Materials for an Energy Efficient Society

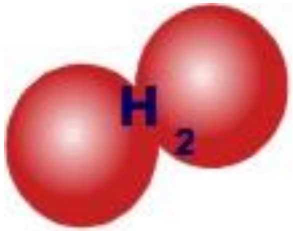
Nuclear Energy

↙ ↘

Solar Energy → Light + Wind

Geothermal Energy → Hot Water (Vapour)

→



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Distribution

Storage

Conversion

Application

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Münster University of Applied Sciences

Steinfurt/Münster, September 09th, 2021

To My Person

CV

• University Bochum (1987 - 1994)	*Coordination Chemistry*
• Max-Planck Institute Mülheim (1995)	*Electrochemistry*
• Philips Research Aachen (1995 - 2004)	*Solid State Chemistry, Luminescence*
• Münster University of Applied Sciences (since 2004)	*Scintillators* *Functional Optical Materials*
• Dean of department „Chemical Engineering“ (since 2013)	

Teaching

- Inorganic Chemistry
  - Solid state chemistry
  - Coordination chemistry
  - Bioinorganic chemistry
- Material Science
  - Optical materials
  - Luminescent materials
  - Material characterisation
- Incoherent Light Sources, Photochemical Water Treat. & History of Science

Research Group Tailored Optical Materials

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TOM Tailored Optical Materials

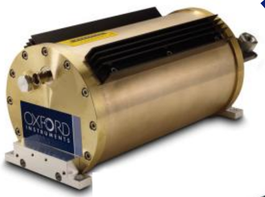
Research Areas
- Luminescent Pigments
- Luminescence Physics
- Nanoscale Pigments
- Core-Shell particles (coatings)
- Optical Spectroscopy
- Solid State Chemistry

Research Group Tailored Optical Materials

Xenon disch. lamp,
wavelength range
200 nm - 900 nm

Fianium supercontinuum
SC450-4 white light laser,
wavelength range 0.46 - 2.4 µm

X-Ray Tube Neptune 5200
Voltage Range: 10 - 50 kV
Max. Power: 100 W



D_2 bulb, wavelength
range 120 - 400 nm

EPL ps Laser,
wavelength 265,
375, or 445 nm

Continuous laser,
wavelength 375,
405, 445, or 488 nm

High brightness
LEDs from 250 -
1100 nm

Americium source,
α- and γ-radiation

Outline

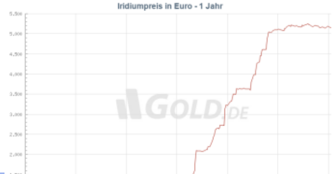
1. Challenges of the 21st century
2. Metals and Materials
3. Matter Radiation Interaction
4. Photovoltaic Materials
5. Photochemical Water Splitting
6. Lighting Towards Ultimate Efficiency
7. Conclusions and Outlook
8. Literature

increasing land and water consumptio

1. Challenges of the 21st Century

- Overview -

- **Increasing land and water consumption**
    - Endangering the safety of drinking water and food supply
    - Loss of arable land and pasture
    - Evaporation of sweetwater lakes
- **Increasing demand on raw materials endangers ressource security**
    - Strategic metals: Li, Co, Cu, Ga, Ge, In, rare earth metals, W, Ir, Bi, …
    - Plastic crises: µ-plastics, biopolymers, recycling, critical additives and optical marker
    - Quarz crisis: Extremely growing demand on constructing materials
    - Phosphate crisis: Mines are driven at the limits
    - Iridium crisis: Water purification process via electrochlorination increases demand



- **µ-Microplastics and input of nutrients into biosphere**
    - Endangering marine and terrestric food chains
    - Reduction of biodiversity
    - Expansion of dead zones in oceans

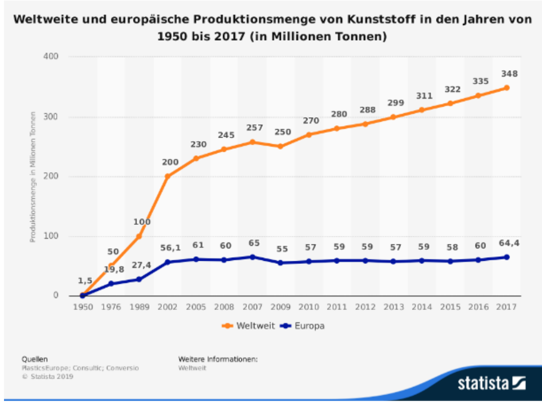
- **Emission of greenhouse gases and climate change**
    - Energy production without CO_2 emission: PV, Wind → H_2, PtG, LNG, Batteries
    - CO_2 deposition: $1 \cdot 10^{12}$ t CO_2 until 2100 for 2° Goal (SdW 08/19) → geochemistry?
    - New types of mobility: Electrical engines, fuel cells, artificial fuels

1. Challenges of the 21st Century

- Air, Soil, and Water Pollution -

Reduce or prevent application of hazardous substances

- Radioactive materials, U, Th, T, Pm, …..
- Heavy metals, e.g. Hg, Tl, Pb, Cd, …..
- Toxic, bioactive, or non-biodegradable organic compounds → plastics: “Great Pacific Garbage Patch”
- 2050: More plastic than fish in ocean water!



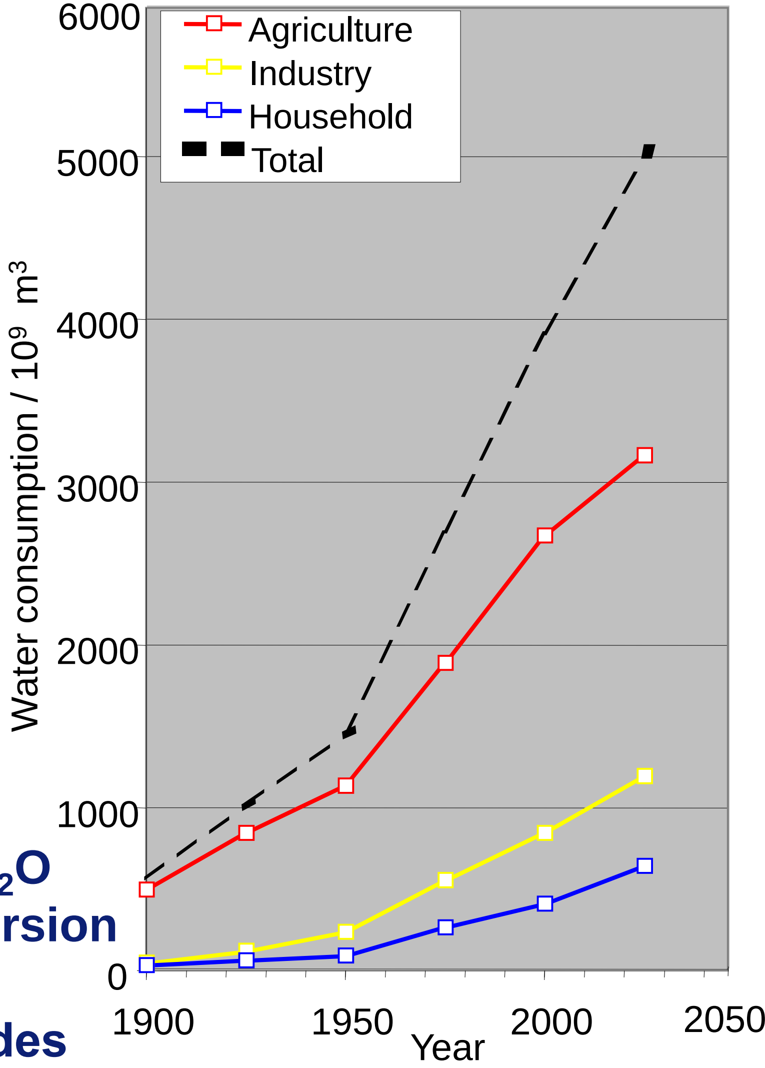
⇒ Apply green chemistry: Technologies that

- minimize or preferably eliminate the formation of waste
- avoid use of toxic & hazardous solvents and reagents
- utilize renewable raw materials
- are energy efficient

- Bioreactors → Biochemistry, microorganism design
- Catalysis → Catalytic pigments/coatings, reactor design
- Photochemistry → Frequency selective radiation sources
- Solar chemistry → Solar radiation + converter or concentrator
- Fast analytics @ point of use → Advanced optical spectroscopy

1. Challenges of the 21st Century

- Air, Soil, and Water Pollution -



- UV-C Radiation (265 nm) inactivates micro organisms due to photochemistry of DNA
- VUV Radiation (180 - 200 nm) oxidizes due to H_2O cleavage into radical species and O_2 to O_3 conversion

