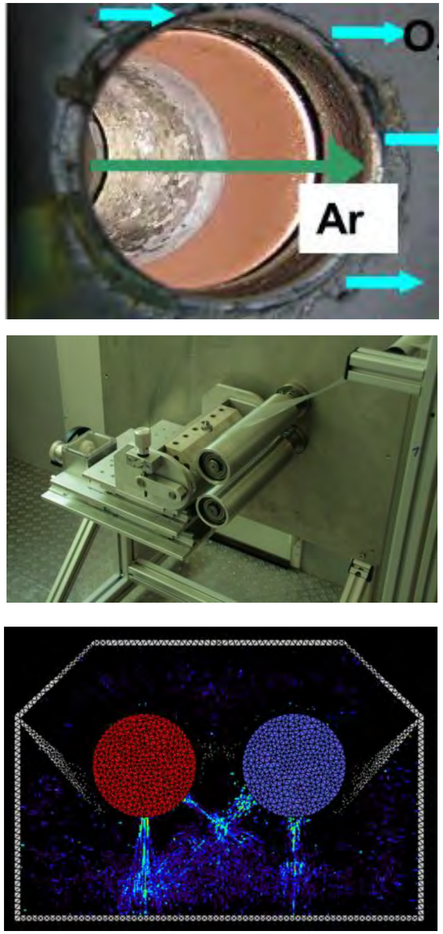
# Material und Prozessinnovationen in der industriellen Schicht- und Oberflächentechnik für die kostengünstige Bereitstellung erneuerbarer Energien



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*Oben: Hohlkatoden-Gasflusssputtern | Mitte: OPV Slot Dye Coating| Unten: Modellbasierte Prozessentwicklung*

# Gliederung

1 Einleitung
  - Erneuerbare Energien und Beschichtungstechnik
  - Einige Fakten

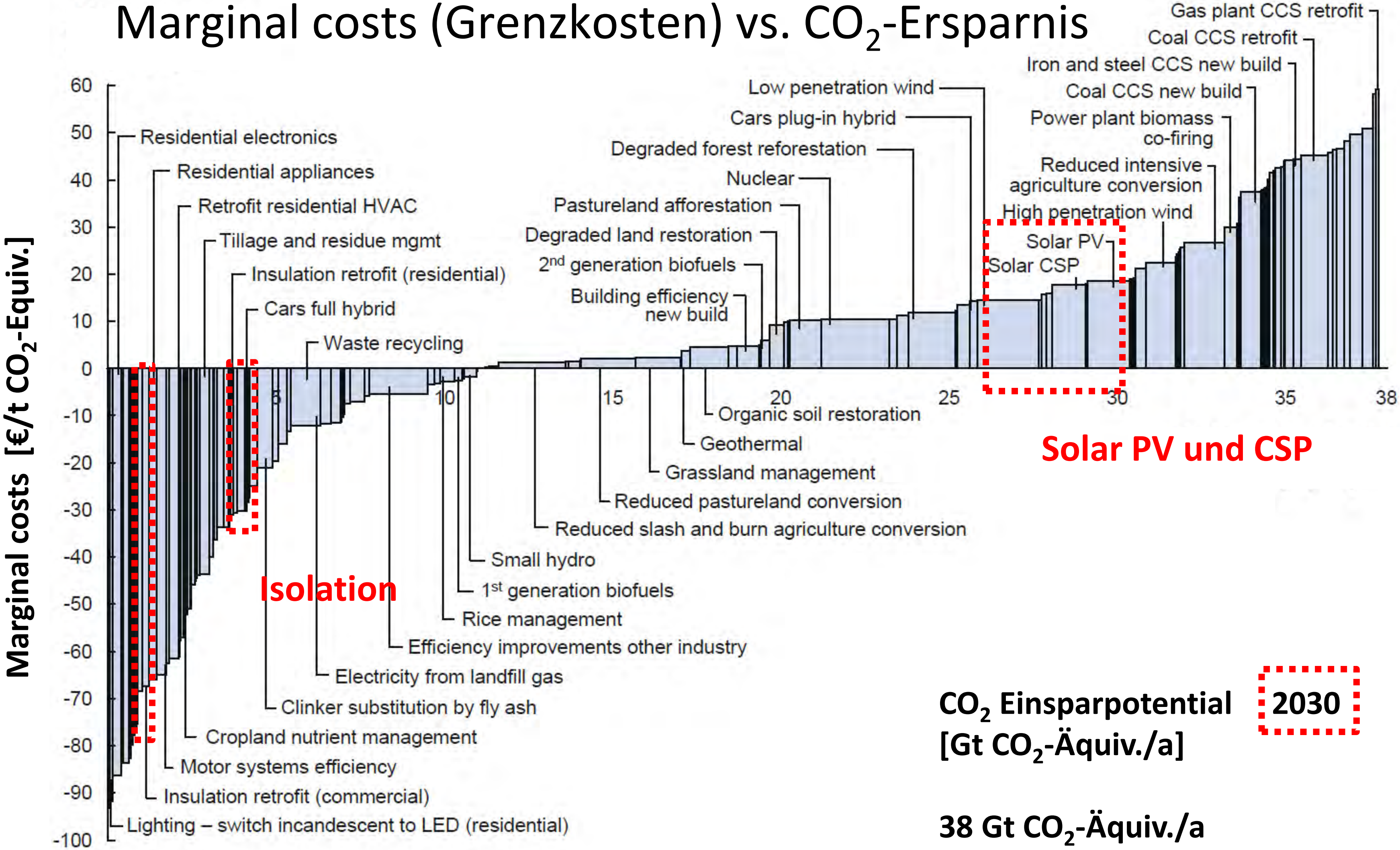
2 Technologien
  - Nanokomposite mittels Gasflusssputtern und ALD
  - Organische Photovoltaik
  - CVD vs. PECVD
  - Multiskalen-Modellierung

3 TU Berlin und PVcomB
  - Konzepte & Technologien

4 Zusammenfassung & Ausblick

# 1 Maßnahmen zur Verminderung der $CO_2$-Emission

## Marginal costs (Grenzkosten) vs. $CO_2$-Ersparnis



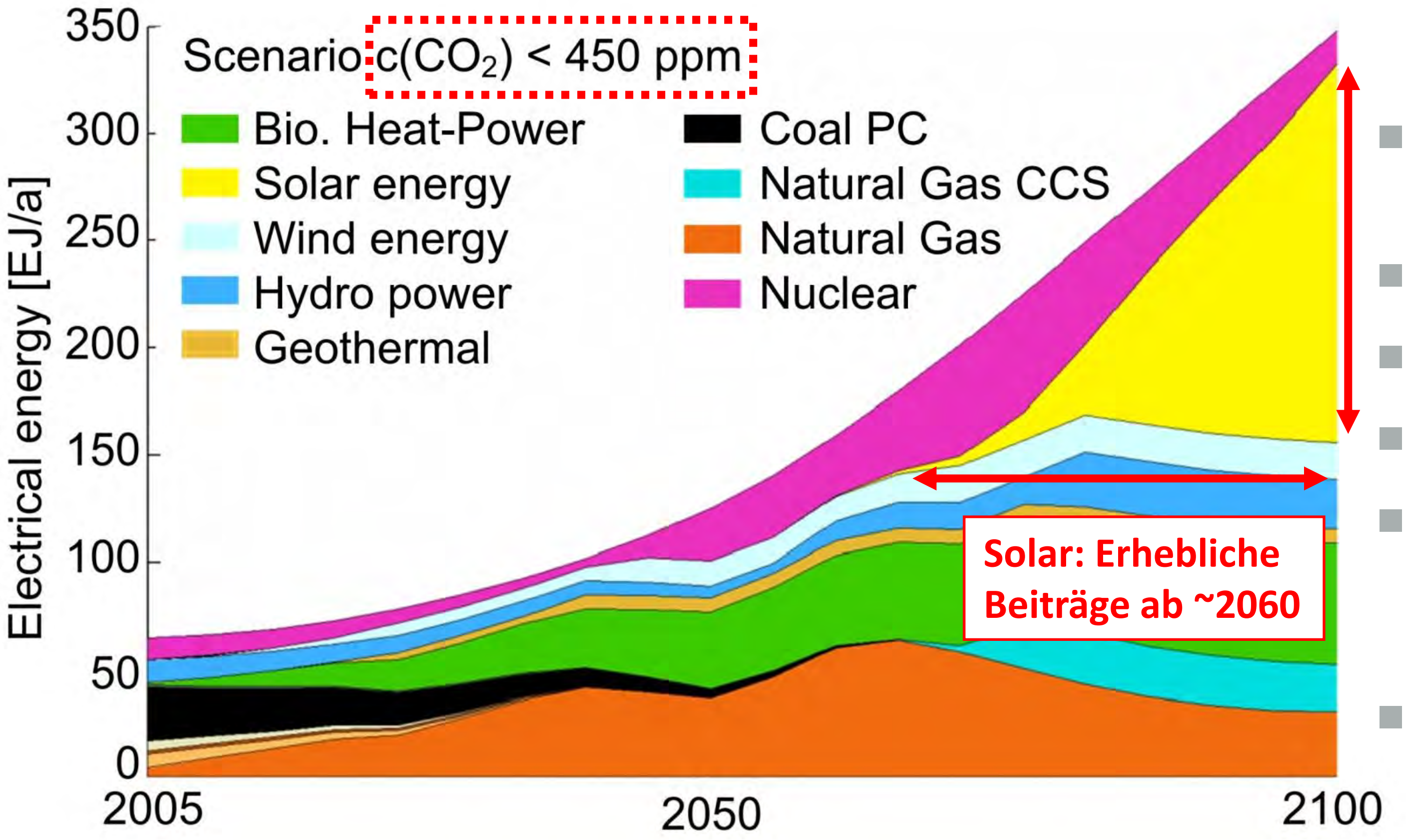
**$CO_2$ Einsparpotential 2030**
**[Gt $CO_2$-Äquiv./a]**

**38 Gt $CO_2$-Äquiv./a**
**Einsparungen sind notwendig**

*McKinsey (Hrsg.): Pathways to a Low-Carbon Economy (2009)*

# 1 Entwicklung des weltweiten Bedarfs an elektrischer Energie

## Szenario für $c(O_2) < 450$ ppm | $\Delta T < 2$°C | Reduktion AKWs

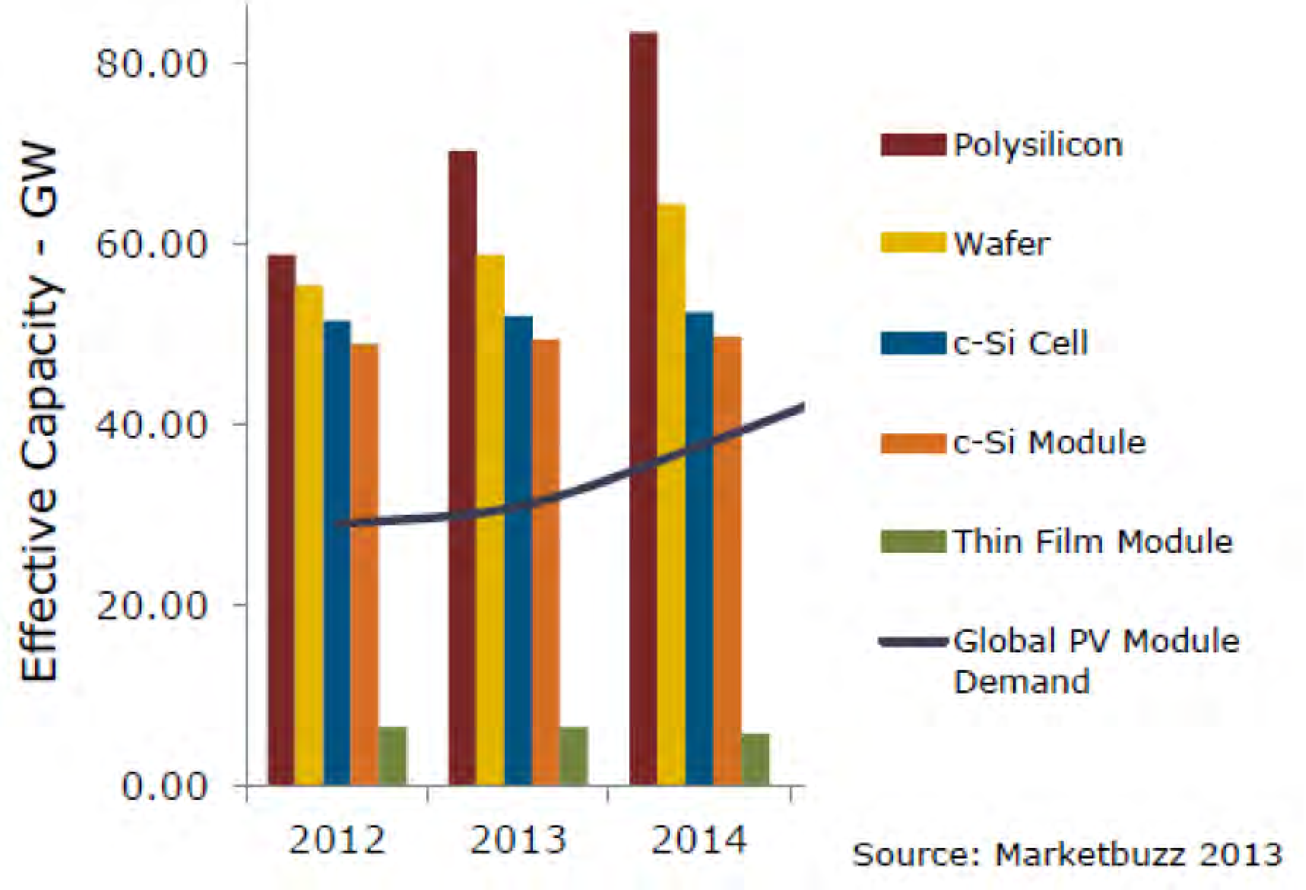


**Solar: Erhebliche Beiträge ab ~2060**

- $\Delta T < 2$ °C erfordert $c(CO_2) < 450$ ppm
- 1 EJ = $10^{18}$ J
- 1 AKW = 1,5 GW
- 1 EJ/a = 21 AKW
- 1 EJ/a =
  50 x 50 $km^2$ PV
  @ $\eta = 10$ %
- 60 EJ/a =
  390 x 390 $km^2$ PV
  @ $\eta = 10$ %

*www.pik-potsdam.de/infodesk/climate-change-knowledge-in-a-nutshell* | *www.pik-potsdam.de/~anders*

# 1 PV Überkapazität – Produktionskapazität vs. Installationen

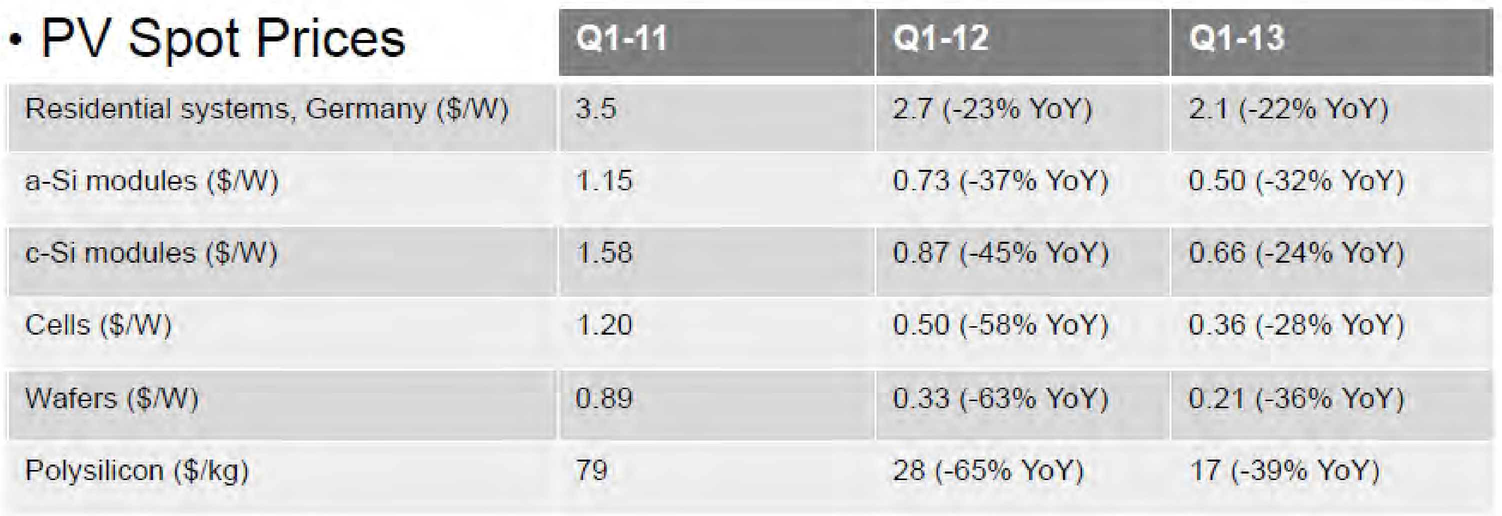


Source: Marketbuzz 2013

- Immer noch deutliche Überkapazität, daher schlechtes Investitionsklima

*F. Wessendorf (VDMA), 5. Thin Film Week 2013*

# 1 Preisentwicklung am Spot-Markt



- PV Spot Prices

| | Q1-11 | Q1-12 | Q1-13 | |
|---|---|---|---|---|
| Residential systems, Germany ($/W) | 3.5 | 2.7 (-23% YoY) | 2.1 (-22% YoY) | 1,61 €/W |
| a-Si modules ($/W) | 1.15 | 0.73 (-37% YoY) | 0.50 (-32% YoY) | 0,38 €/W |
| c-Si modules ($/W) | 1.58 | 0.87 (-45% YoY) | 0.66 (-24% YoY) | 0,50 €/W |
| Cells ($/W) | 1.20 | 0.50 (-58% YoY) | 0.36 (-28% YoY) | 0,28 €/W |
| Wafers ($/W) | 0.89 | 0.33 (-63% YoY) | 0.21 (-36% YoY) | 0,16 €/W |
| Polysilicon ($/kg) | 79 | 28 (-65% YoY) | 17 (-39% YoY) | 13 €/kg |