Industrial installations → discharge lamps

Mobile devices → discharge lamps / (laser) diodes

1. Challenges of the 21st Century

- Demand for Strategic Metals -

- **Electric & hybrid vehicles (~30 kg Rare Earth / hybrid car): Growing mobility!**
  Co, Li (ion batteries), Rare Earth Elements (REE), Cu

- **Fuel cells**
  Pt, (Ru, Pd, Au)
- **Thermoelectrics, Optoelectronics, ILEDs, OLEDs, (µ-LED) displays**
  Bi, Te, Si, In, Ga, As, Se, Ge, Sb, Ir, Pt

- **Photo voltaics**
  Si, Ag, In, Ga, Se, Te, Ge, (Ru)
- **Wind turbines, generators, electrical engines, magnets**
  Nd, Sm, Pr, Dy, Cu

1. Challenges of the 21^{st} Century

- Dissipation of Heavy Metals -

- Hg from discharge lamps, batteries, thermometers, combustion of coal ends up at earth's cold spots, mainly at polar regions

- Pb and Ba from accumulators, displays, and high refractive glass ends up in Ca metabolism

- Sn from paints goes into aquatic system + reacts to toxic metalorganic compounds

- Cr, As, Sb, and Bi from paints, pigments modify DNA

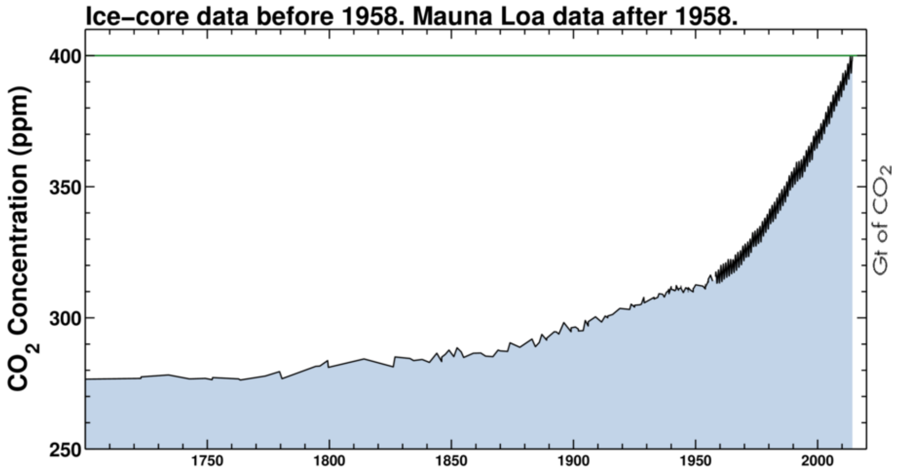
- Ga and In from LEDs, LCDs, OLEDs are harmful to the kidney and liver metabolism

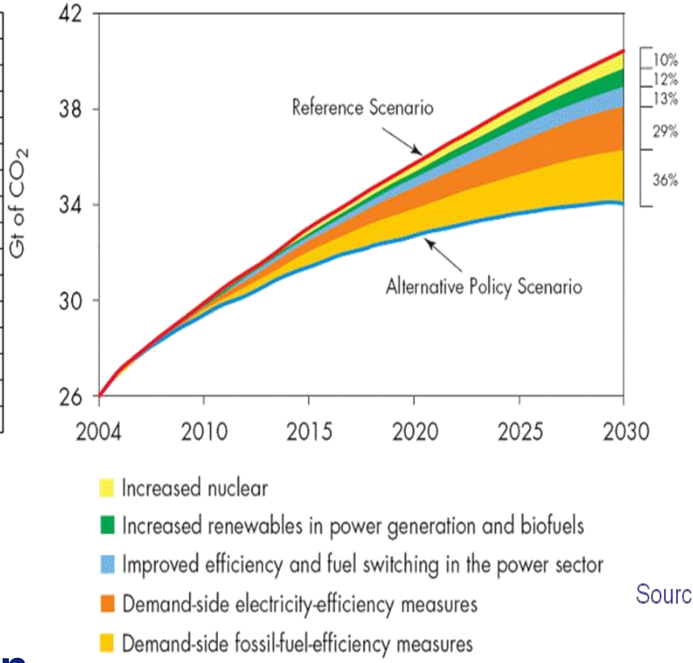
- Cu, Ag, Pt, and Au from electronic devices are bioactive

- Actinides from nuclear industry, U also from artificial fertilisers (phosphates)

1. Challenges of the 21st Century

- Climate Change Due to CO_2 Emission -





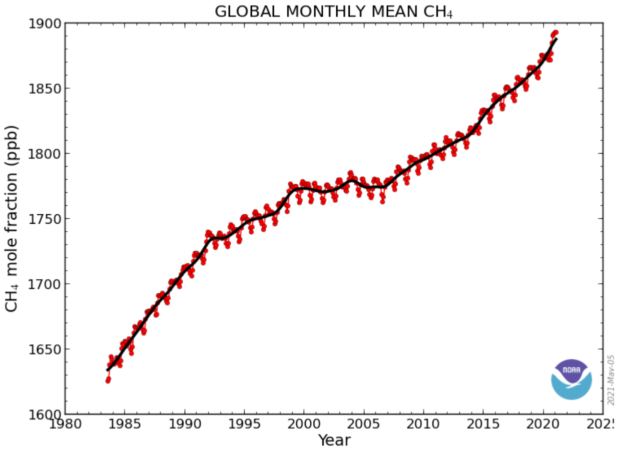
Source: International Energy Agency
World Energy Outlook 2006

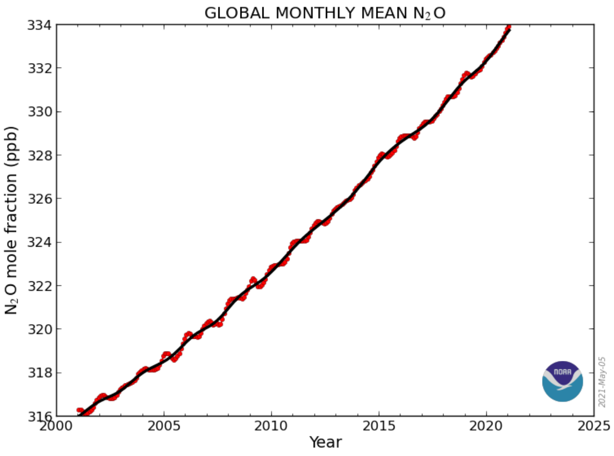
Further consequences of CO_2 emission

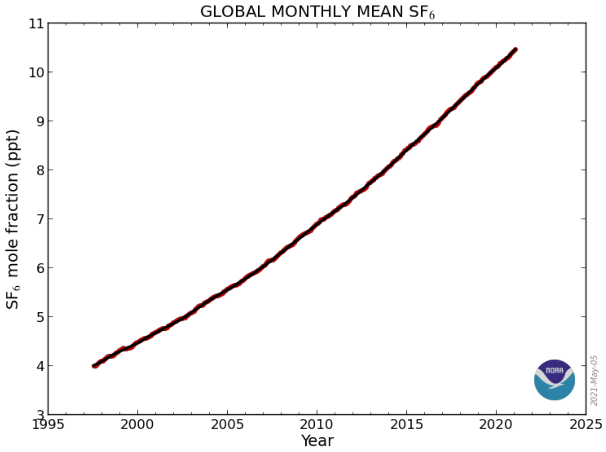
- Acidification of oceans: endanger marine ecosystems
- Reduction of glacier and polar ice: sea water level rise
- Modification of plant physiology: increasing sugar content
- Increasing water and soil temperature: Emission of CH_4 from permafrost areas
- Reduction of air quality

1. Challenges of the 21st Century

- Climate Change Due to other Greenhouse Gas Emission -







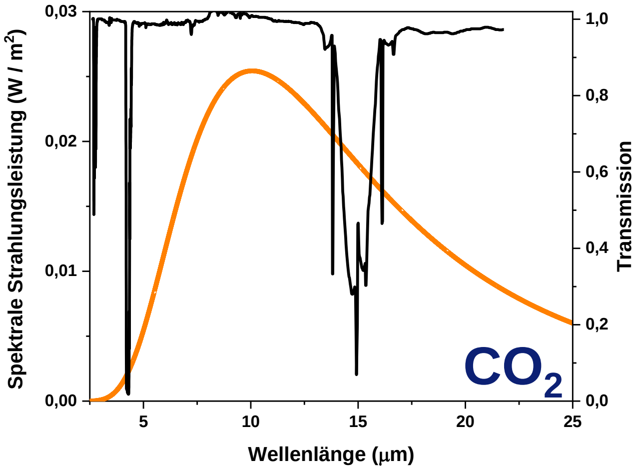
Greenhouse gas	concentration 2021	GTP100
CO_2	417 ppm	1
CH_4	1891 ppb	11
N_2O	334 ppb	297
CF_4	~ 90 ppt	9560
SF_6	10.56 ppt	28200

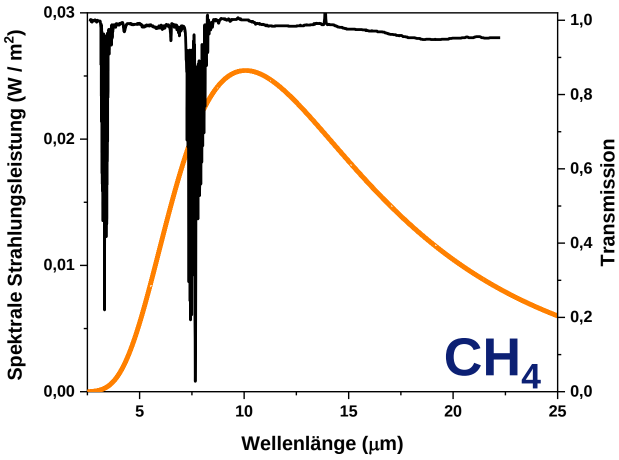
Source: Mauna Loa, Hawaii, https://gml.noaa.gov/ccgg/trends)

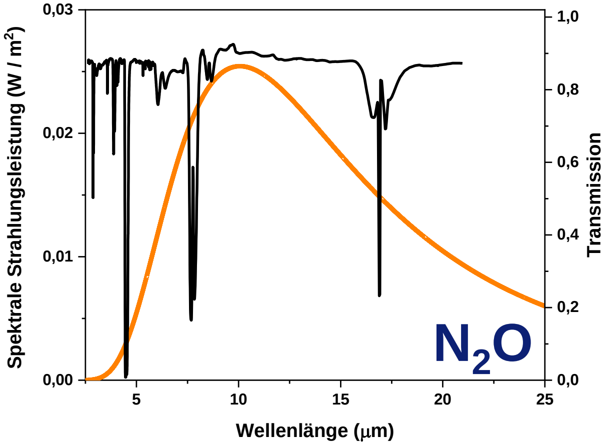
1. Challenges of the 21st Century

- Climate Change Due to Greenhouse Gases -

Greenhouse gas potential depends on the absorption spectra of trace gases and average global temperature of the Earth‘s surface (T_e ~ 288 K ~ Planck spectrum)

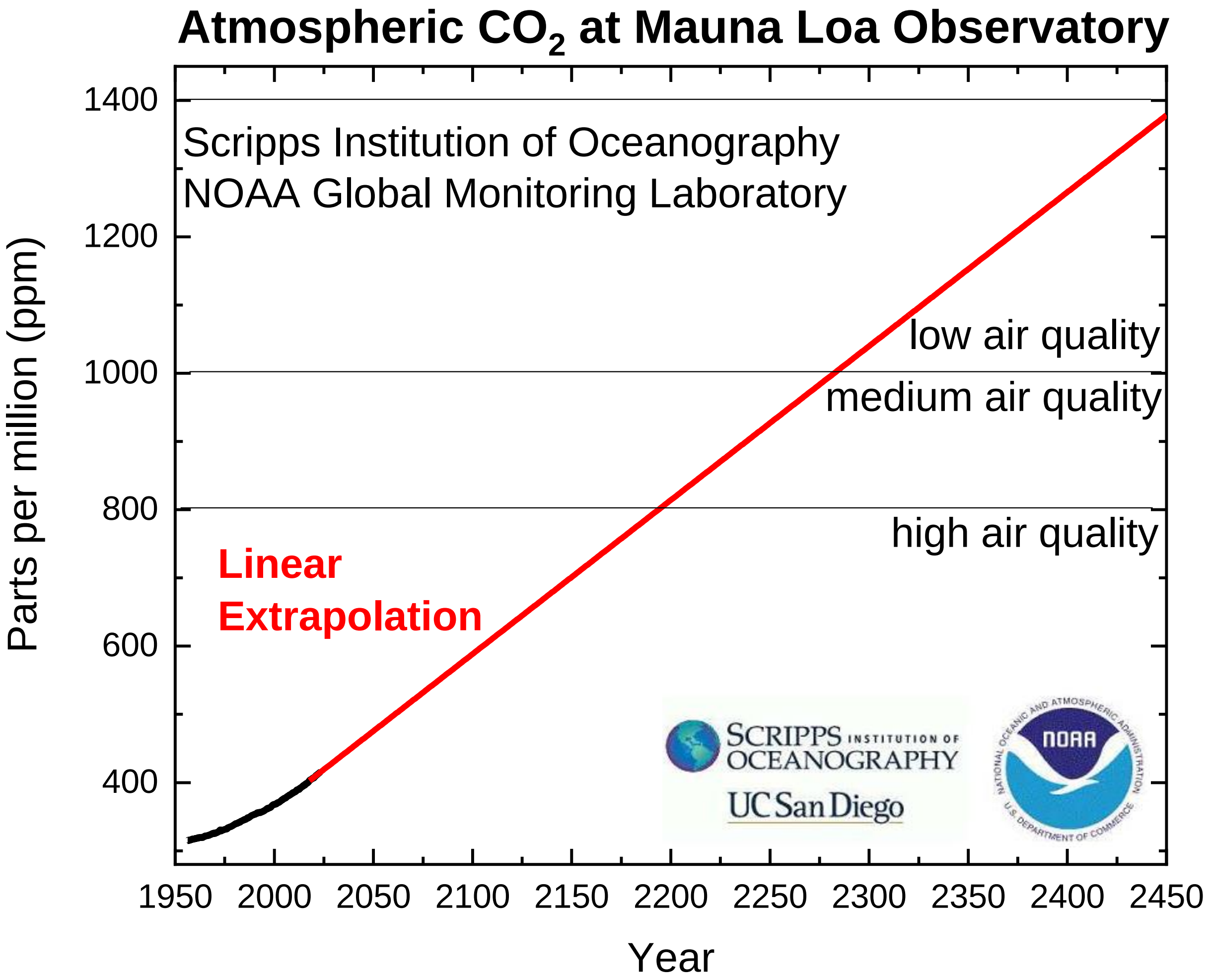






1. Challenges of the 21st Century

- Loss in Brain Power Due to CO_2 Emission -



1. Challenges of the 21st Century

- Causes of Greenhouse Gas Emission -

CO_2

• Illumination	(5%)	LED technology
• Transport	(~ 25%)	Novel engines and fuels
• Buildings	(6%)	Thermal insulation
• IT	(2%)	Server architecture, PV use
• Steel production	(5%)	H_2 as reductive agent
• Cement production	(6-7%)	Reduction of cement fraction in concret
• Ammonia synthesis	(1-2%)	N_2 hydration by water vapor, N_2 photolysis
• Chloralkali electrolysis	(~1%)	Change to membrane process, heat recovery

CH_4/N_2O

• Agriculture and feedstock	Reduction of meat consumption
• HNO_3 and Nylon production	Optimisation of Ostwald process,

SF_6/NF_3

• (Consumer) Electronics	Other insulator gases, optimisation of processes for the production of displays & solar cells

1. Challenges of the 21st Century

Energy Efficient Date Storage and Transfer: Rebound Effect

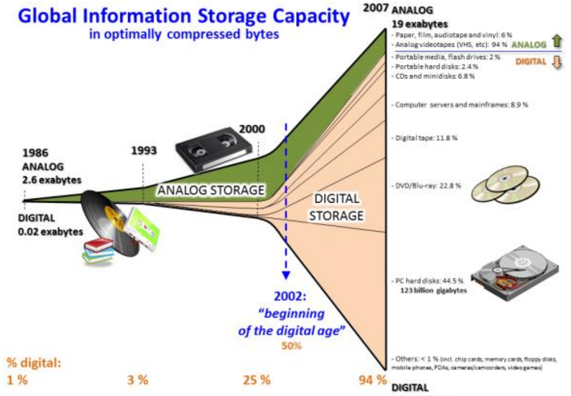
Discoveries & inventions for knowledge management

1015	Ibn Al Haythem (Basra, 965 – 1040) “Book of Optics“
1455	Gutenberg Bible: 1st book printed with movable metal types
1815	Fresnel and the wave nature of light
1865	Maxwell and electromagnetic waves
1915	General relativity – light in space and time
1945	Z4 of Konrad Zuse (2200 Relais)
1965	Cosmic microwave background & Optical fibre technology
1989	Birth year of the WWW
2002	Beginning of the digital age
2007	~ 300 exabyte stored
2010	50 Gbps transmitter (by four laser)
2014	Data transfer rate > 100 Gbps
2015	International Year of Light (IYL), > 1 ZB stored….
2018	~ 4-5 ZB stored, 1+ bill. google searches, 294 bill. mails, and 230 mill. tweets/day
2020	~ 44 ZB stored
2030	Internet ~ 21% of projected electricity demand (Ref.: Nature 561 (2018) 163)