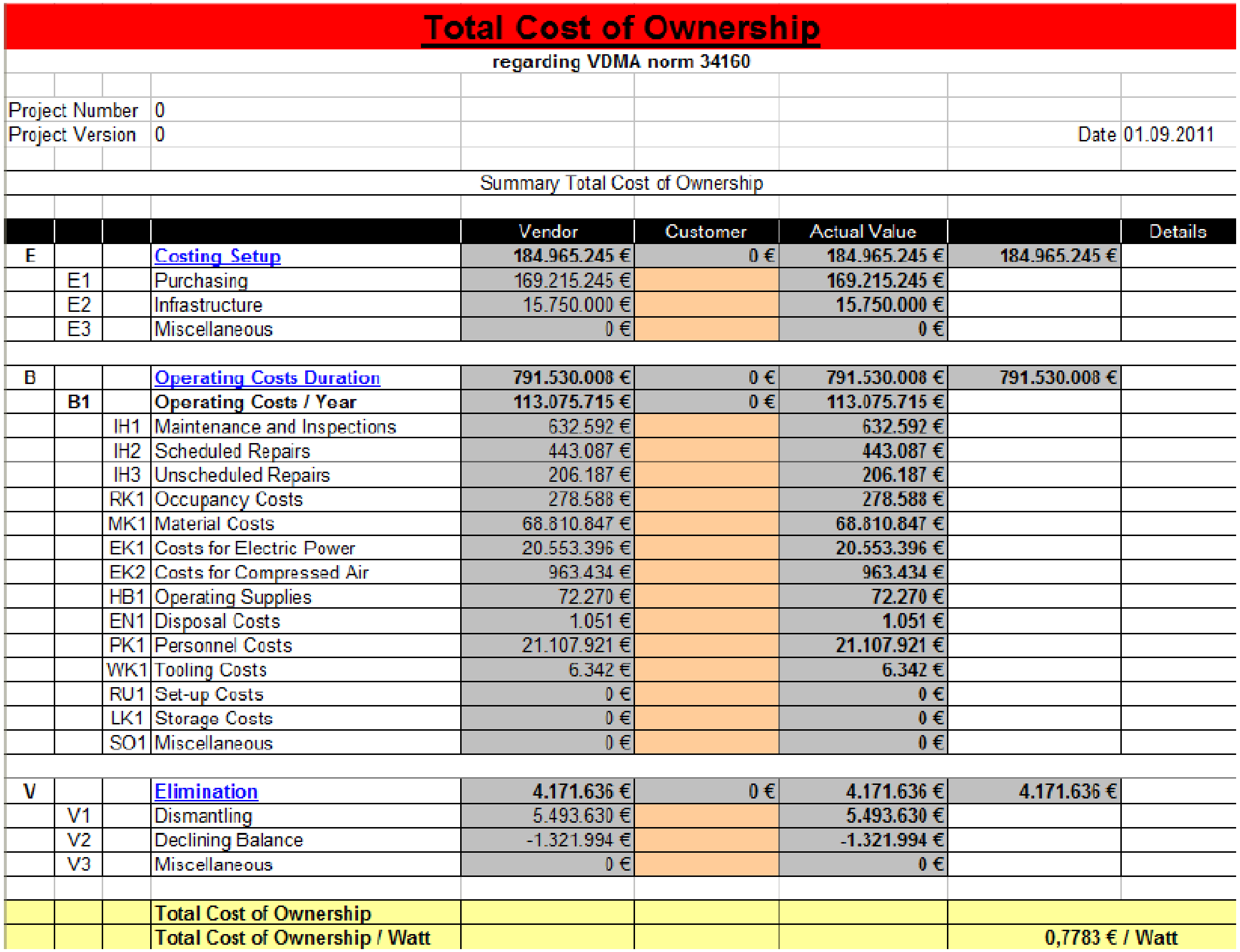
- Extremer Kostendruck!
- Spot-Preis für a-Si Module in der Größenordnung bzw. unterhalb der Herstellungskosten
  - Vgl. Prognose von Tokyo Elektron in 2012: Produktion in China für 0,35 €/Wp Produkt: Mikromorphe Module, 154 $W_p$, entsprechend $\eta$ = 10,8 %
  - Hiesige Hersteller sind von diesen Kosten weit entfernt!

*S. de Haan, 5. Thin Film Week April 2013* | T. Eisenhammer, IWTSSC-4, März 2012

# 1 Kostenlage bei der Herstellung von CIS Solarzellen

## Abschätzung 180 MWp Fab, Grenzebach, Standort D

- 180 MWp Fab für 185 Mio € Invest
- 113 Mio €/a Betriebskosten
- $\eta$ = 12 %, 270 W Module
- Abschreibung 7 a
- TOC: 0,78 €/$W_p$
- Zellaufbau:
  G / Mo (400 nm) /
  CIGS (1,9 µm) /
  CdS (50 nm) /
  i-ZnO (50 nm)
  ZnO:Al (1000 nm)



**Total Cost of Ownership**

regarding VDMA norm 34160

Project Number 0
Project Version 0
Date 01.09.2011

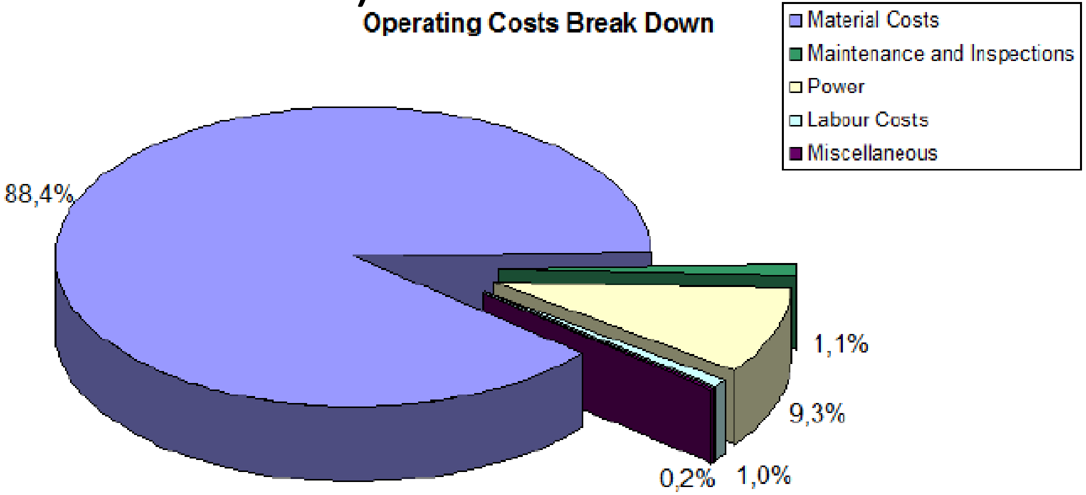
Summary Total Cost of Ownership

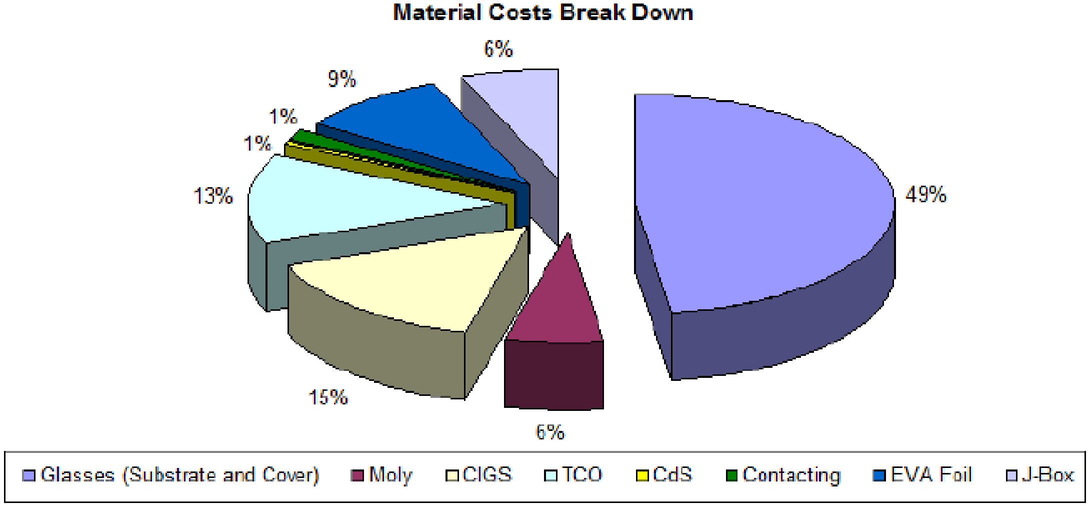
| | | | | Vendor | Customer | Actual Value | | Details |
|---|---|---|---|---|---|---|---|---|
| E | | | Costing Setup | 184.965.245 € | 0 € | 184.965.245 € | 184.965.245 € | |
| | E1 | | Purchasing | 169.215.245 € | | 169.215.245 € | | |
| | E2 | | Infrastructure | 15.750.000 € | | 15.750.000 € | | |
| | E3 | | Miscellaneous | 0 € | | 0 € | | |
| | | | | | | | | |
| B | | | Operating Costs Duration | 791.530.008 € | 0 € | 791.530.008 € | 791.530.008 € | |
| | B1 | | **Operating Costs / Year** | 113.075.715 € | 0 € | 113.075.715 € | | |
| | | IH1 | Maintenance and Inspections | 632.592 € | | 632.592 € | | |
| | | IH2 | Scheduled Repairs | 443.087 € | | 443.087 € | | |
| | | IH3 | Unscheduled Repairs | 206.187 € | | 206.187 € | | |
| | | RK1 | Occupancy Costs | 278.588 € | | 278.588 € | | |
| | | MK1 | Material Costs | 68.810.847 € | | 68.810.847 € | | |
| | | EK1 | Costs for Electric Power | 20.553.396 € | | 20.553.396 € | | |
| | | EK2 | Costs for Compressed Air | 963.434 € | | 963.434 € | | |
| | | HB1 | Operating Supplies | 72.270 € | | 72.270 € | | |
| | | EN1 | Disposal Costs | 1.051 € | | 1.051 € | | |
| | | PK1 | Personnel Costs | 21.107.921 € | | 21.107.921 € | | |
| | | WK1 | Tooling Costs | 6.342 € | | 6.342 € | | |
| | | RU1 | Set-up Costs | 0 € | | 0 € | | |
| | | LK1 | Storage Costs | 0 € | | 0 € | | |
| | | SO1 | Miscellaneous | 0 € | | 0 € | | |
| | | | | | | | | |
| V | | | Elimination | 4.171.636 € | 0 € | 4.171.636 € | 4.171.636 € | |
| | V1 | | Dismantling | 5.493.630 € | | 5.493.630 € | | |
| | V2 | | Declining Balance | -1.321.994 € | | -1.321.994 € | | |
| | V3 | | Miscellaneous | 0 € | | 0 € | | |
| | | | | | | | | |
| | | | **Total Cost of Ownership** | | | | | |
| | | | **Total Cost of Ownership / Watt** | | | | 0,7783 € / Watt | |

*E. Wenninger (Grenzebach), Otti Glas und Solar 2011*

# 1 Aufteilung der Betriebskosten
(welche 81 % der TCO ausmachen)

- Die Materialkosten sind der bei weitem größte Kostenfaktor
- Und von den Materialien trägt Glas ganz wesentlich bei!
- Die Kosten für CIS & CdS (16 %) sind niedriger als die Kosten für TCO & Mo (19 %)

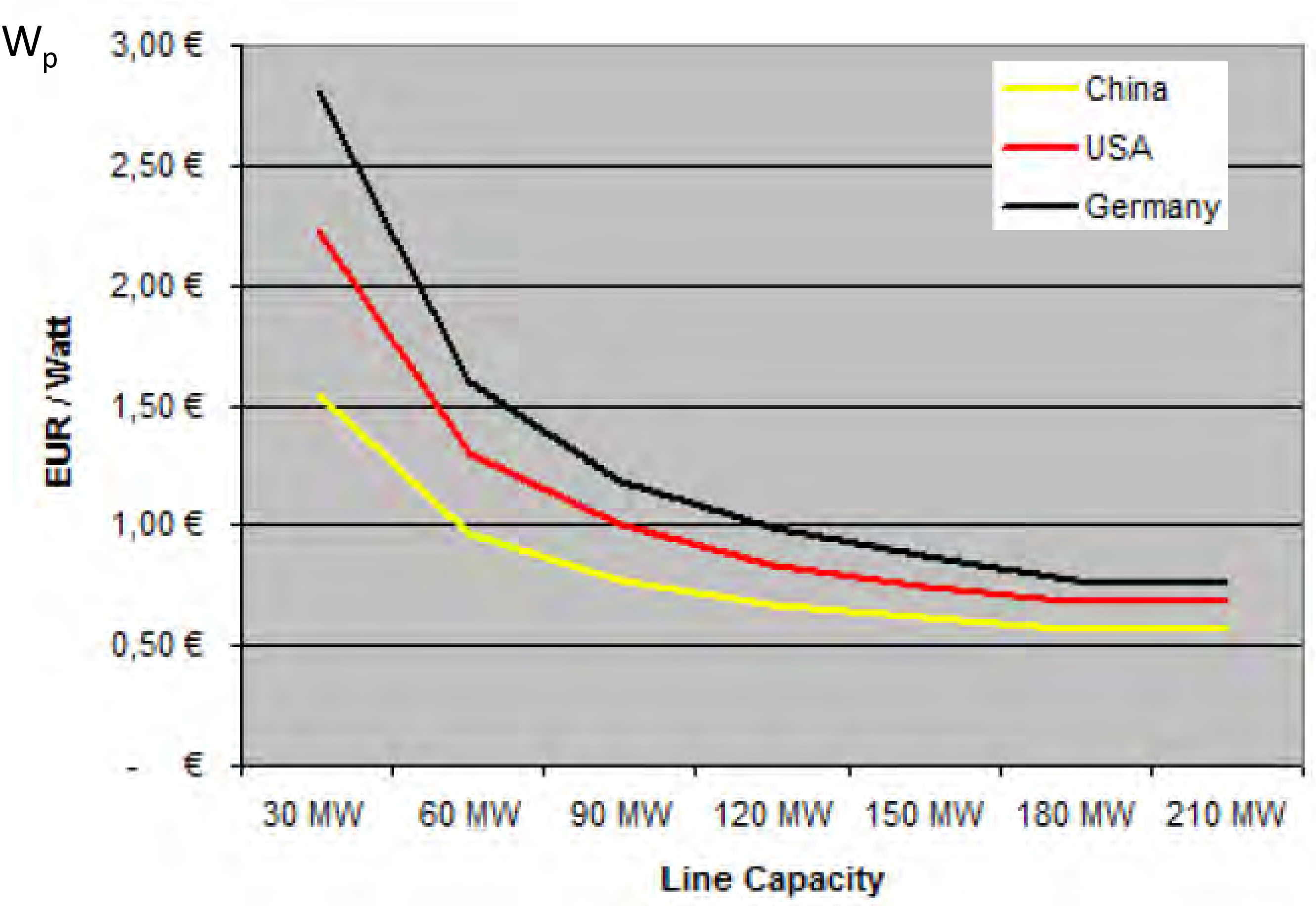




*E. Wenninger (Grenzebach), Otti Glas und Solar 2011*

# 1 Standortvergleich und Skaleneffekte

- Kapazität > 100 $MW_p$ anzustreben
- Ca. 20 % Kostenvorteil bei Fertigung in China gegenüber Deutschland