Energy demand / bit ↓

Efficiency ↑

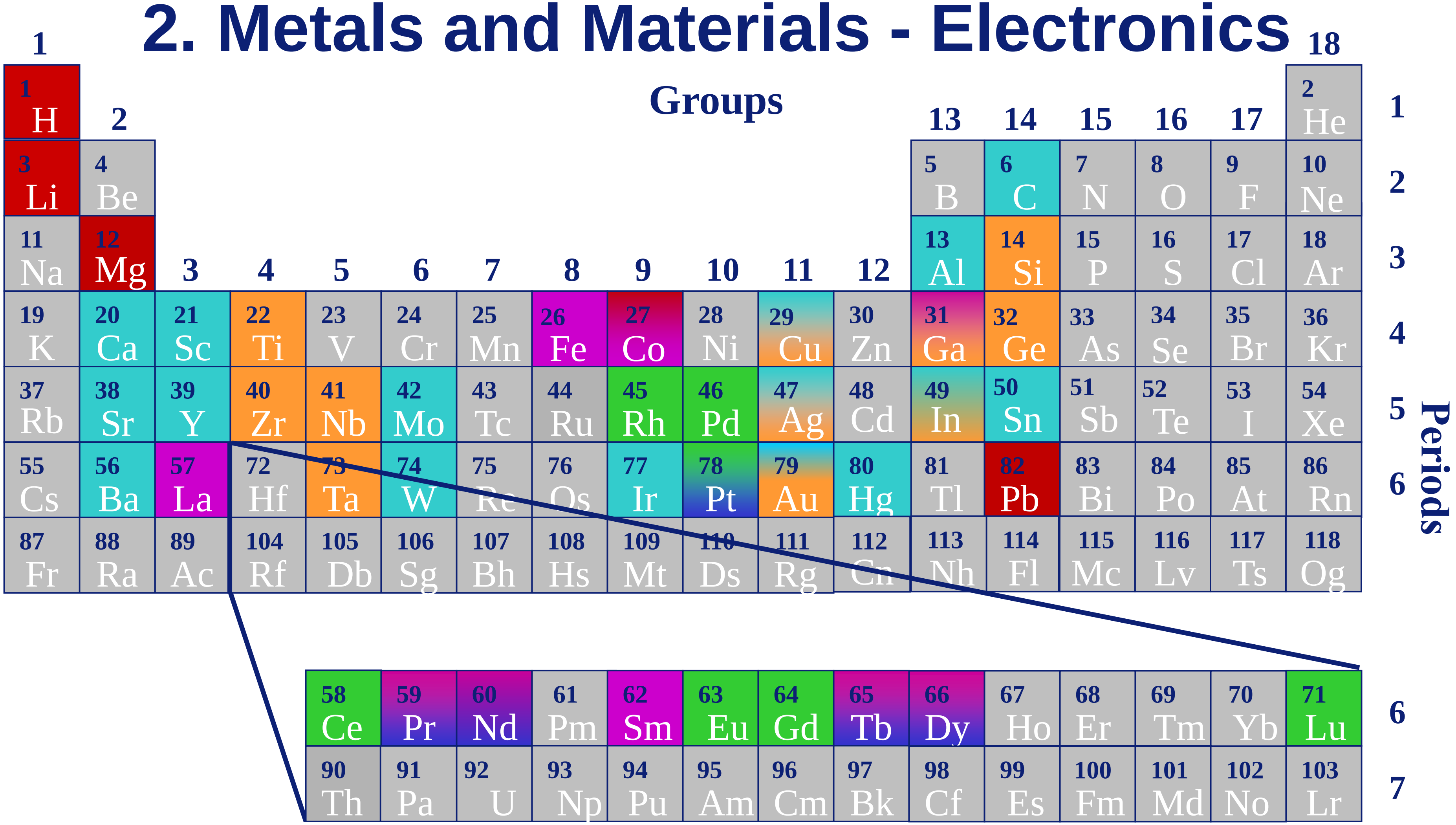
Limit: $E_{bit,min} = \ln(2) \cdot k_B \cdot T$



Source: Hilbert, M., & López, P. (2011). The World's Technological Capacity to Store, Communicate, and Compute Information. *Science*, 332(6025), 60 –65. http://www.martinhilbert.net/WorldInfoCapacity.html

Data volume ↑↑↑

2. Metals and Materials - Electronics



Groups

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1 H																	2 He	1
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	2
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	3
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	4
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	5
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	6
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	

Periods

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	6
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	7

Energy storage materials

Active or passive components

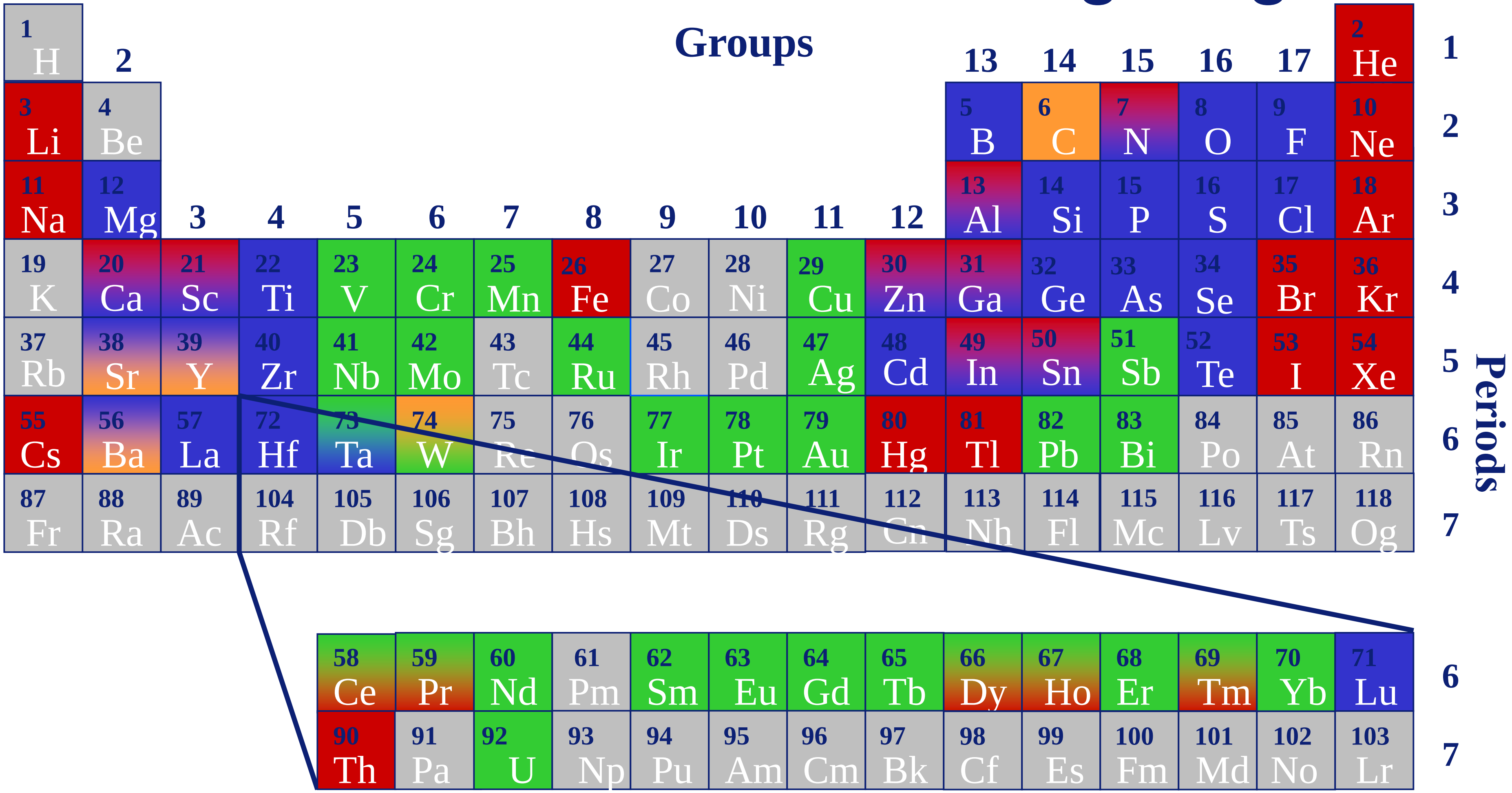
Electrical engines/magnets

Detectors/catalysts

Solid oxid fuel cells (components)

Electrode/conductor materials

2. Metals and Materials - Lighting



Groups

Periods	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

6	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
7	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Filling of metal halide lamps