*E. Wenninger (Grenzebach), Otti Glas und Solar 2011*

# 1 **Investitionskosten vs. Betriebskosten**
## für einen Betrieb der Anlage über 7 Jahre

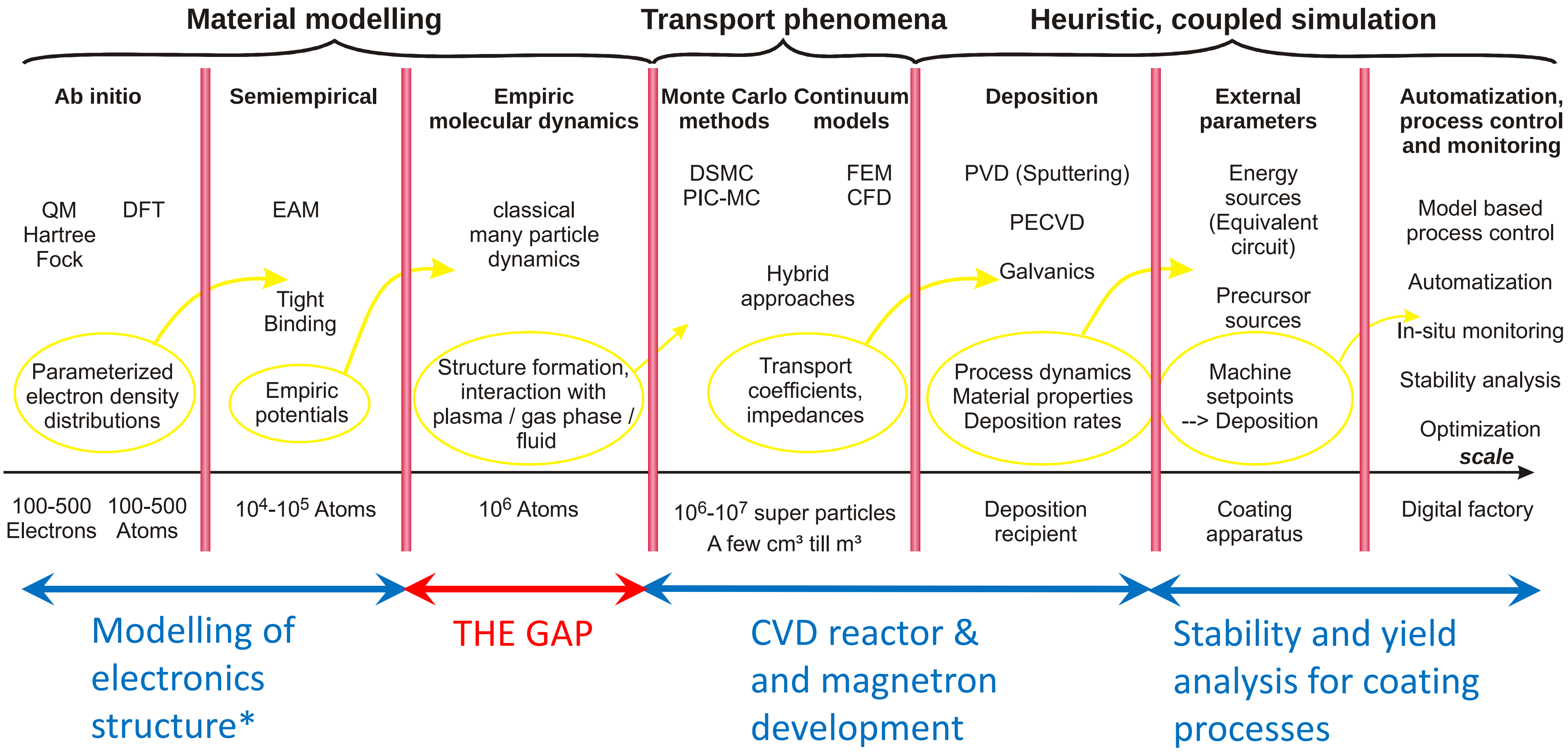
- Investitionskosten: 185 Mio €
- Betriebskosten: 791 Mio €
- Konsequenz für TCO: 0,775 € / Wp
  mit 19 % Anteil Investitionskosten
  und 81 % Anteil Betriebskosten

- Konsequenz:
  - Geringer Impact bei Substitution bestehender Beschichtungslösungen (Hochvakuumtechnik) durch kostengünstigere Lösungen (Atmosphärendruckbeschichtung)
  - Starker Impact für: (i) Wirkungsgradsteigerung und (ii) Minimierung der Materialkosten, hier sind die Glaskosten ganz wesentlich

# 2 Technologie

| | |
|---|---|
| Modellierung | Multiskalen-Modellierung für die digitale Fabrik<br>DFT / DSMC / PIC-MC Rechnungen |
| Vakuumverfahren | MEGATRON$^{TM}$ Sputtern<br>Hohlkatoden-Gasflusssputtern |
| Technologisch neue Ansätze | OPV Bandbeschichtung mittels Slot Dye Coating |

# 2.1 Model based development: Filling the gap from 1st principle DFT modeling up to the digital factory



**Material modelling** | **Transport phenomena** | **Heuristic, coupled simulation**

**Ab initio**
QM Hartree Fock
DFT
Parameterized electron density distributions
100-500 Electrons
100-500 Atoms

**Semiempirical**
EAM
Tight Binding
Empiric potentials
$10^4$-$10^5$ Atoms

**Empiric molecular dynamics**
classical many particle dynamics
Structure formation, interaction with plasma / gas phase / fluid
$10^6$ Atoms

**Monte Carlo methods**
DSMC
PIC-MC

**Continuum models**
FEM
CFD

Hybrid approaches
Transport coefficients, impedances
$10^6$-$10^7$ super particles
A few cm³ till m³

**Deposition**
PVD (Sputtering)
PECVD
Galvanics
Process dynamics Material properties Deposition rates
Deposition recipient

**External parameters**
Energy sources (Equivalent circuit)
Precursor sources
Machine setpoints --> Deposition
Coating apparatus

**Automatization, process control and monitoring**
Model based process control
Automatization
In-situ monitoring
Stability analysis
Optimization
Digital factory

***scale***

Modelling of electronics structure*

THE GAP

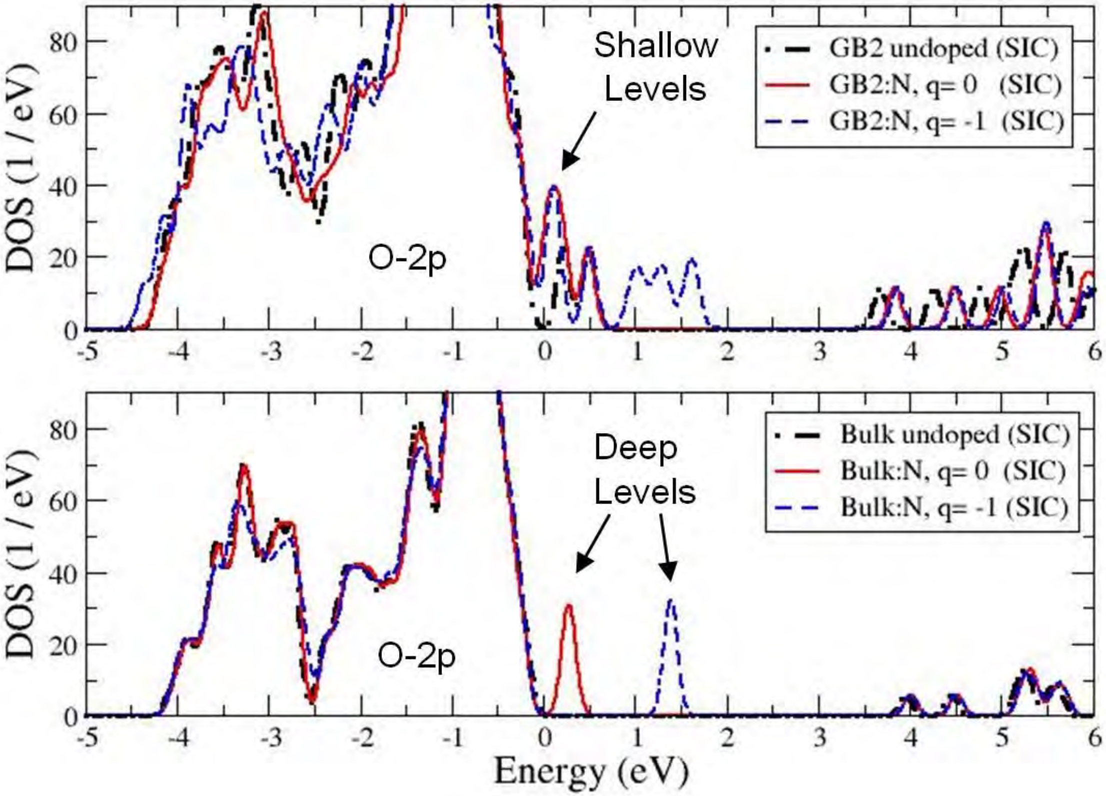
CVD reactor & and magnetron development

Stability and yield analysis for coating processes

*K. Roths et al., Forschungsagenda Oberfläche, DFO Service 2006, ISBN-10: 3834912301*
** W. Körner, C. Elsässer, Physical Review B 81 (2010) 85324*

# 2.1 Beispiel: Diskussion grundlegender Materialfragen mittels Density-Functional-Theory (DFT): Zustandsdichte ZnO:N

- Dotierung Korngrenzen
  - Flache Zustände nahe am Valenzband
  - Bilden Akzeptor-Niveaus aus
- Dotierung Einkristall
  - N-Dotierung liefert tief liegende Zustände
  - Als Akzeptor-Niveaus ungeeignet



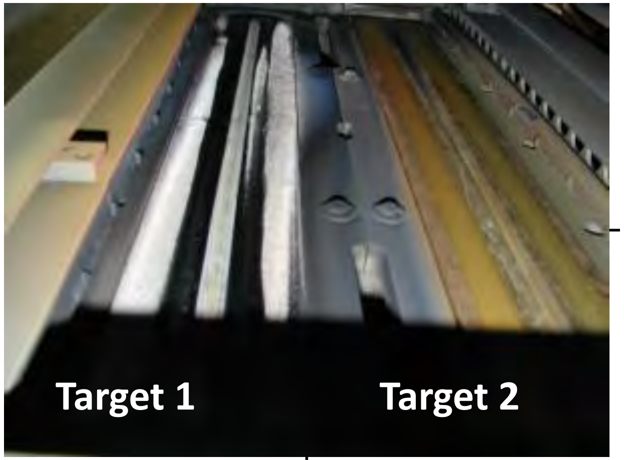
- Fazit: An experimentelle Daten (Bandlücke) angepasste DFT unter Einbeziehen von Defekten (Korngrenzen) als praktisches Werkzeug für das Materialdesign!

*B. Szyszka et al., Thin Solid Films 518 (2010) 3109*

# 2.1 Exp. to model: 2D Simulation of a magnetron discharge

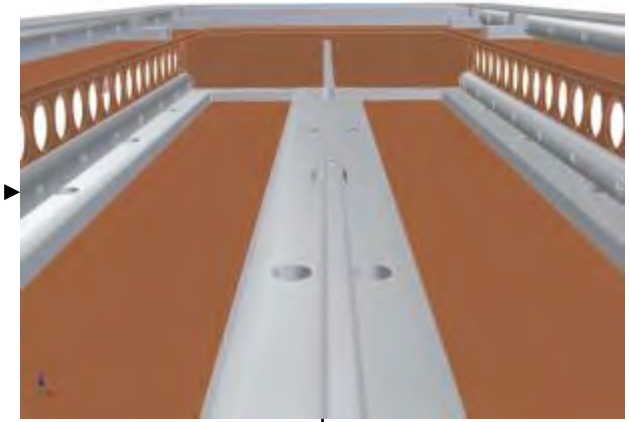
## Geometric decomposition of a reactor chamber

**Empirical geometry**

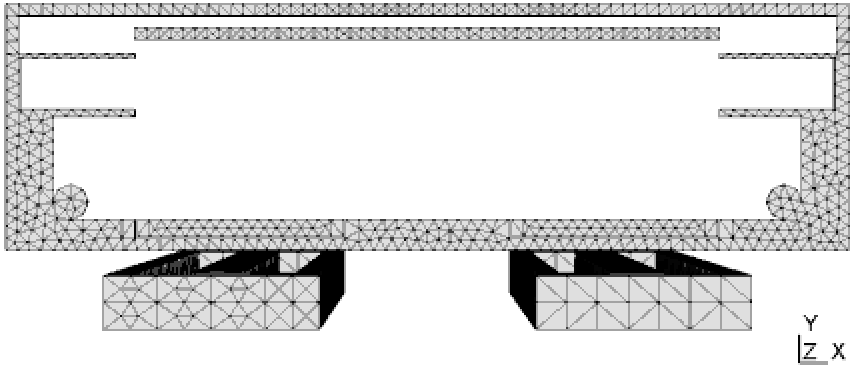


**Available as…**

**CAD drawing (file format: IGES, STEP, etc…)**



**Finite element mesh**



**Abstraction with GMSH**

**Import into GMSH**

*A. Pflug et al., Proc. SVC 52 (2009) 364*

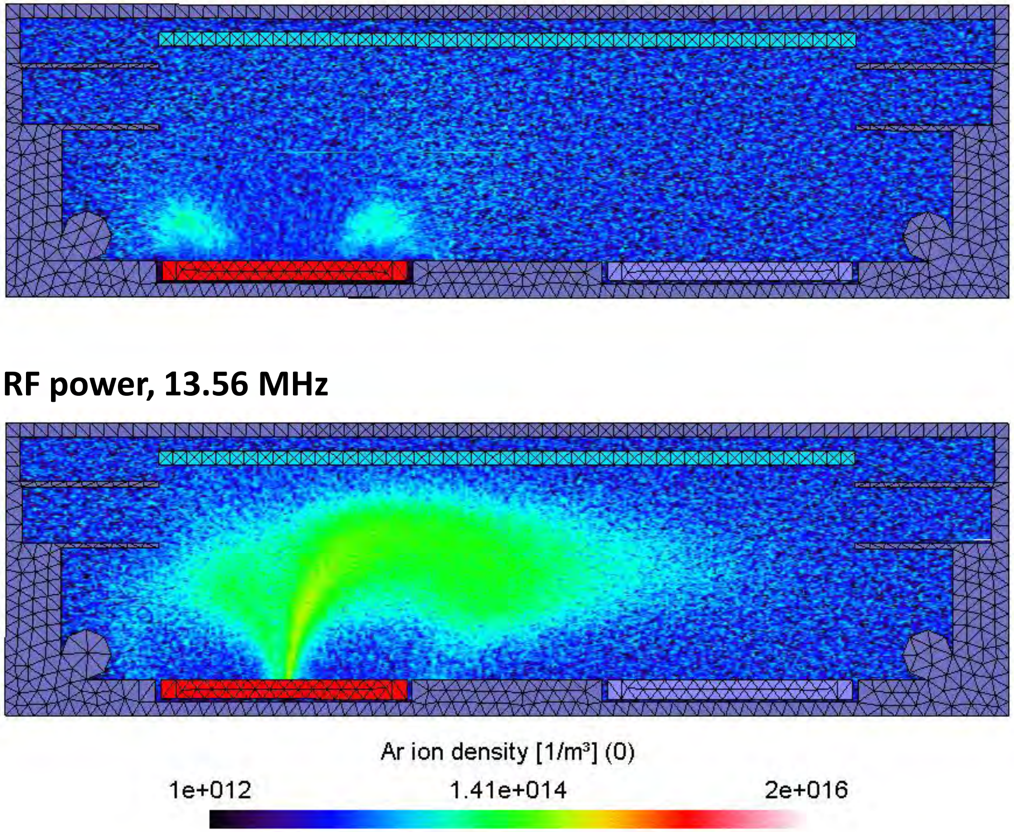
# 2.1 2D Simulation of magnetron discharges

## Difference between DC and pulsed mode

- Features in RF mode different to DC mode
  - Plasma density in bulk significantly increased
  - Strongly enlarged positive plasma potential
  - $Ar^+$ / $O_2^+$ ions escape in every direction
  - High ion flux and ion energy on substrate

**DC power, 1.0 Pa, 50 W/m, 40 % $O_2$ in Ar**

**RF power, 13.56 MHz**



*A. Pflug et al., Materials Technology 26 (2011) 10*

# 2.2 Model -> Experiment: Serial Co-Sputtering

## Problems during sputtering with conventional cathodes

### Target poisoning

- Unwanted reactions at the target: Rate ↘ Stability ↘ Film properties ↘

### Target composition

- Target composition is fixed & limited due to manufacturing constrains.

### Coupling of process parameters

- ZnO:Al: Change of $p(O_2)$ or $T_S$ yields change of c(Al). How to separate?

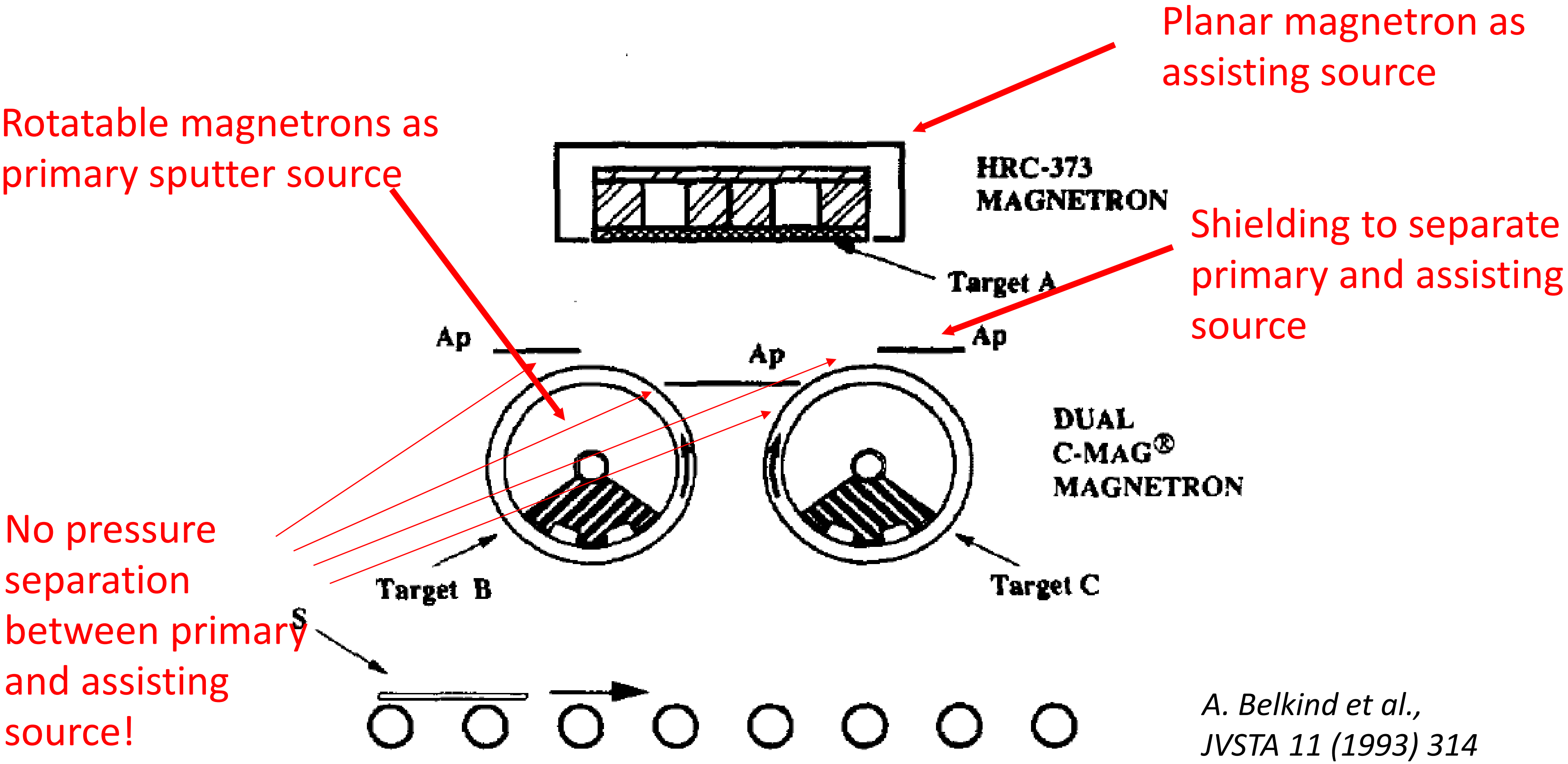
### In-situ control of deposition rate

- Complex optical monitoring. Implementation! Maintenance!

### Low sputter yield

- Low deposition rate, costly machinery, waste of energy.

# 2.2 A solution for these problems:



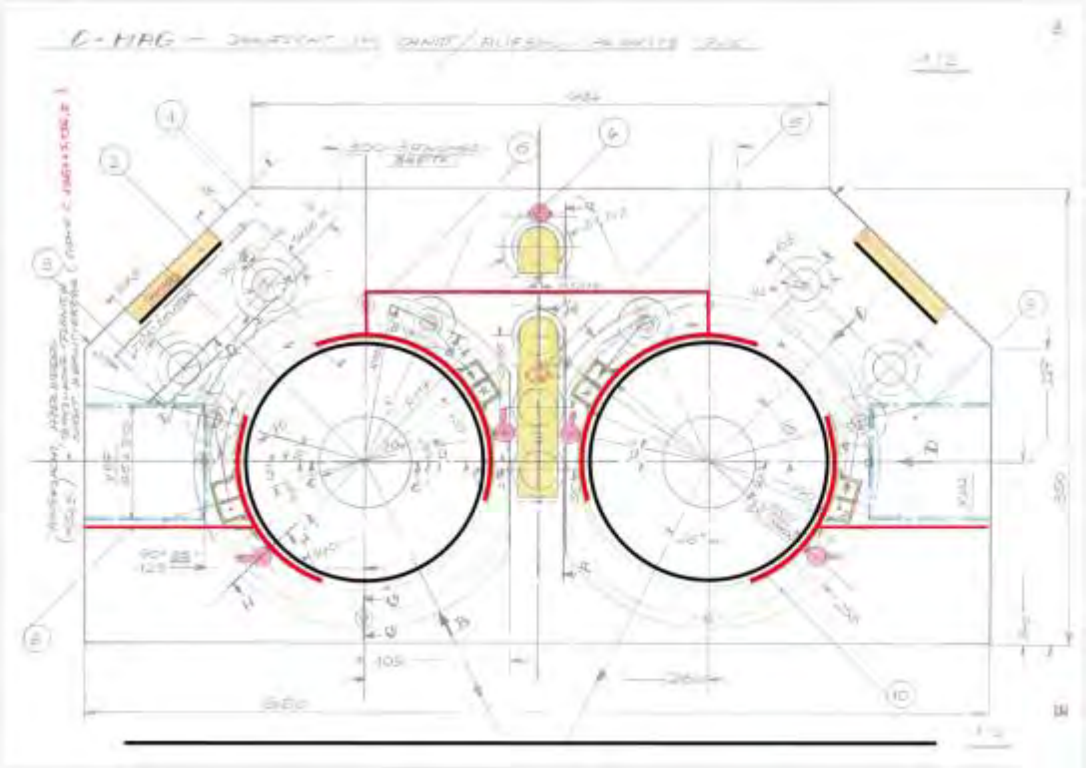
*A. Belkind et al., JVSTA 11 (1993) 314*

- Target composition of the primary target can be modified.
- Setup allows for sputter yield amplification for metallic targets.

# 2.2 Experimental realization of the MEGATRON$^{TM}$ process

## Serial co-sputtering with pressure separation

*ZnO:Al*
*$SnZnO_x$*
*$TiO_x$:Nb*
*In-Ga-Zn-O*
*CIGS*
*$TiO_2$:X*



- Synthesis of new materials and control of doping levels -> n-TCO for PV applications, n-ASO for TFT application
- Available for retrofit by Fraunhofer IST / Interpane

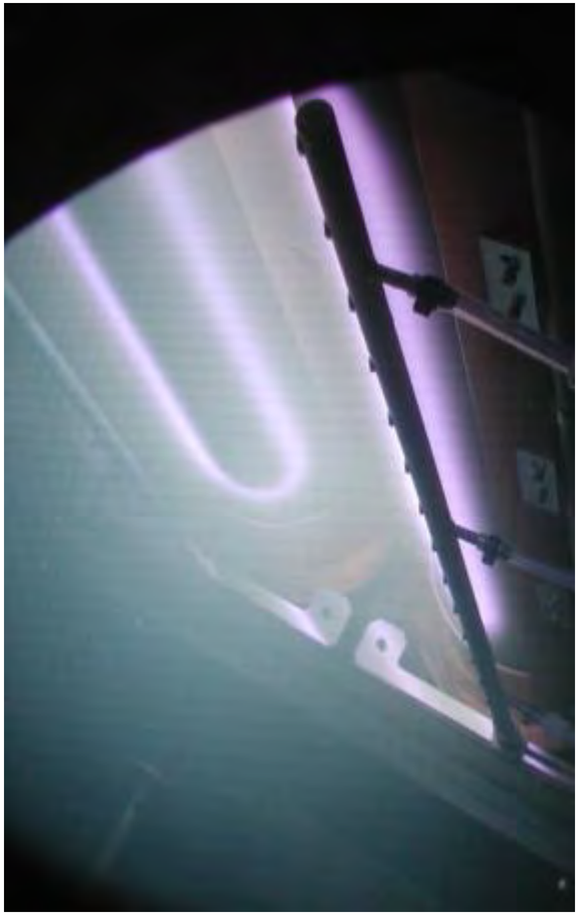
*B. Szyszka et al. Cur. Appl. Phys. 12 (2012) S2 | EP1697555B1: Method and device for magnetron sputtering*

# 2.2 Experimental realization of the MEGATRON$^{TM}$ process

## Serial co-sputtering with pressure separation

a) Serial co-sputtering source (model)

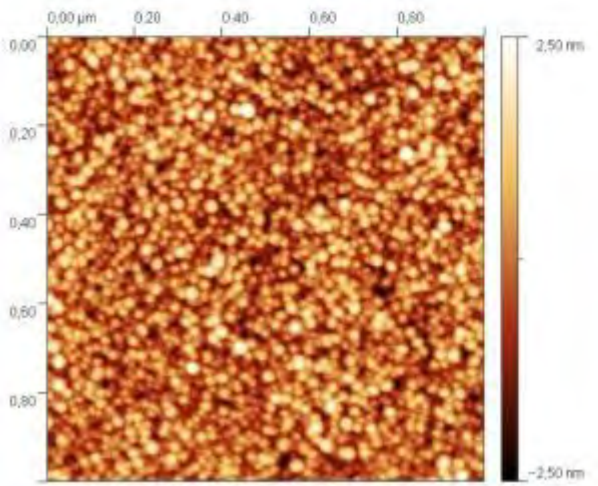
b) First plasma in June 2010



# 2.2 Example: Bi-doping of $TiO_2$

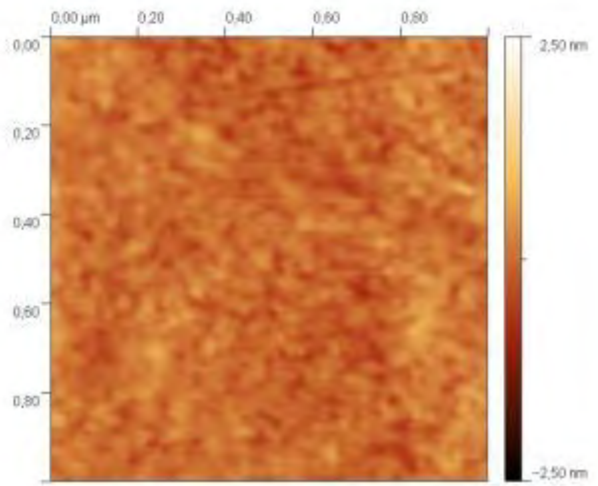
## Improvement of morphology and enhancement of rate

a) $TiO_2$ @ 18.9 nm m/min



$R_q$ = 0.81 nm, $R_a$ = 0.65 nm
d = 210 nm

b) $TiO_2$:3.8 at.%Bi @ 29.4 nm m/min



$R_q$ = 0.21 nm, $R_a$ = 0.17 nm
d = 326 nm

- AFM reveals fine grain size for both films
- Substantial decrease of surface roughness for $TiO_2$:Bi
- $TiO_x$:$BiO_x$ targets are not available due to metallurgical reasons

# 2.2 Summary MEGATRON™
## Ferchau Innovation Price 2011

**Rotatable magnetron sputter source for serial co-sputtering at Fraunhofer IST**

- For the 1st time, we've realized a magnetron coating module based on DSMC gas flow simulation and PIC-MC plasma simulation.
- Shielding tube allows for proper gas separation & increase of ion energy.

**Serial co-sputtering of $TiO_2$:Bi**

- Ceramic $TiO_2$ tube sputtering: Rate enhancement by 35 %
  due to serial cosputtering using Bi.
- Deposition rate of 34.2 nm m/min @ 18 kW for $TiO_2$:Bi
  (corresponds to 90 kW for 3.75 m cathode): Increase of dep. rate by 35 %.
- Excellent film properties:
  - Improved smoothness due to Bi-doping
  - No change of optical properties (550 nm: $k < 2 \times 10^{-3}$, $n > 2.45$)
  - Dense films, glass like morphology, moderate stress (~ -200 MPa)

# 2.2 Summary MEGATRON™

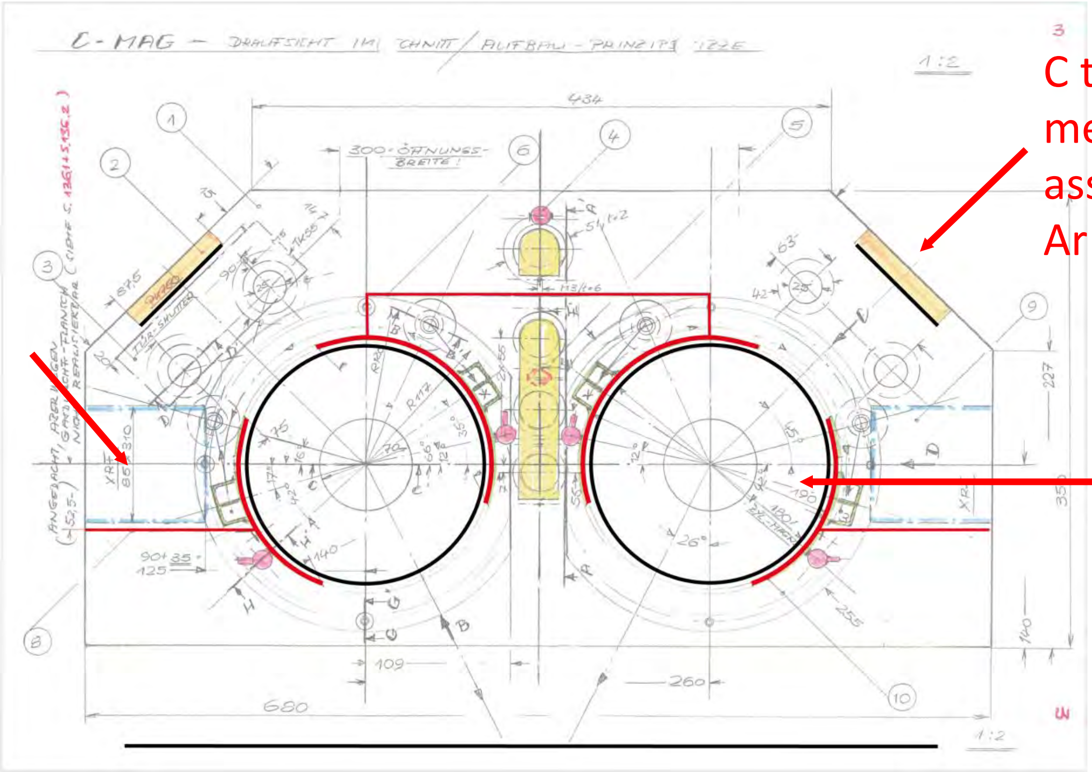
## Serial co-sputtering of $TiO_2$:W

- Ceramic $TiO_2$ tube sputtering: Rate enhancement > 100 % due to serial cosputtering using W.
- Limit: Performance of the shielding: Onset of unwanted increase of p(O2) at highest growth rate conditions.
- Deposition rate of 55 nm m/min achieved: Increase of dep. rate by 100 %.

## Serial co-sputtering of $TiO_2$:Nb

- Pathway for the control of Nb-doting.
- Preliminary results: $\rho$ = 2100 $\mu\Omega$cm for 210 nm thick film after annealing at 350 °C for 1 h in vacuum (large grain size anatase film)

# 2.2 Outlook: Further operation modes of the MEGATRON



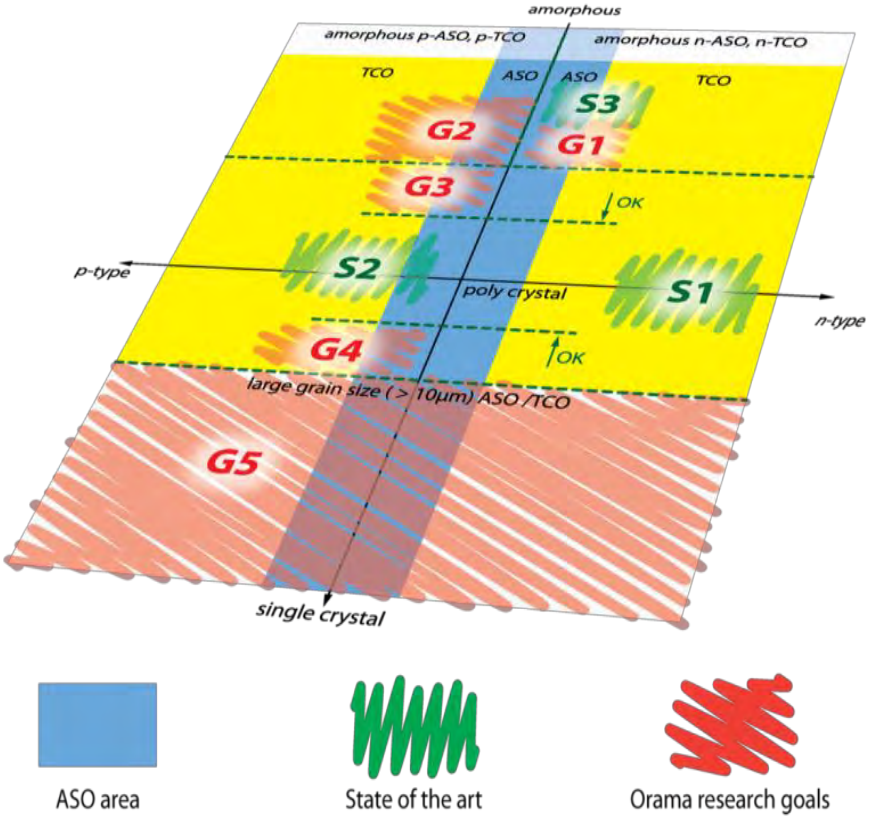
XRF unit for measurement of target stoichiometry

C tubes are metallized by assistant sources in Ar plasma.