Electrode component

Activator in phosphors/laser gain media

Host component of phosphors/laser gain media

2. Metals and Materials

Transition Metals

Electron configuration of the 3d transition metals

	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
4s	2	2	2	1	2	2	2	2	1	2
3d	1	2	3	5	5	6	7	8	10	10

Electron configuration of the 4d transition metals

	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd
5s	2	2	1	1	1	1	1	0	1	2
4d	1	2	4	5	6	7	8	10	10	10

Electron configuration of the 5d transition metals

	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg
6s	2	2	2	2	2	2	2	1	1	2
5d	1	2	3	4	5	6	7	9	10	10

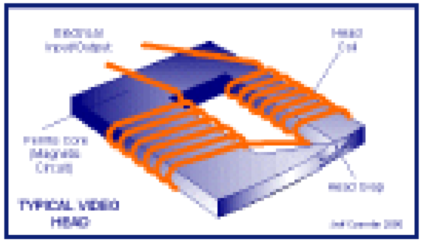
Transition metals are very common catalysts due to

- **many redox states**
- **coordinative bonds**
- **crystal-field effects**
- **high-spin ↔ low-spin transitions**
- **cluster formation**
- **magnetic interaction**
- **rather high abundance of 3d transition metals and thus reasonable costs**
- **long-term catalytic activity (Ru, Rh, Pd, Re, Ir, and Pt)**

⇒ **Stable configurations due to lower energetic states of the nd-orbitals**

2. Metals and Materials

The Transition Metal Iron



Use in Ferrites

Magneto ceramic materials

⇒ Binary/ternary iron oxides

Soft ferrites

- are easily and efficiently magnetised by an external magnetic field
- Magnets in writing and reading heads in audio and video recorders, hard drives etc.
- Electrical isolators, ferrimagnetic compounds with low saturation magnetisation in combination with low anisotropy in terms of the crystal structure
- MFe_2O_4 (spinels) with M = $Zn^{2+,}$ Mn^{2+}, Ni^{2+}, Co^{2+}, Mg^{2+}
- Typical composition: Fe-Mn-Zn-oxide with 70% Fe, 25% Mn, and 5% Zn

Hard ferrites

- maintain their magnetic properties after the initial magnetisation
- Permanent magnets in electric motors, speaker, generators, and son on
- $MFe_{12}O_{19}$ with M = Sr^{2+}, Ba^{2+}

2. Metals and Materials

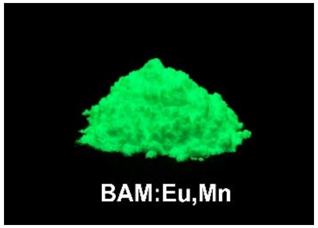
The Transition Metal Manganese

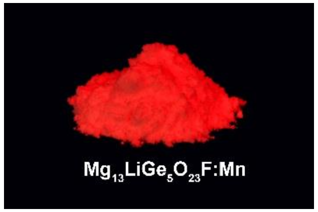
Mn Ions in (photo)catalysis

a)	Mn dependent catalase	$2\,H_2O_2 \rightarrow 2\,H_2O + O_2$
b)	Percarbonate decomposition	$2\,Na_2CO_3{\cdot}H_2O_2 \rightarrow 2Na_2CO_3 + 2H_2O + {}^1O_2$
c)	Superoxide dismutase	$O_2^{-\cdot} + Mn^{3+} \rightarrow O_2 + Mn^{2+}$
d)	Photosystem II	$2\,H_2O \rightarrow 4\,H^+ + 4\,e^- + O_2$
e)	Photocatalytic water splitting	$2\,H_2O \rightarrow 2\,H_2 + O_2$

Mn Ions in photoluminescence

a)	Green CRT and PDP phosphor	$Zn_2SiO_4{:}Mn^{2+}$
b)	Green FL phosphor	$BaMgAl_{10}O_{17}{:}Eu^{2+}Mn^{2+}$
c)	Orange electroluminesc. pigment	$ZnS{:}Mn^{2+}$
d)	Dichromatic FL phosphor	$Ca_5(PO_4)_3(F,Cl){:}Sb^{3+}Mn^{2+}$
e)	Red LED phosphor	$K_2SiF_6{:}Mn^{4+}$
f)	Deep red FL phosphor	$Mg_{14}Ge_5O_{24}{:}Mn^{4+}$





2. Metals and Materials

Rare Earth Metals

Metals

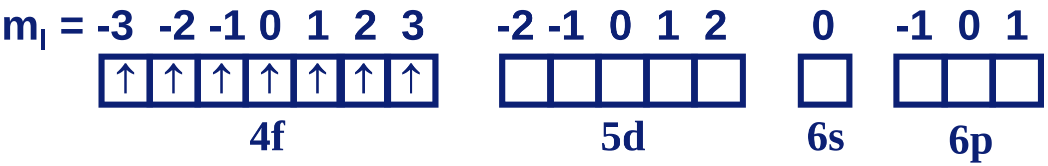
[Xe]	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
6s	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5d	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1
4f	0	1	3	4	5	6	7	7	9	10	11	12	13	14	14

Cations

[Xe]	La^{3+}	Ce^{3+}	Pr^{3+}	Nd^{3+}	Pm^{3+}	Sm^{3+}	Eu^{3+}	Gd^{3+}	Tb^{3+}	Dy^{3+}	Ho^{3+}	Er^{3+}	Tm^{3+}	Yb^{3+}	Lu^{3+}
	Ce^{4+}	Pr^{4+}	Nd^{4+}				Sm^{2+}	Eu^{2+}	Dy^{4+}					Tm^{2+}	Yb^{2+}
								Tb^{4+}							
4f	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

Electron configuration

e.g. of $Gd^{3+}/Eu^{2+}/Tb^{4+}$ $[Xe]4f^7$



Ce^{3+} - Yb^{3+}, Pr^{4+}, Nd^{4+}, Tb^{4+}, Dy^{4+}, Sm^{2+}, Eu^{2+}, Tm^{2+} → paramagnetic ions

Gd^0, Tb^0, Dy^0 → ferromagnetic ordering (T_C<RT)

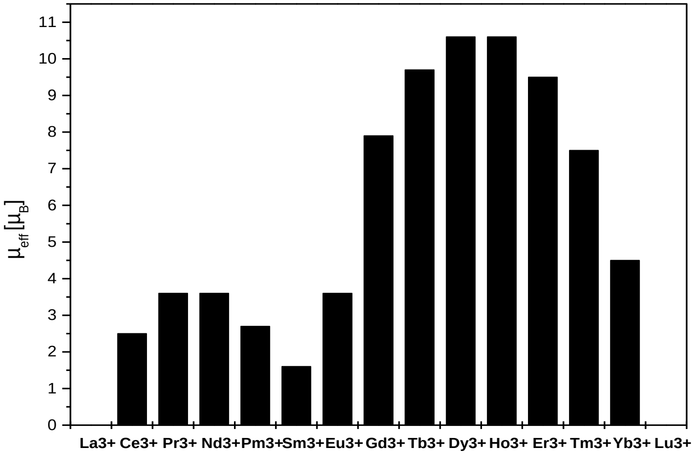
2. Metals and Materials

Rare Earth Alloys and Compounds: Application Areas in Electrics

Magnets	*Superconductors*	*Ion Conductors*	*Thermistors*
Engines, generators, speakers, microphones, telephones, headphones, hearing aids, magnetic couplers, sensors, cranes, overhead platforms, ….	**NMR devices** **Particle accelerators** **Fusion reactors** **SQUIDs**	**Fuel cells** **Lambda probes** **Sensors**	**Temperature sensors** **Inrush current limiter** **Voltage stabilisers**
$Nd_2Fe_{14}B$ $SmCo_5$ Sm_2Co_{17}	$(La.Ba)_2CuO_4$ $YBa_2Cu_3O_7$	$LaCoO_3:Sr$ $CeO_2:Sm$ $ZrO_2:Y$ $LaCeO_3:Ba$	$Sm_2O_3\text{-}Tb_2O_3$

2. Metals and Materials

Rare Earth Alloys and Compounds: Advantages in Magnets



Highly paramagnetic as cations

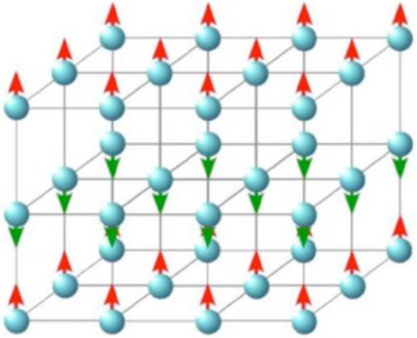
- Gd^{3+} ⇒ magnetic contras agent [Gd^{3+}(dota)]
- Dy^{3+}/Ho^{3+} ⇒ maximal magnetic moment of all elemental cations ~ 10.6 μ_B
- For comparison: Fe^{3+}/Mn^{2+} $\mu_{eff} = 5.9\ \mu_B$