C targets: Will produce only $CO_2$ in Ar / $O_2$

- XRF: Measurement of target stoichiometry @ known Bi metallization: Allows for calculation of deposition rate.
- C tubes: Metallization is oxidized at the substrate, transfer of the precision of Ar sputtering to oxide film growth, similar to Meta Mode.

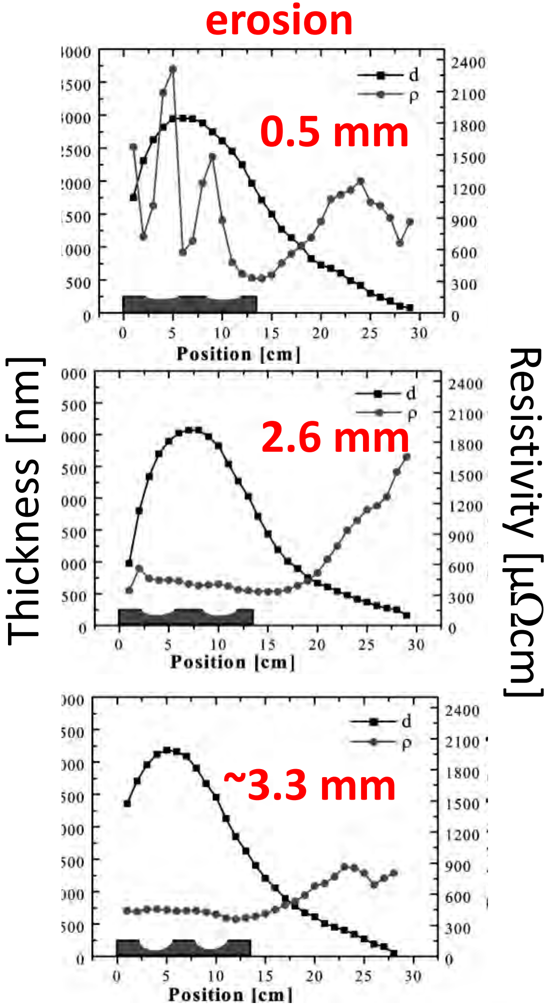
# 2.2 Transparent conductive oxides



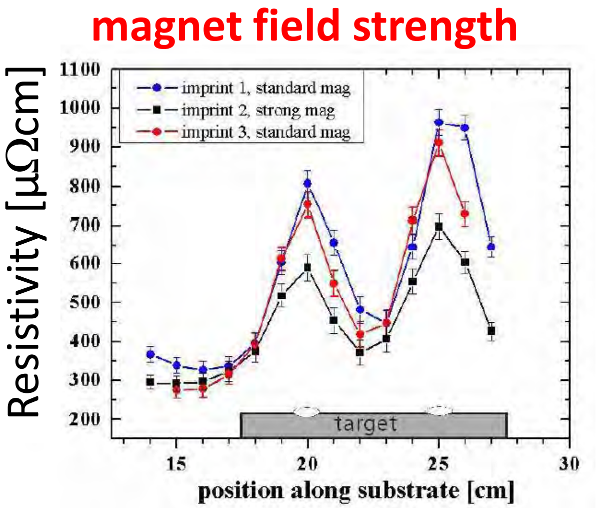
- Plasma damage in DC ceramic target TCO sputtering
- Rotatable target damage modeling
- Prevention of plasma damage by reactive deposition
- Prevention of plasma damage by RF superimposed DC deposition

# 2.2 Plasma damage and target erosion / magnetic field

## Ceramic target ZnO:Al deposition, static deposition


erosion

- Resistivity increase at racetrack position
- High energy particles damage on the growing film
- Due to negative oxygen ions, which are accelerated in the cathode sheath
- Strong dependence on target erosion and discharge voltage
- Strong need for low impedance sputter processes
- In particular for rotatable magnetrons

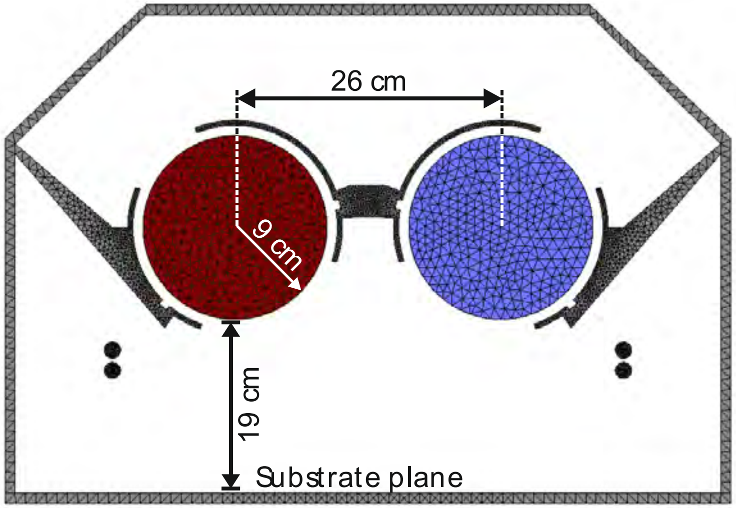

magnet field strength

*W. Dewald et al., Thin Solid Films 518 (2009) 1085 | W. Dewald et al., Proc. PVSEC 24 (2009) 2824*

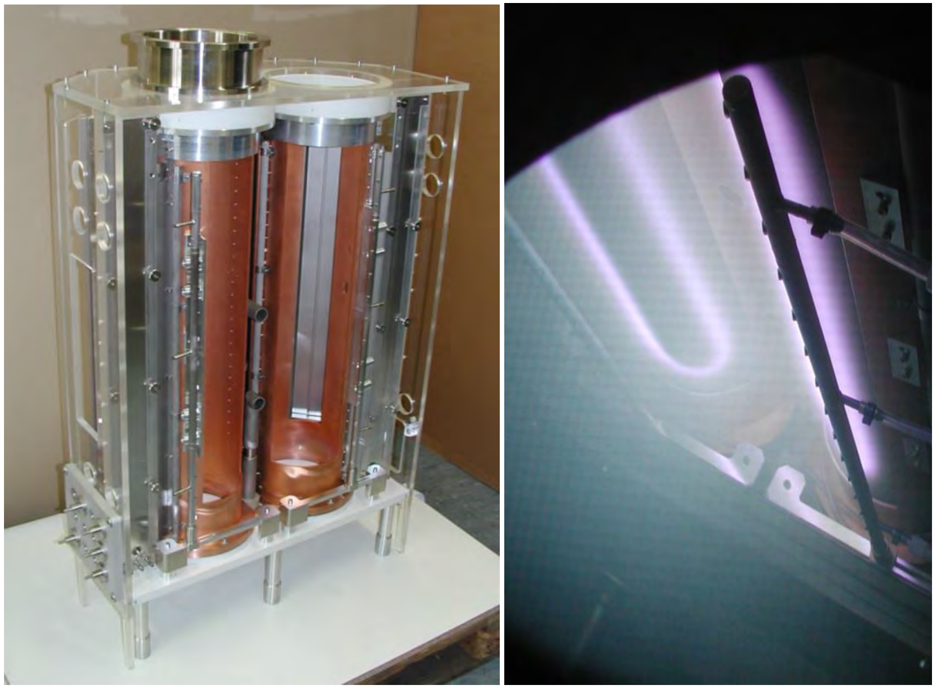
# 2.2 Modeling of TCO deposition process

## Negative oxygen ion issue

- Model geometry



- Corresponding hardware (Fraunhofer IST)



# 2.2 Modeling of TCO deposition process

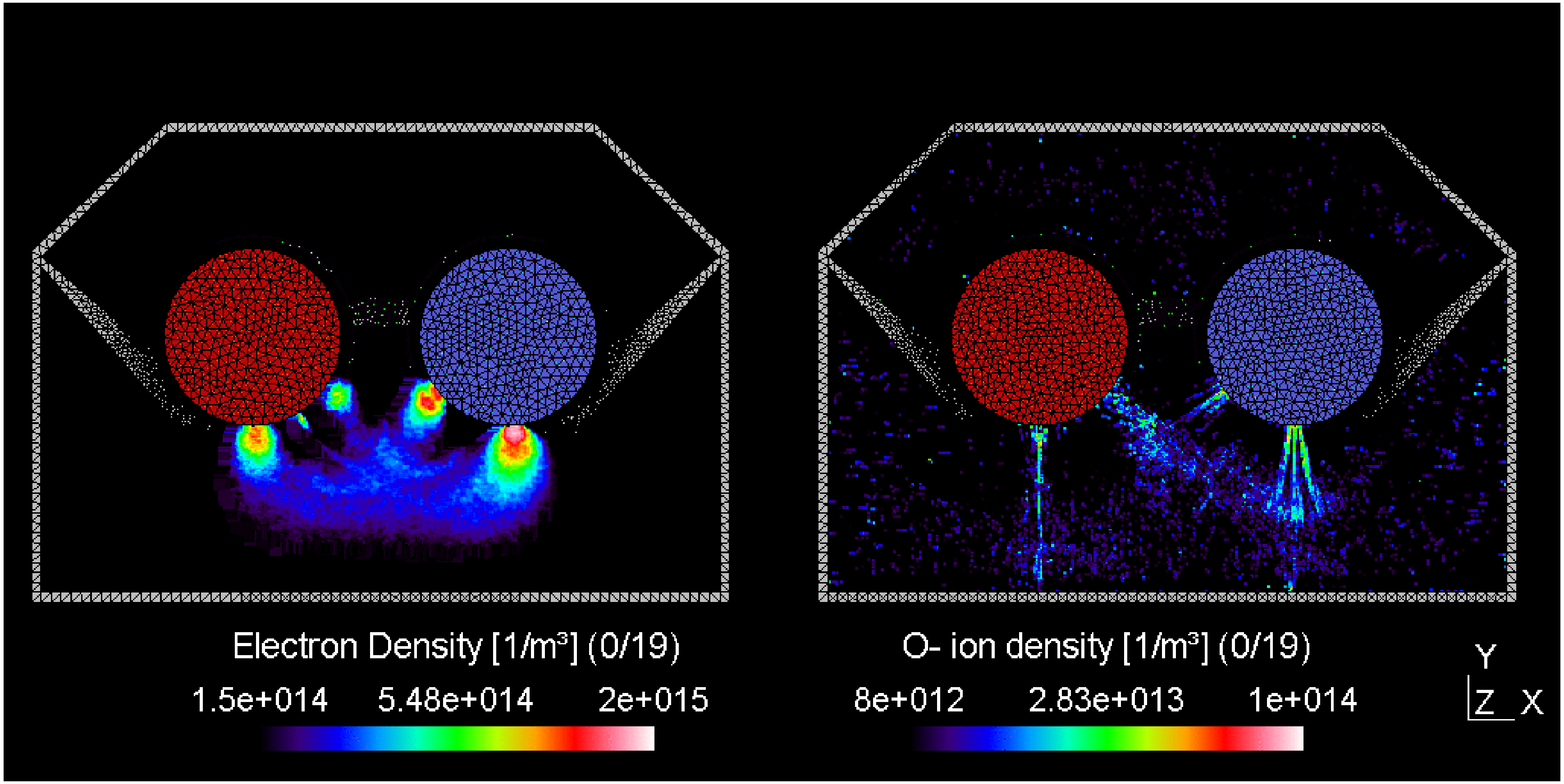
## Model features

- Simplified plasma chemistry
  - Species: Ar, $O_2$, $Ar^+$, $O_2^+$, $O_2^-$, $O^-$, $e^-$
  - Elastic collisions between elecrons, ions and neutrals
  - Charge exchange collisions between ions and neutrals
- Negative $O^-$ ions can be created at the target surface upon ion impact
- Parameters
  - Bipolar sine wave voltage ±250 V, 100 kHz
  - Total pressure = 300 mPa
  - Time step = 10 ps
  - Total physical time interval = 60 µs (→ 6 x $10^6$ PIC-MC iterations)

# 2.2 Modeling of TCO deposition process

## Visualization of electrons and negative O⁻ ions

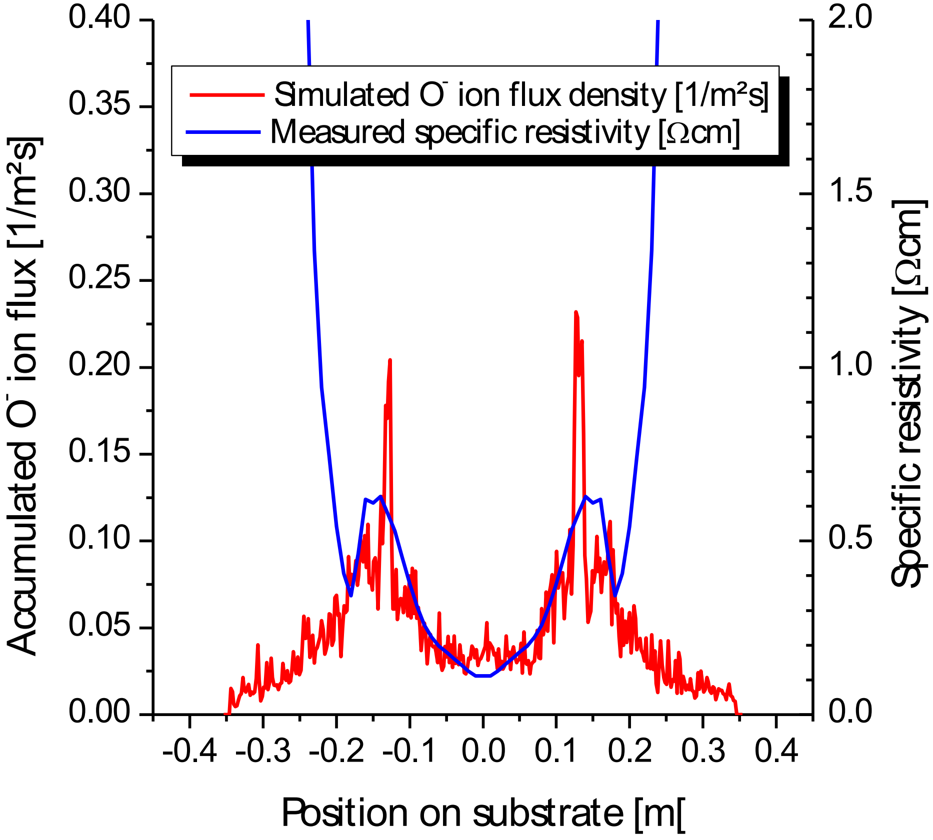
- 100 kHz sine wave, time interval between 50…60 µs shown



# **2.2** $ZnSnO_x$ TCO Beschichtungsprozess

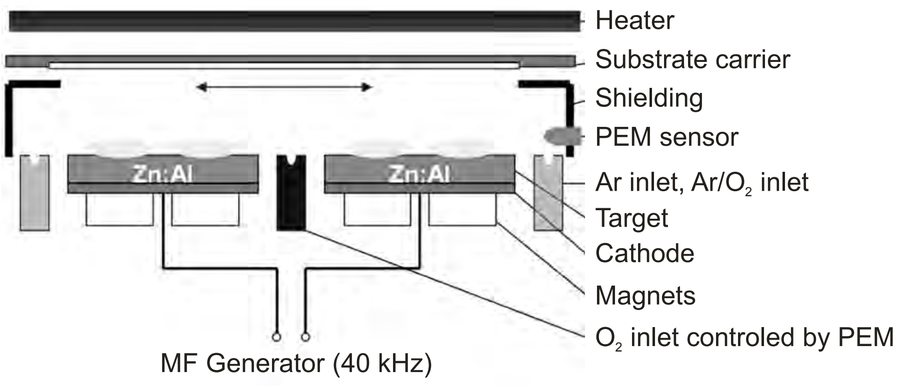
## Widerstandsprofil vs. Modellierung des $O^-$ Bombardements

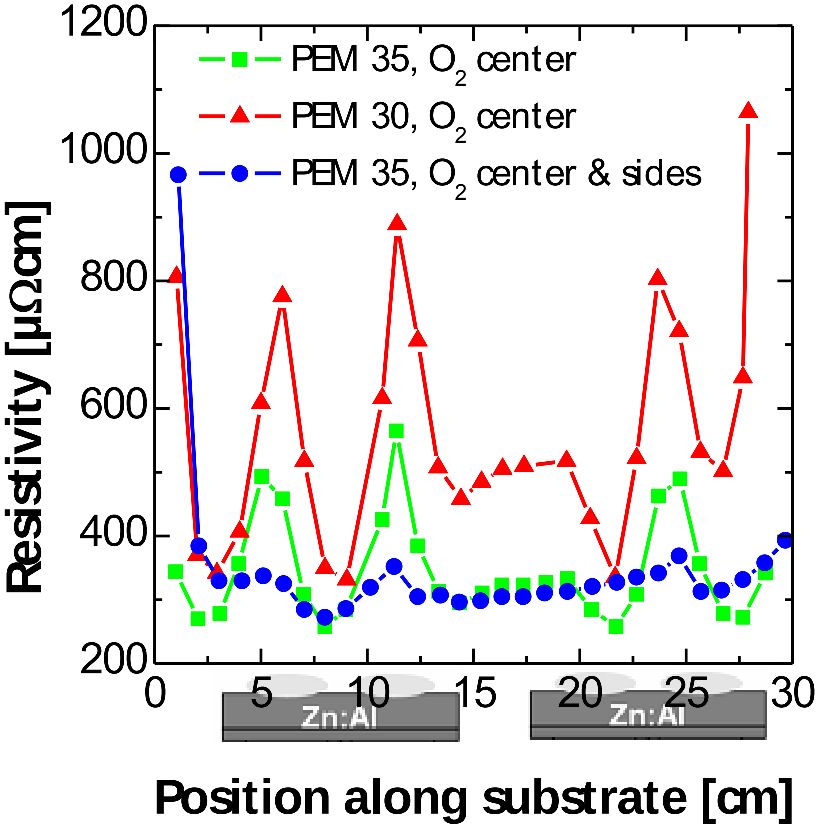
- Experiment:
  - Widerstandsüberhöhung vor den Racetracks.
- Simulation:
  - Modellierung der negativen Sauerstoffionen (Erzeugung, Beschleunigung, Transport, Teilchenstrombilanz am Substrat)