Ferromagnetic as metal or alloy

- Gd/Tb/Dy
- $Nd_2Fe_{14}B$
- $SmCo_5$ and Sm_2Co_{17}

As building block in ferromagnetic materials

- $Y_3Fe_5O_{12}$ „YIG“
- $Gd_3Fe_5O_{12}$ „GdIG“

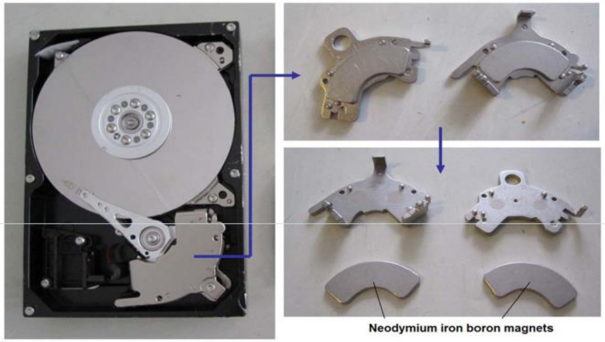


Ferromagnetic ordering in 4f ferromagnets

2. Metals and Materials

Application Areas of $Nd_2Fe_{14}B$, $SmCo_5$, and Sm_2Co_{17}

- Application in electric engines in automotive industry
  > 25 actuating motors per car
  electric drive & brake



- Hard Disc Drives (HDDs)
  Magnets: 2 wt-% of HDD
  Rare earths: 0.6 wt-% of HDD

- Wind power stations
  Off-shore: 650 kg Nd/station
  ~ 100 kg/MW power output

2. Metals and Materials

Magnetic Properties of TM and RE Based Alloys

Important figures of magnetic materials:

- Coercitive field strength ⇒ Soft- or hard magnetic materials

- Energy density ⇒ Conversion efficiency

Alloy	Coercitive field strength H_c [kA/m]	Typical energy density $(BH)_{max}$ [kJ/m³]
Steel (0.9% C, 1.0% Mn)	4	1.6
Martensitic Steel (9% Co)	11	3.3
AlNiCo (21% Ni, 12% Al, 5% Co, Fe)	35	11
CuNiFe (60% Cu, 20% Fe, 20% Ni)	44	12
$SrFe_{12}O_{19}$	260	29
$SmCo_5$	760	200
Sm_2Co_{17}	720	250
$Nd_2Fe_{14}B$:Dy,Pr	880	360

2. Metals and Materials

Replacement of $Nd_2Fe_{14}B$, $SmCo_5$, and Sm_2Co_{17}?

- Permanent magnets on the basis of iron oxides by addition of other oxides? Problem: Energy product $(BH)_{max}$ ~ 10times smaller than that of RE magnets
  ⇒ Not applicable in high performance engines and turbines!

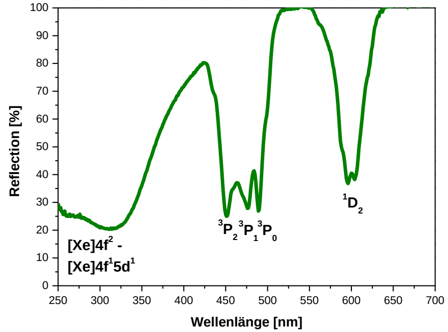
- Nanoscale Fe/Co compounds?
  Nano rods with magnetic ordering resulting in a matrix of particles which are equal to ferromagnetic domains
  ⇒ Rather demanding technology

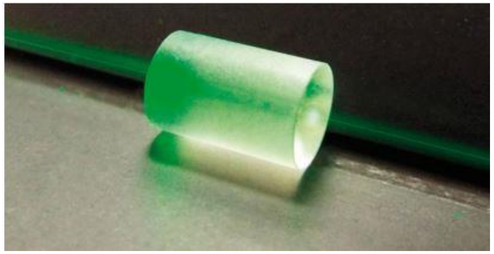
- Molecular magnets?
  $[Mn_{12}O_{12}(CH_3COO)_{16}(H_2O)_4]\cdot 2CH_3COOH\cdot 4H_2O$ „Mn_{12}ac“
  Prussian Blu analagous: „Fe_4“ or „Fe_8“
  ⇒ long-term R&D projects

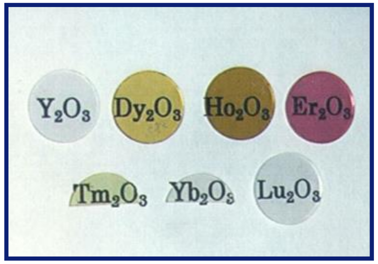
2. Metals and Materials

Optical Properties of RE: Absorption

La	**La_2O_3**	**Highly refractive glasses for lenses in cameras or telescopes (Galilei type)**
Ce	**Ce_2O_3/CeO_2**	**UV filters in light sources**
Pr	**Pr_2O_3/PrO_2**	**Colour filters**
Nd	**Nd_2O_3**	**Colour filters**
Tb	**KTb_3F_{10}** **$Tb_3Ga_5O_{12}$**	**High power laser Faraday isolator**