# 2 Properties of reactive MF sputtered ZnO:Al films

## Static deposition





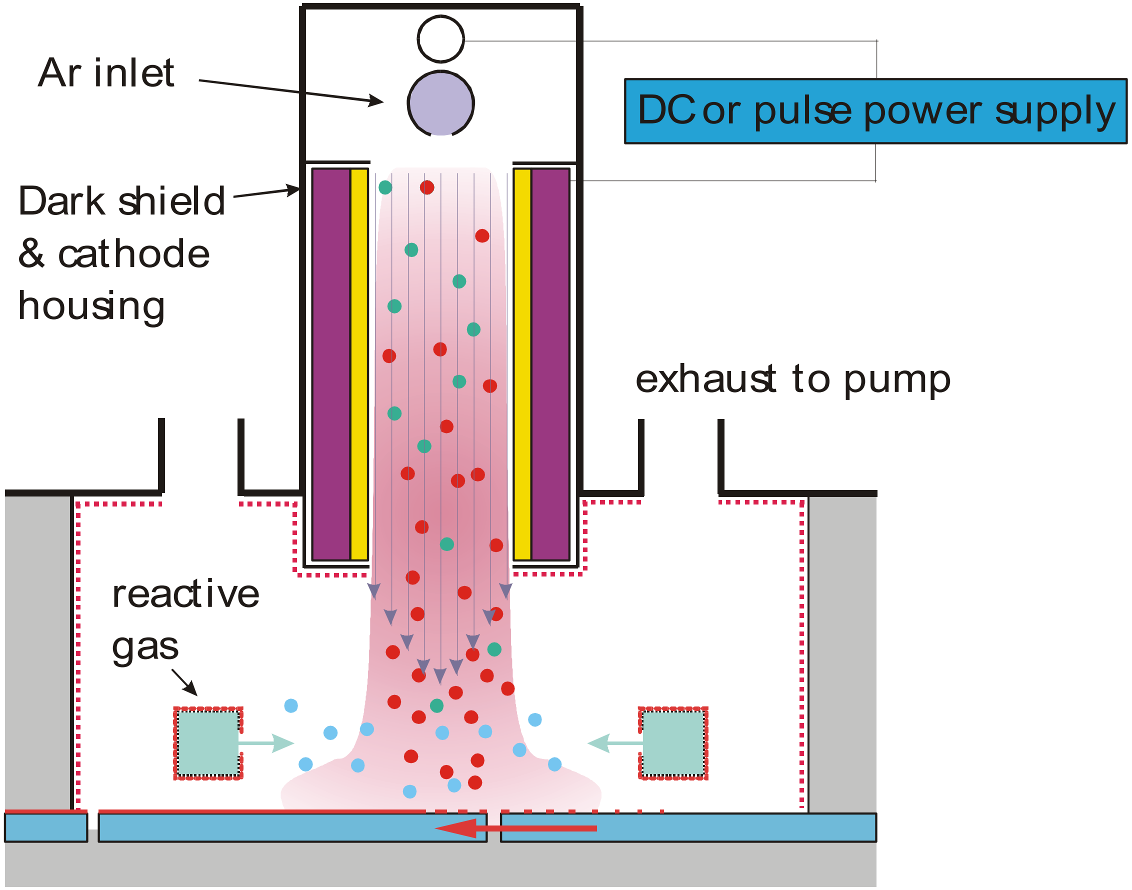
- Dependence of plasma damage on gas inlet system
- Formation of negative ions *can* be suppressed in reactive sputtering.

*S. Calnan et al., Thin Solid Films 516 (2008) 1242*

# 2 Hohlkatoden-Gasflusssputtern (GFS Prozess)

- $p_{tot}$ = 0.1 … 1 mbar
- Keine Targetvergiftung
- Beschichtung mit sehr hoher Rate
- Hohe Plasmadichte
- Niederenergetische Beschichtung
- Targetausnutzung > 80 %

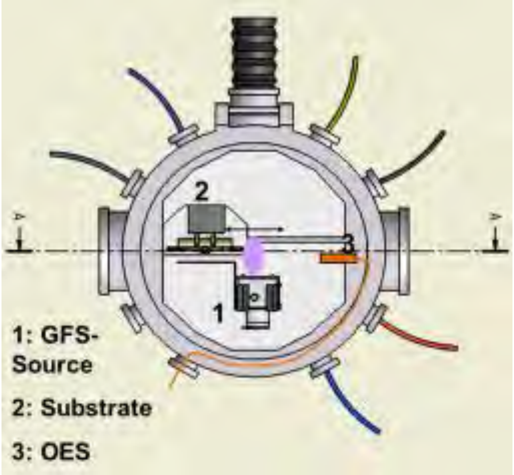
- Die GFS-Technologie wurde in den 1980er Jahren in Adlershof entwickelt.*



* *Akademie der Wissenschaften, Zentralinstitut für Elektronenphysik, Rudower Chaussee 5*
*T. Jung et al., Mat. Sci. Eng. A140 (1991) 528*

# 2 Material development using hollow cathode gas flow sputtering (GFS)

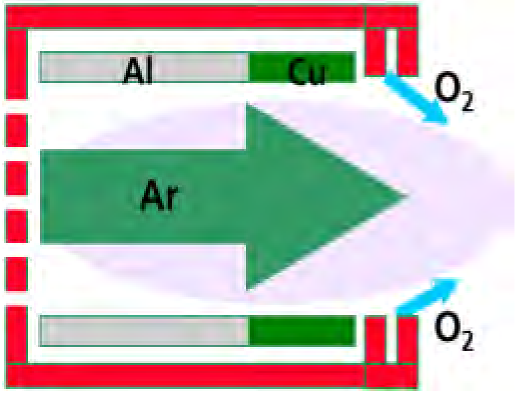
Hollow Cathodes Gas Flow Sputter System



- Scale-able system up to 1m, offered by FhG-IST
- More than 20 units installed

➡ **Simple and rugged, no turbo**

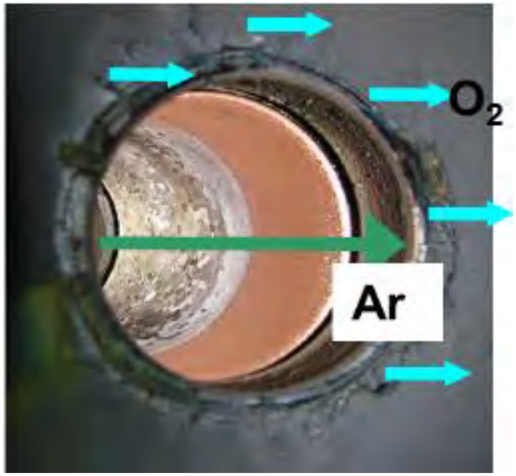
GFS Co-sputter process for Delafossite



- Remote process, no arcing due to purge gas
- Dense plasma / low energy, mbar, high rate

➡ **Soft growth DC sputtering**

Experiment



- Sputtering of Cu and Cr ring segments
- Control by OES and / or pressure

➡ **Adjustable composition**

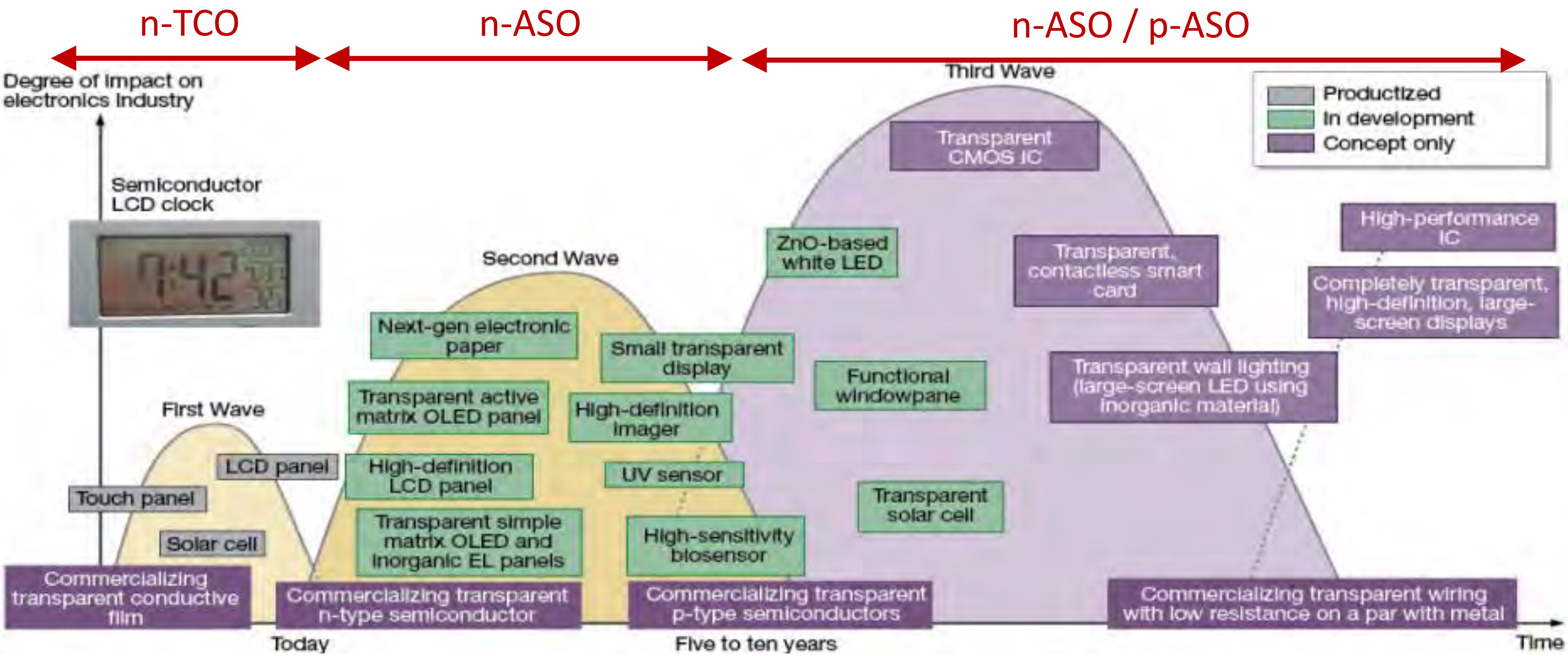
*T. Jung et al., Surf. Coat. Technol. 86-87 (1996) 218 | B. Szyszka et al., Thin Solid Films 518 (2010) 3109*

# 2 Potential of the GFS technology

- Recent results
  - ZTO layers with mobility exceeding 50 $cm^2/Vs$
  - $TiO_2$:W layers capable for visible light induced decomposition of fatty acids
  - p-type delafossite films using reactive GFS
  - UV-protection of polycarbonate with organic modified ZnO capable for more than 4 000 h global radiation.
- Industrialization
  - Pilot lines for 3D parts are being installed in industrial scale at Fraunhofer IST currently

*K. Ortner et al., TCM 2012 | D. Koeßler et al., TCM 2012 | B. Szyszka et al., TSF 518 (2010) 3109 | Minerva Project*

# 2 Road map for oxide based, transparent electronics

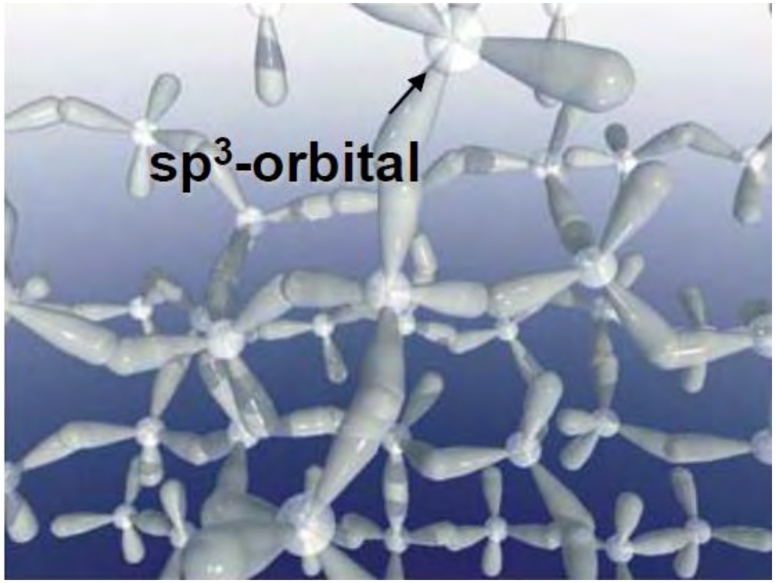


- **1st wave: n-TCOs as transparent conductors**
- **2nd wave: n-ASOs for oxide TFTs and related products**
- **3rd wave: oxide p-n junctions for oxide LEDs and oxide µ-electronics**

*Nikkei Electronics Asia November 2007 – Transparent electronic products soon a reality*

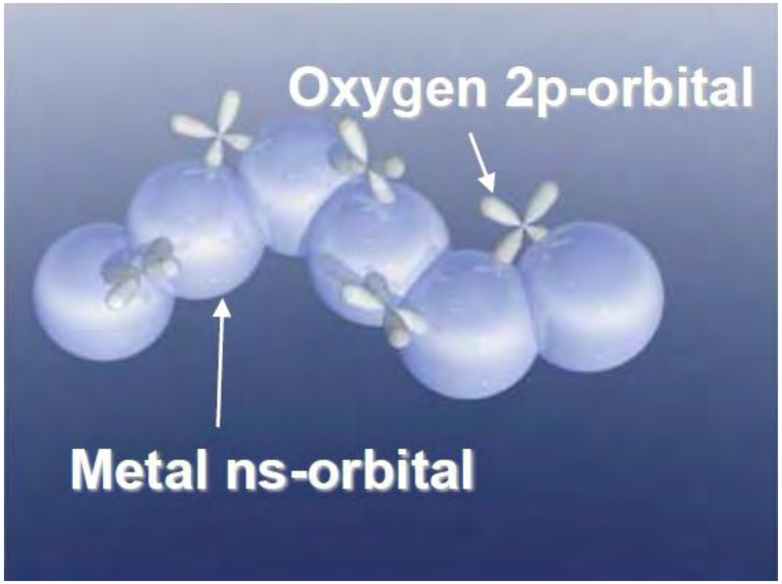
# 2 Amorphous oxides as high quality semiconductive materials

a) Covalent amorphous semiconductor (e.g. a-Si:H)



- ➡ $sp^3$-overlap (cryst. ordering) important for high mobility

b) Amorphous metal oxide (with $(n-1)d^{10}s^0$ $(n \geq 4)$, e.g. $InO_x$)

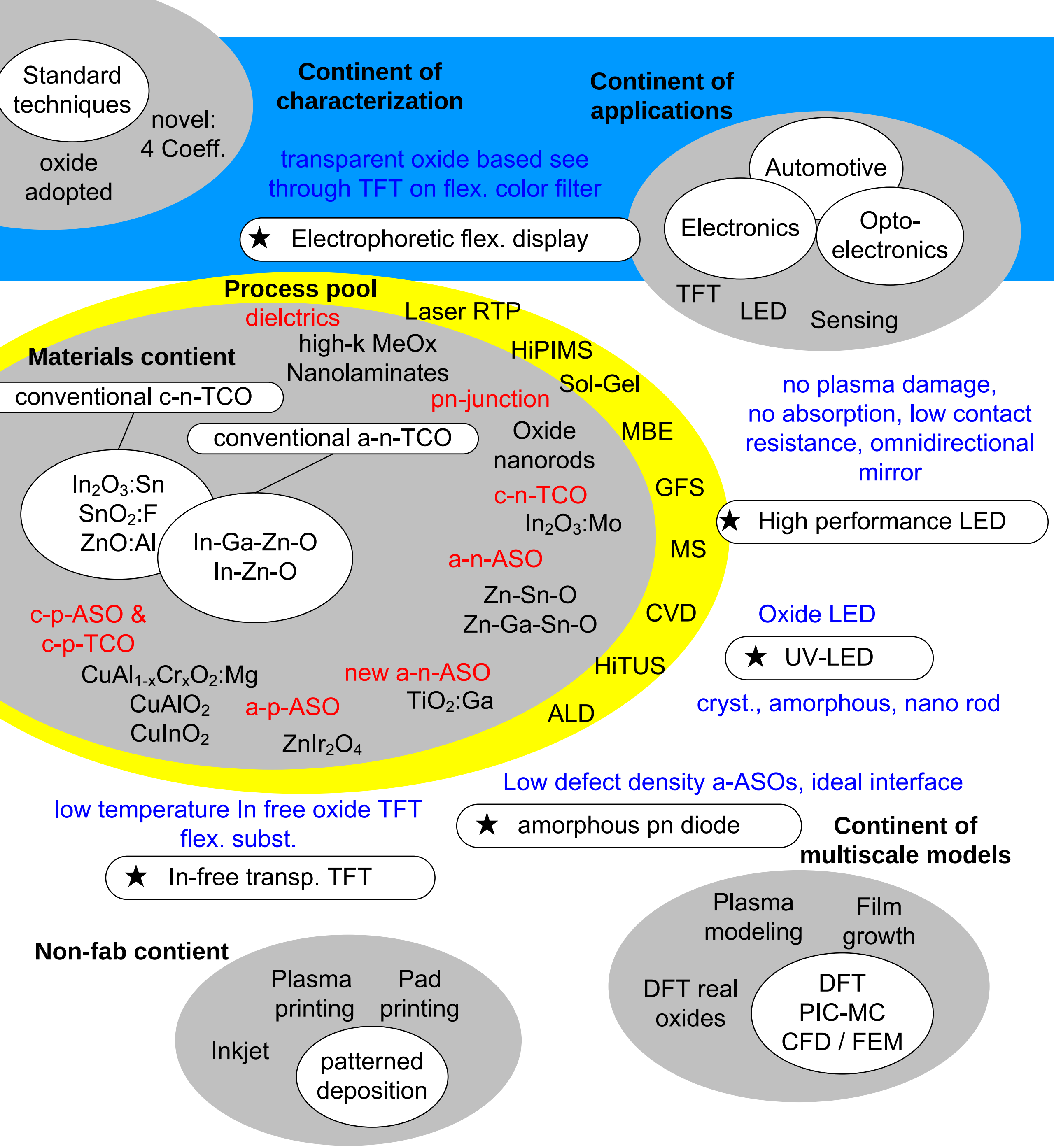


- ➡ Spherical ns-orbitals overlap in a-$MeO_x$
- ➡ High mobility, even in amorphous state.

*K. Nomura et al., Nature 432 (2005) 488 | H. Hosono et al., J. Non Cryst. Sol. 198-200 (1996) 165*

# Oxide electronics: the unknown sea map

## *ORAMA FP7 R&D topics*



Standard techniques

novel: 4 Coeff.

oxide adopted

**Continent of characterization**

**Continent of applications**

Automotive

Electronics

Opto-electronics

TFT

LED

Sensing

transparent oxide based see through TFT on flex. color filter

★ Electrophoretic flex. display

**Process pool**

dielctrics

Laser RTP

high-k MeOx

Nanolaminates

HiPIMS

Sol-Gel

pn-junction

MBE

Oxide nanorods

GFS

c-n-TCO

$In_2O_3$:Mo

MS

a-n-ASO

Zn-Sn-O

Zn-Ga-Sn-O

CVD

HiTUS

new a-n-ASO

$TiO_2$:Ga

ALD

**Materials content**

conventional c-n-TCO

conventional a-n-TCO

$In_2O_3$:Sn

$SnO_2$:F

ZnO:Al

In-Ga-Zn-O

In-Zn-O

c-p-ASO & c-p-TCO

$CuAl_{1-x}Cr_xO_2$:Mg

$CuAlO_2$

$CuInO_2$

a-p-ASO

$ZnIr_2O_4$

no plasma damage, no absorption, low contact resistance, omnidirectional mirror

★ High performance LED

Oxide LED

★ UV-LED

cryst., amorphous, nano rod

Low defect density a-ASOs, ideal interface

★ amorphous pn diode

low temperature In free oxide TFT flex. subst.

★ In-free transp. TFT

**Continent of multiscale models**

Plasma modeling

Film growth

DFT real oxides

DFT

PIC-MC

CFD / FEM

**Non-fab contient**

Plasma printing

Pad printing

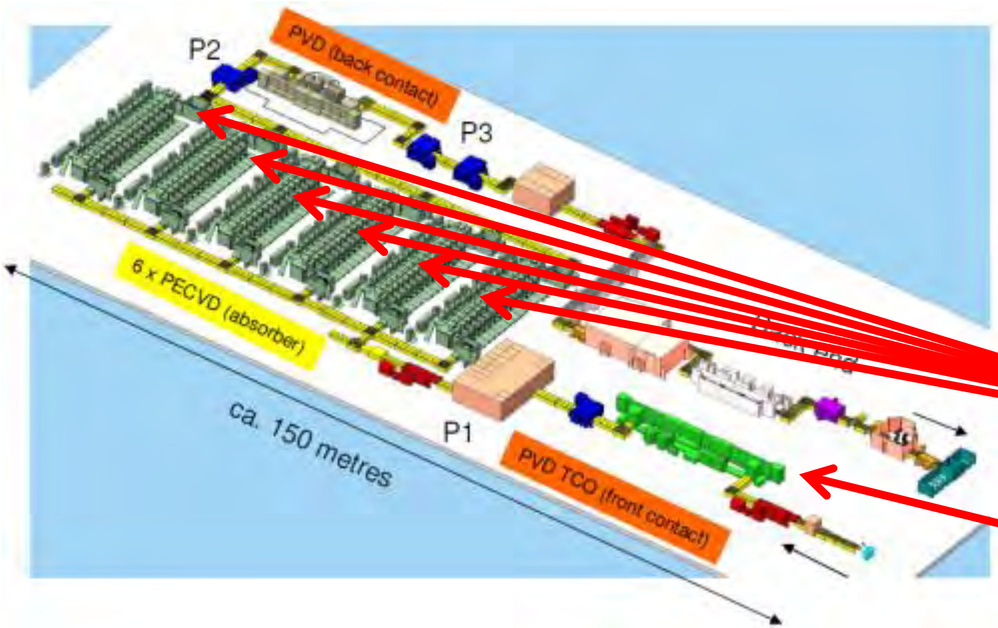
Inkjet

patterned deposition

*www.orama-fp7.eu*

# 2.2 Conventional a-Si:H / µc-Si:H 50 MWp plant

More challenging than expected…but a story to be continued



- 50 MWp production
- Cycle time: 70 s
- Status 2009: η = 8.5 %
- Status 2012: η = ~10.5 %

**… feeds them all!**

**One TCO coater ….**

- Cost driver #1: Low efficiency
- 2014: DEMO 14 project, 14 % cell efficiency, 12 % module (stable)

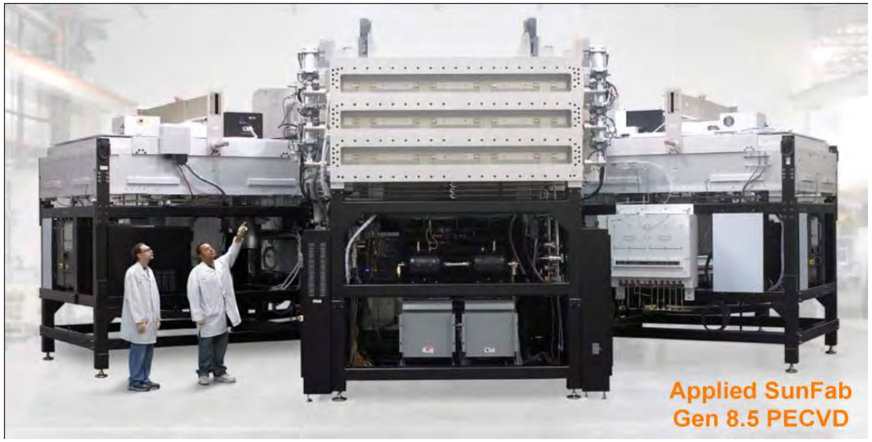
- Cost driver #2: Large area PECVD (6 RF or VHF cluster tools!)

- Cost driver #3: TCO
- Ceramic target ZnO:Al, insufficient light management

*M. Liehr et al. (Leybold Optics), Presentation V2009 (Dresden, Oct. 2009)*

# 2.2 Substitution of PECVD by novel processes

## Hot wire CVD (CAT CVD)

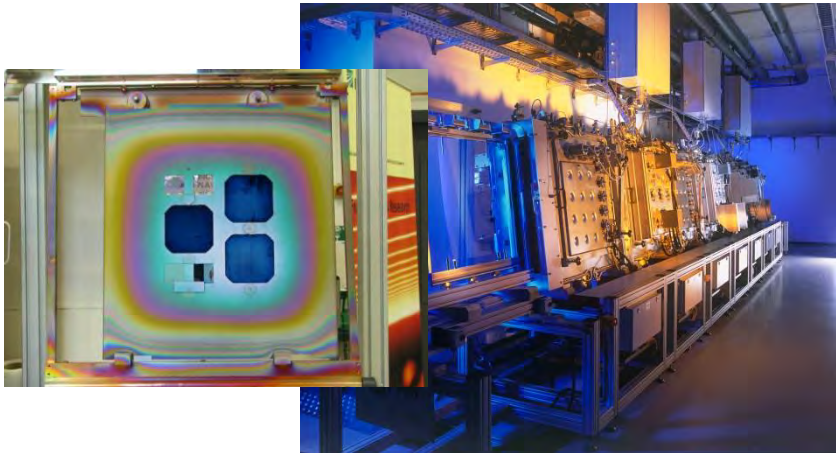


**a) State of the art: Large Area PECVD**

- ➡ AMAT SunFab: Gen. 8.5 (5,7 $m^2$)
  Oerlikon KAI 1200: Gen 5 (1,5 $m^2$)
- ➡ Low rate (< 1 nm/s)
- ➡ Poor material utilization
- ➡ Complex technology
- ➡ Adopted from flat panel display

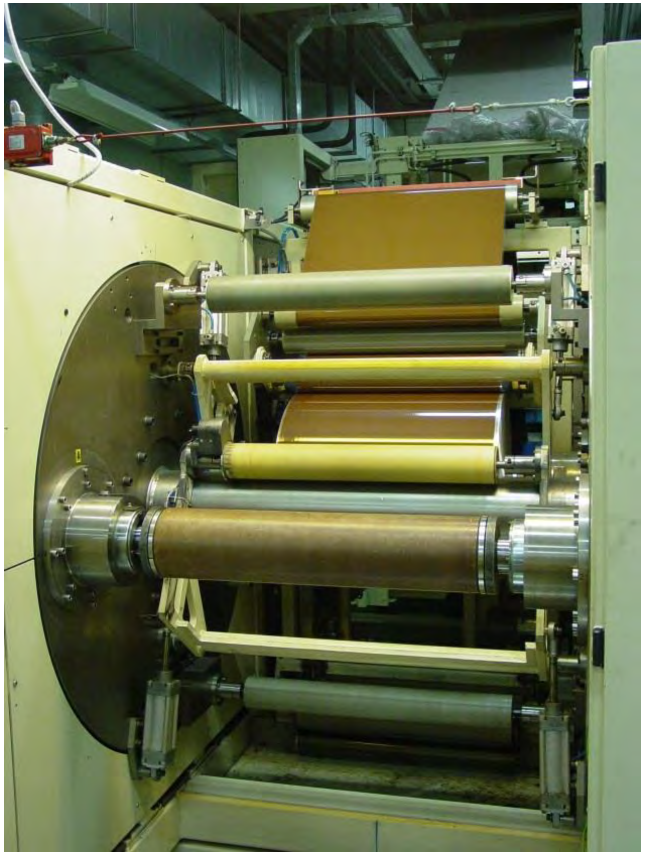
**b) Hot-wire CVD**

- ➡ Activation of $SiH_4$ at the hot wire
- ➡ Simple, robust, in-line compatibel
- ➡ Lab: a > 1.5 nm/s achieved
- ➡ Scaling: 50 x 60 $cm^2$ @ FhG-IST
- ➡ Material utilization > 80 %



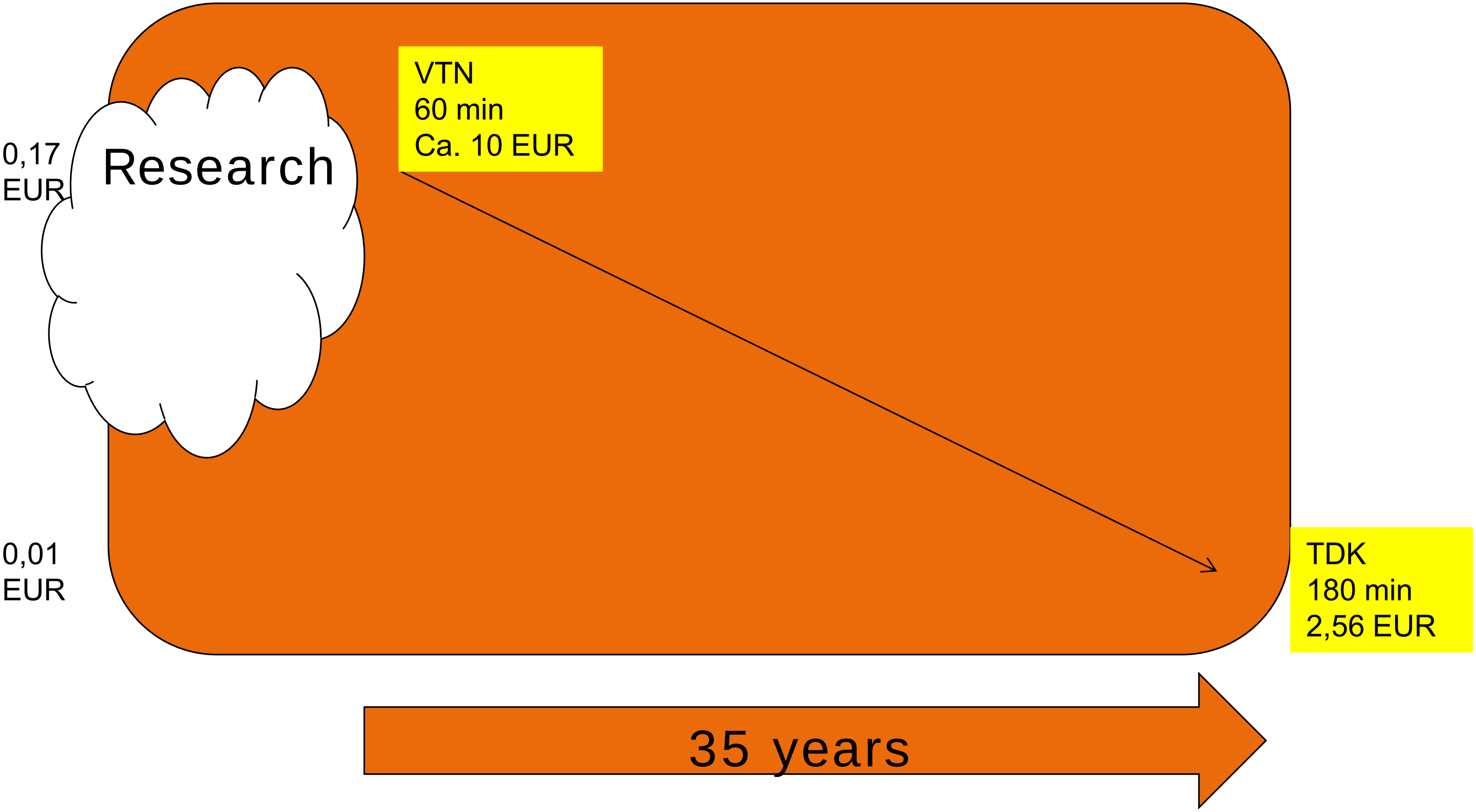
# 2.3 Rückblick: Herstellung von Videoband mittels Slot-Dye-Coating

- Schnelle Beschichtung von Rolle zu Rolle:
  - Atmosphärendruckprozess
  - Schichtdicke ~40 µm
  - 1200 m/min bei 120 cm Breite, 24/7 Betrieb
- Prozessschritte:
  - Lack-Vorbereitung (Suspension herstellen, mischen, filtern)
  - Band Reinigung
  - Hochgeschwindigs-Coating endlos von Rolle-zu-Rolle
- Aufgabe OPV:
  - Transfer auf OPV Stacks
  - Kontaktierung / Barrieren / Effizienz / Lebensdauer