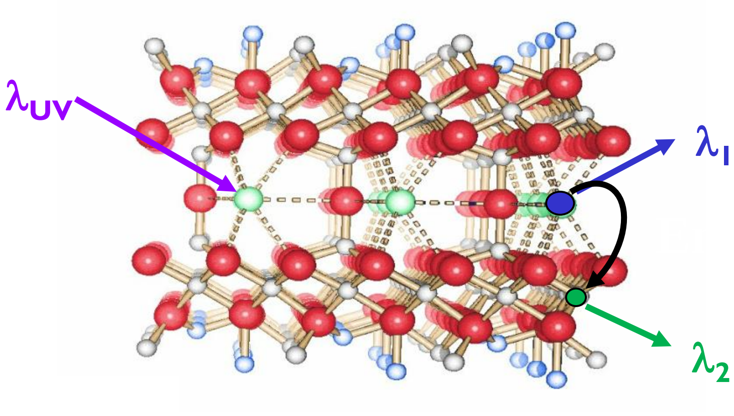


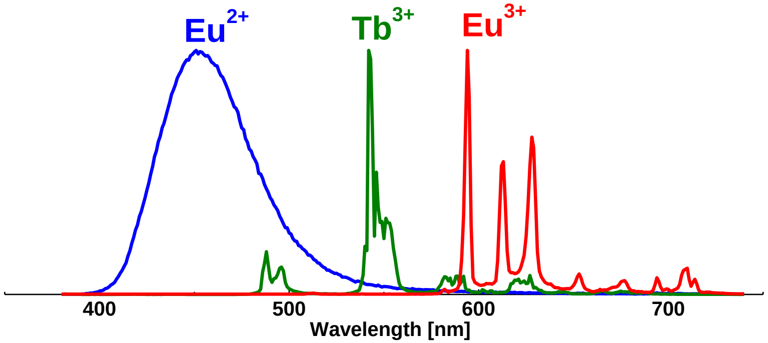


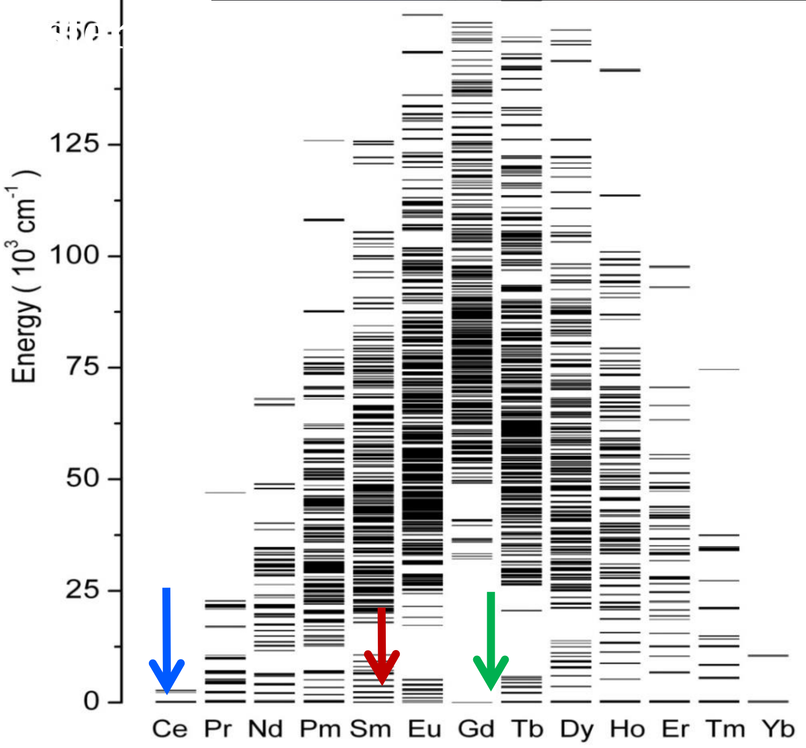


2. Metals and Materials

Optical Properties of RE: Luminescence



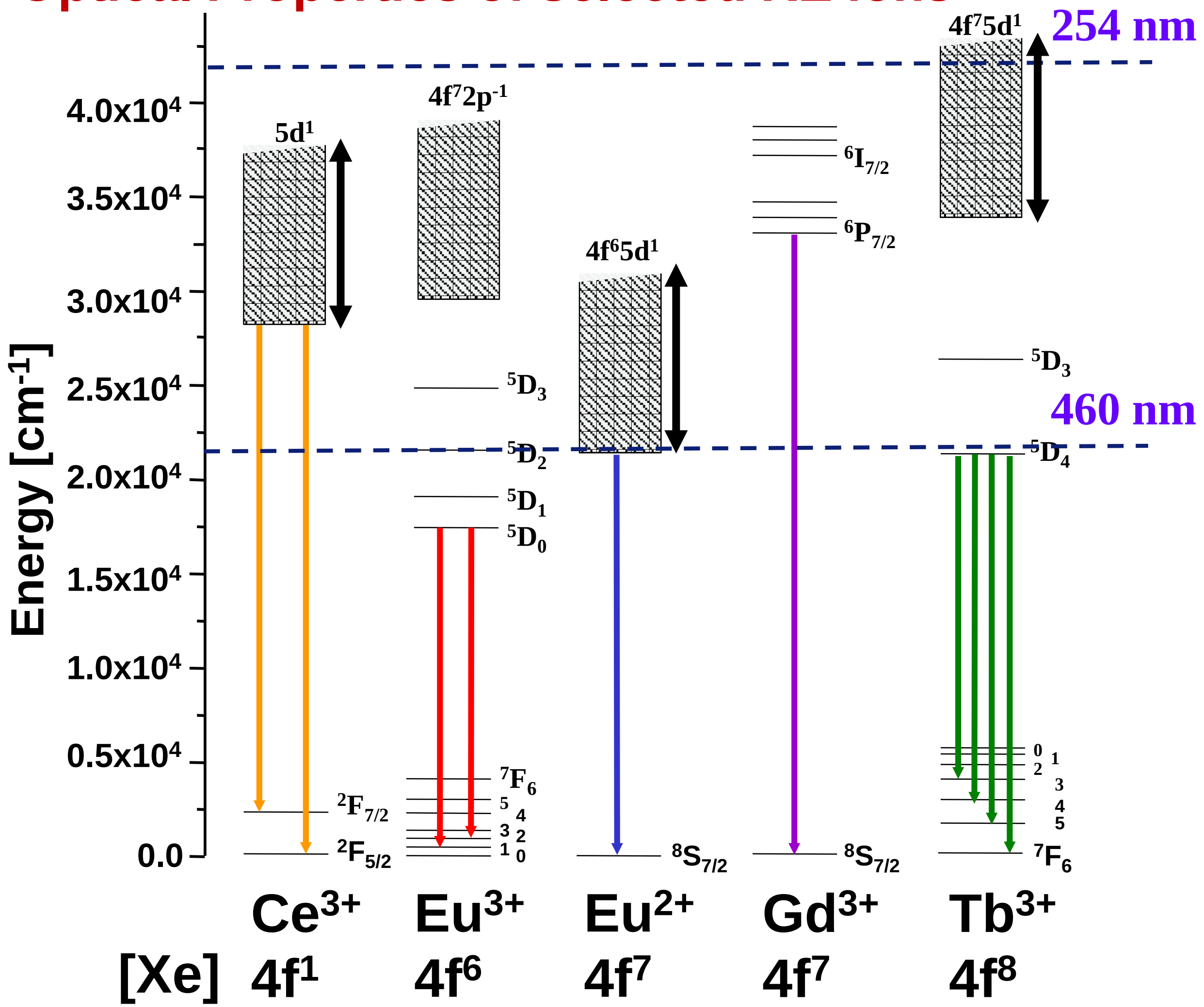




Ln^{3+} ⇒ Multiple energy levels and thus many optical transitions in the UV, VIS and NIR range

2. Metals and Materials

Optical Properties of selected RE ions



<u>Typical Line emitter</u>	
Pr^{3+}	Scintillators
Nd^{3+}	Laser gain media
$Sm^{2+/3+}$	Detectors
Eu^{3+}	Fluorescent lamps
Gd^{3+}	UV-B lamps
Tb^{3+}	Fluorescent lamps
Dy^{3+}	Afterglow pigments
Ho^{3+}	Laser gain media
Er^{3+}	Laser
Tm^{3+}	Plasma displays
Yb^{3+}	Laser gain media

<u>Typische Bandenemitter</u>	
Ce^{3+}	LEDs, UV lamps
Pr^{3+}	Detectors
Nd^{3+}	UV lamps
Eu^{2+}	LEDs
Yb^{2+}	Laser

2. Metals and Materials

Rare Earth Alloys and Compounds: Application Areas in Optics

Thermo luminescence

Gas mantle:
99% ThO_2 +
1% CeO_2

Flint stones:
„Misch metal“ =
30% Fe + 70% La-Sm

Thermal Radiators

Incandescent and halogen lamps

Glass additives
La_2O_3 / Ce_2O_3

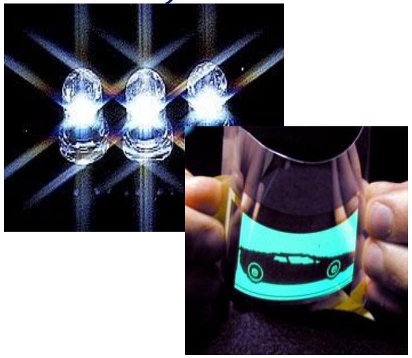
Low and High Pressure Discharges

Na and Hg Vapour lamps
Metal halide lamps

Electrodes: Sc^{3+}, Y^{3+}
Gas fillings:
DyI_3, HoI_3, TmI_3
+ Phosphors

Electro luminescence

Inorganic LEDs, OLEDs, and PLEDs



Ceramic lenses
Y, La, Ce, Eu, Gd, Tb, Lu comprising
Phosphors

3. Matter Radiation Interaction

Physics and chemistry of the photon are key for advances in 21st century

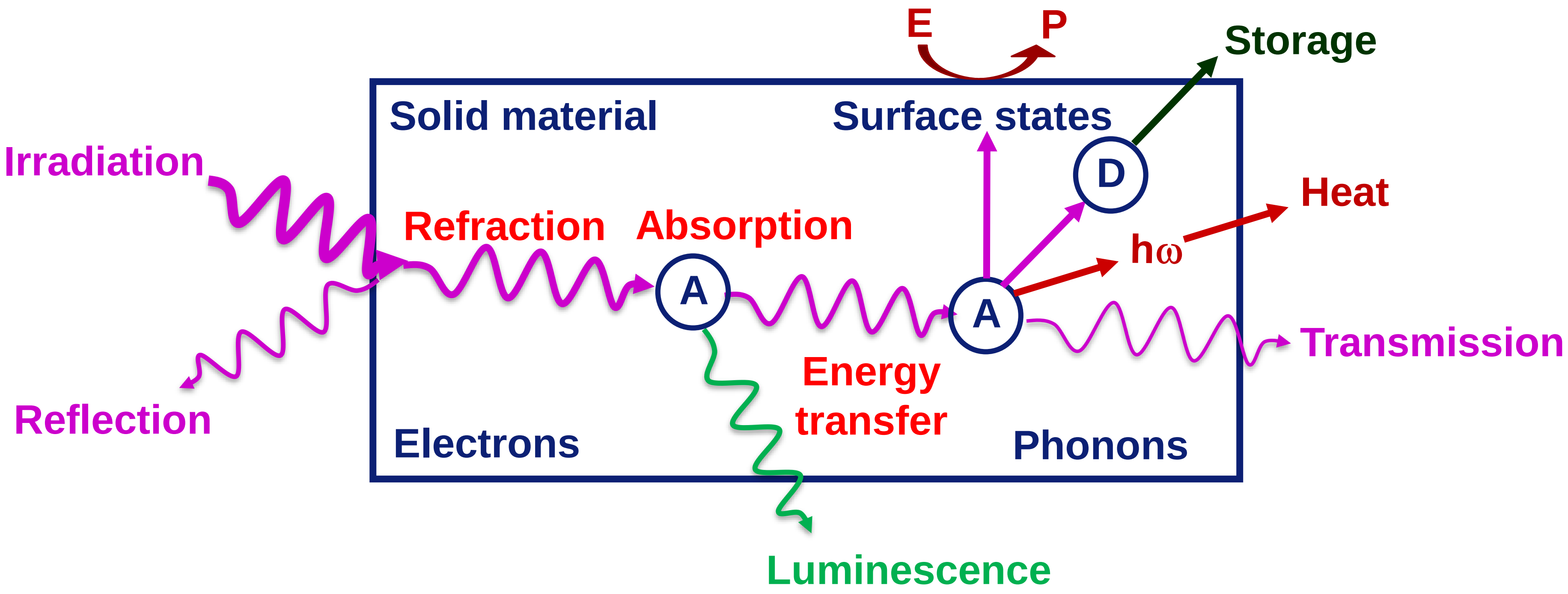
1. Life Science
   - Photoreactor: Earth‘s atmosphere and „surface layer“
   - Photoreactor: Plants and algae → Photosynthesis
   - Photoreactor: Eye
   - Photoreactor: Skin
   - Medical diagnostics
   - Medical therapy