*D. Teckhaus, IDTechEx Printed Electronics & Thin Film Week, April 2013*

# 2.3 Entwicklung der Kostensituation bei Videotapes: Faktor 17 in 35 Jahren



0,17
EUR

Research

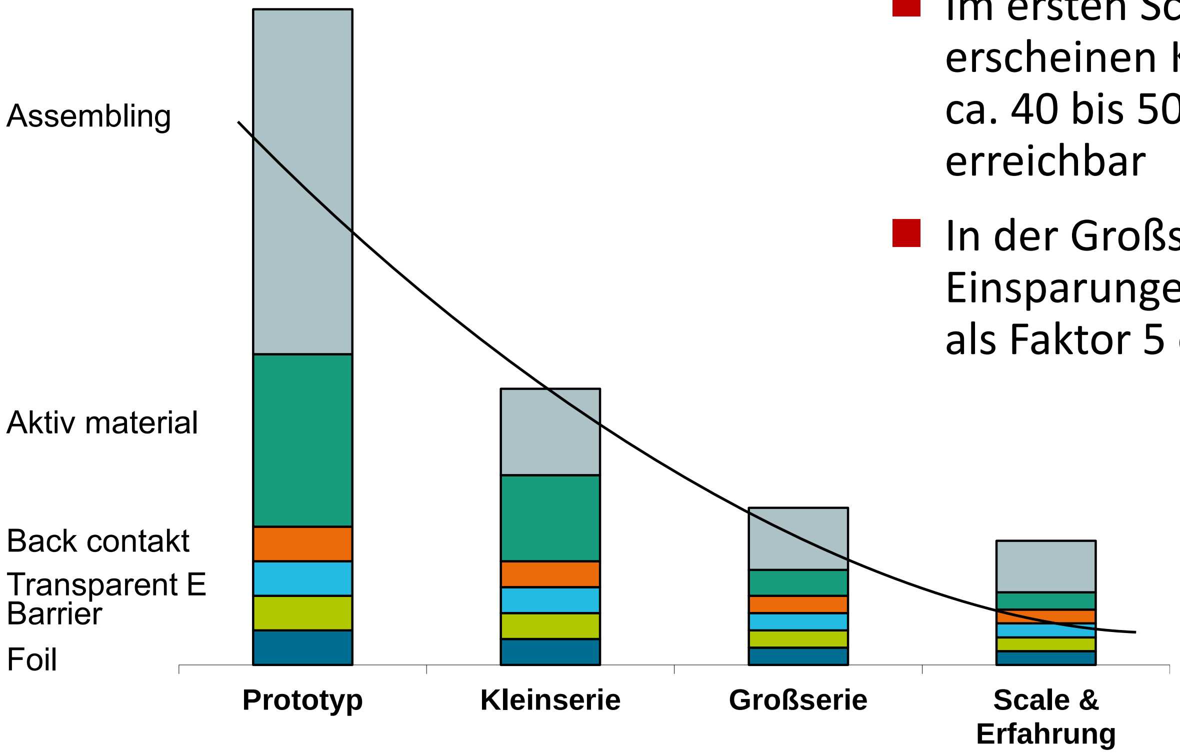
VTN
60 min
Ca. 10 EUR

0,01
EUR

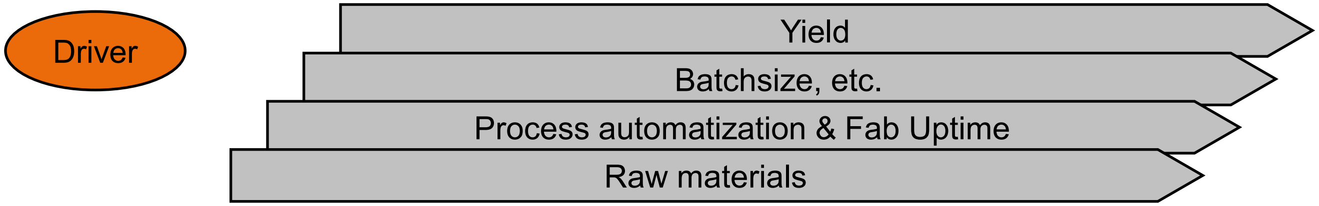
TDK
180 min
2,56 EUR

35 years

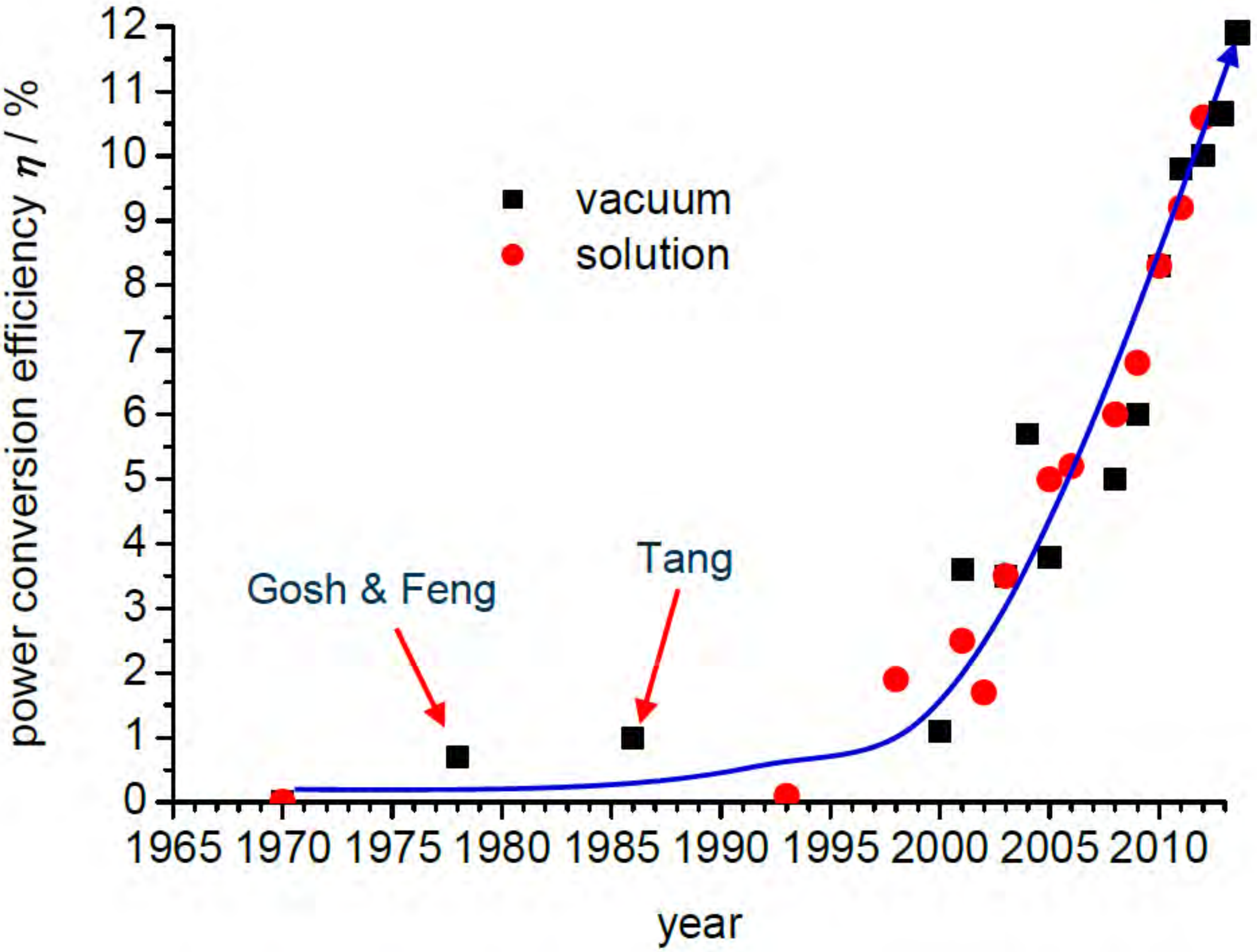
# 2.3 OPV Kostenszenario



- Im ersten Schritt erscheinen Kosten von ca. 40 bis 50 €/m² erreichbar
- In der Großserie Einsparungen um mehr als Faktor 5 erreichbar



# 2.3 OPV: Vakuumbasierte vs. nasschemische Prozesse

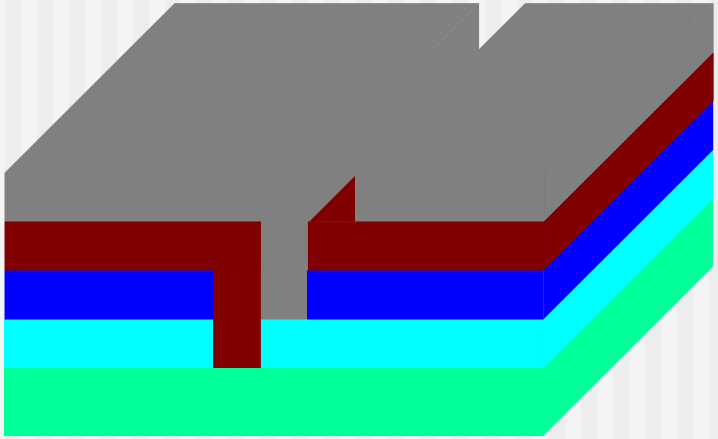


*H. Hoppe, IDTechEx Printed Electronics & Thin Film Week, April 2013*

# Results PPP-Project R2R OPV System

# Gen1 (Starting PPP)

| layer | back electrode |
|---|---|
| process | P3: laser ablation |

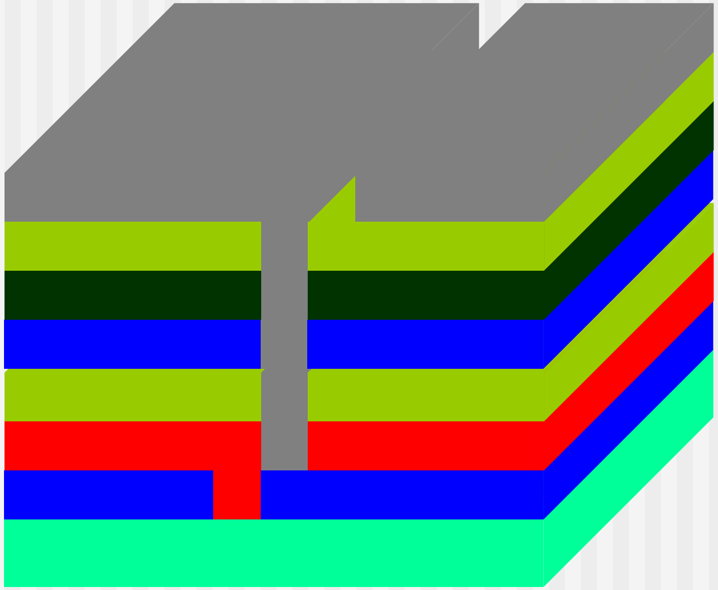


| Generation | 1 |
|---|---|
| semitransparent electrode | ITO/PEDOT:PSS |
| active layer | P3HT:PCBM |
| ETL interlayer | none |
| back electrode | aluminium |
| efficiency target | 2.5% |

*D. Teckhaus, IDTechEx Printed Electronics & Thin Film Week, April 2013*

# Gen4 (planed PAPPA)

| layer | back electrode |
|---|---|
| process | P3: laser ablation |



| Generation | 4 |
|---|---|
| semitransparent electrode | silver grid & PH1000 (ZnO) |
| active layer 1 | to be defined |
| ETL interlayer | TiOx |
| HTL interlayer | PEDOT:PSS |
| active layer 2 | to be defined |
| ETL interlayer | TiOx |
| back electrode | AL (AG or AU) |
| efficiency target | 8-10% |

*D. Teckhaus, IDTechEx Printed Electronics & Thin Film Week, April 2013*

# 3 Zusammenfassung und Ausblick

| | |
|---|---|
| Relevanz des Themas „Beschichtungen für erneuerbare Energien“ | Schlüsselthema für die Energiewende und für das Erreichen der $CO_2$-Einsparziele<br>Massiver Ausbau notwendig |
| Vakuumverfahren | Neue Ebene des Verständnis durch Modellierung<br>Megatron$^{TM}$: Schlüsseltechnologie für PVD<br>Hohlkatoden-Gasflusssputtern: Neue Basistechnologie für die Materialentwicklung |
| OPV mittels Slot-Dye Bandbeschichtung | Basierend auf der Video-Tape-Fertigung<br>Hoch innovatives und ausbaufähiges Verfahren |

**Crystals are like people, it is the defects in them which tend to make them interesting!**

Prof. John Ziman
(solid state physicist and humanist,
born1925, died 2005)

**Vielen Dank für die Aufmerksamkeit**

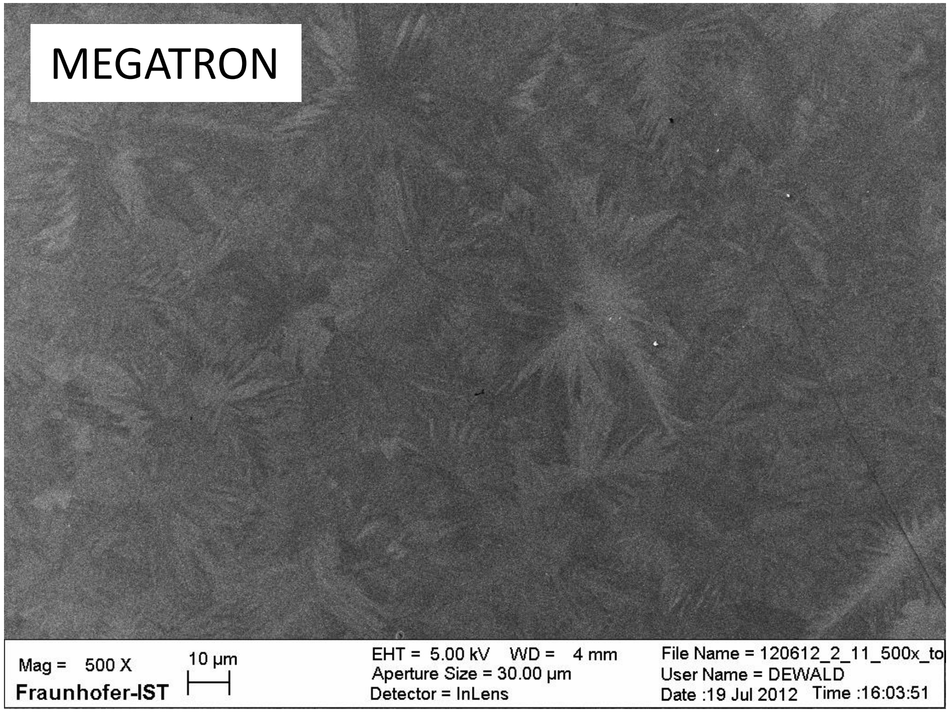
# 2 Conditions for $ZnSnO_x$ deposition by C-Mag sputtering

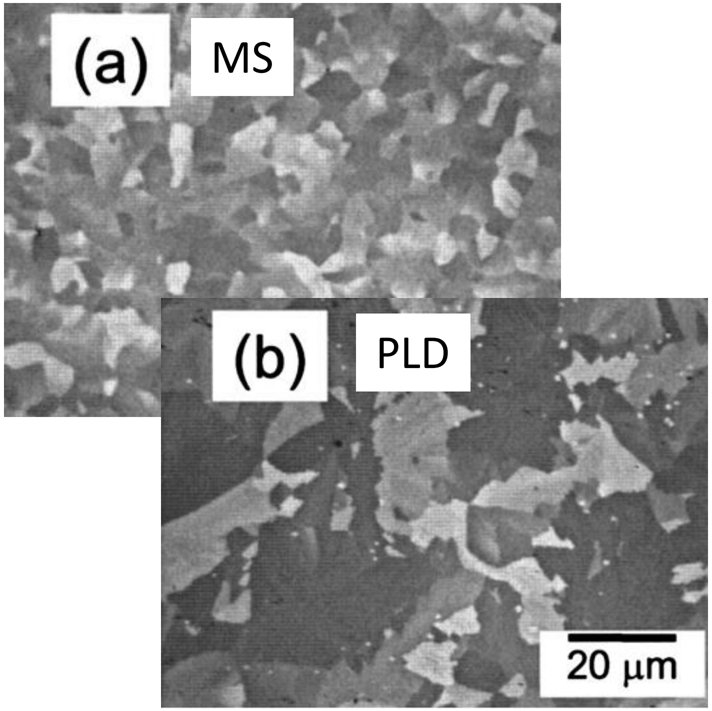
| | | | |
|---|---|---|---|
| Process | Bipolar CMAG 61.5 kHz | | |
| System parameters | Base pressure | $P_0$ | $< 5 \times 10^{-6}$ mbar |
| | Cathode | | Dual cylindrical cathode (Interpane) |
| | Generator | | AE Crystal |
| | Target to substrate dist. | $d_{ST}$ | 190 mm |
| | Target material | | $ZnO:SnO_2$ (Zn:Sn = 68:32) |
| Process parameters $ZnO:SnO_x$ deposition | Gas flows | q(MG) | Ar: 190 sccm,<br>Ar+10%$O_2$: 50 sccm |
| | Total pressure | $P_{tot}$ | ≈ 400 mPa |
| | Power | P | ~ 15 kW / bipolar MF @ 61.5 kHz |
| | Substrates | | Float glass |
| | Carrier speed | $v_C$ | Static, 15 min |
| | | | |

# 2.2 Example: Nb-doping of $TiO_2$

## Synthesis of $TiO_2$ based TCOs by MEGATRON sputtering

- 2 x 1 kW with $TiO_2$ rotatable, 2 x 200 W with Nb planar targets
- Annealing at 350 °C in vacuum for 1 h -> large anatase grains > 10 µm
- $d = 211$ nm, $R_{Sh} = 99.8\ \Omega$, $\rho = 2100\ \mu\Omega cm$, $T_v = 67.6\%$, $n = 2.45$





*a, b: T. Hitosugi et al., JVSTA 26 (2008) 1027*