2. Material Science
   - Converter for LEDs, Laser diodes, and OLEDs
   - Novel materials for photovoltaic cells
   - Photocatalysts for photoreactors (solar chemistry)
   - Photonic sensors
   - Photonic switches
   - Photonic computing
   - Solar driven disinfection

3. Matter Radiation Interaction

Inorganic Solid State Materials

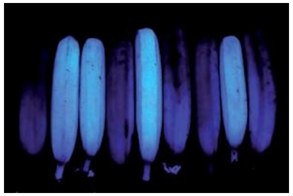
• Absorption	Photothermalisation	Pigments
• Activation	Photochemistry	Photocatalysts
• Emission	Photoluminescence	Phosphors
• Charge separation	Photoconductivity	Photovoltaics
• Charge trapping	Photostorage	Photoimaging, afterglow



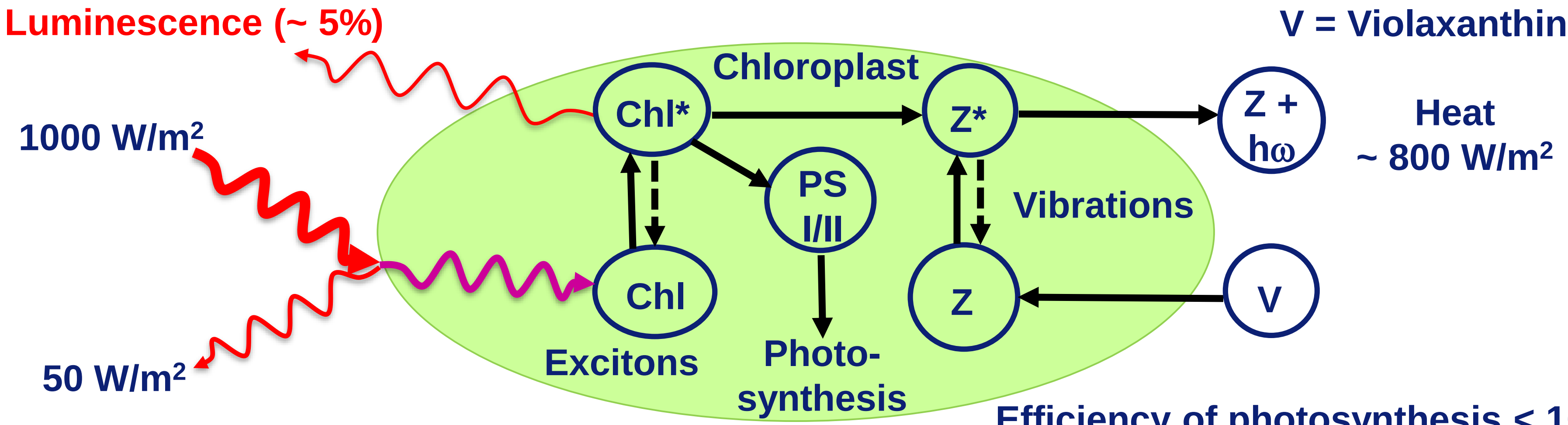
3. Matter Radiation Interaction

Organic Biomatter

• Absorption	Multiphononrelaxation	Plant pigments
• Activation	Photochemistry	Photocatalytic pigments
• Emission	Photoluminescence	Plants, scorpios
• Charge separation	Water cleavage	Photosynthesis
• Charge trapping	Photostorage	???



Z = Zeaxanthine
V = Violaxanthine



Efficiency of photosynthesis < 10%

3. Matter Radiation Interaction

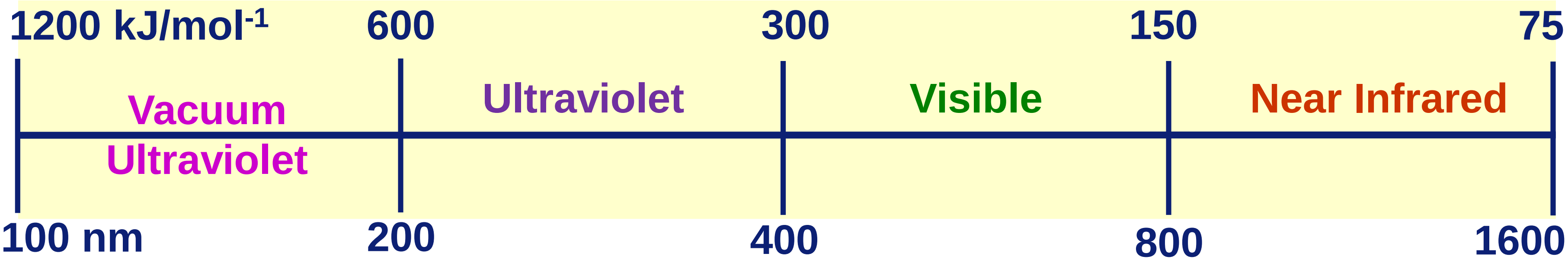
Photochemistry

Energy of chemical bonds
10 – 1100 kJ/mol

Energy of optical radiation
$E = N_A hc/\lambda = 119226 /\lambda \text{ kJmol}^{-1}$

E-E	100 – 500 kJ/mol	F-F C-C	159 kJ/mol 348 kJ/mol
E=E	400 – 700 kJ/mol	O=O C=C	498 kJ/mol 648 kJ/mol
E≡E	800 – 1100 kJ/mol	N≡N C≡C	946 kJ/mol 839 kJ/mol

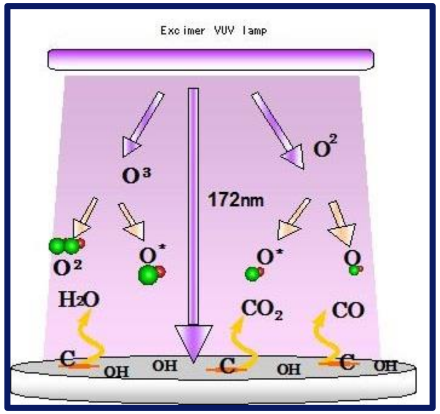
H-bridges 10 - 160 kJ/mol H···F > H···O > H.··N
Van-der-Waals 0.5 - 5 kJ/mol



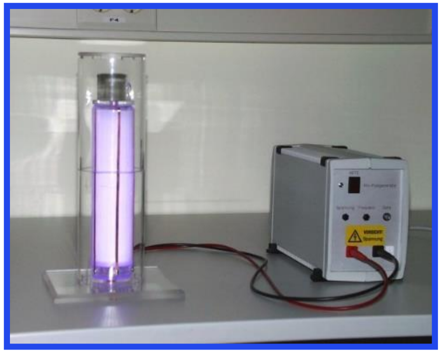
Thus (V)UV to VIS radiation is able to cleave covalent chemical bonds

3. Matter Radiation Interaction

Penetration Depth of UV Radiation

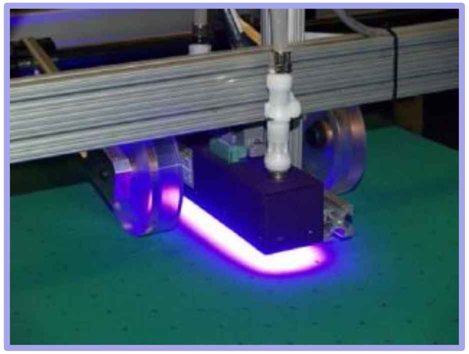


Vacuum UV



UV-C

UV-B



UV-A

Penetration depth increases ... but solely within µm range

100 nm 200 nm 280 nm 320 nm 400 nm

3. Matter Radiation Interaction

Into Earth‘s Atmosphere

Vacuum UV (100 - 200 nm)

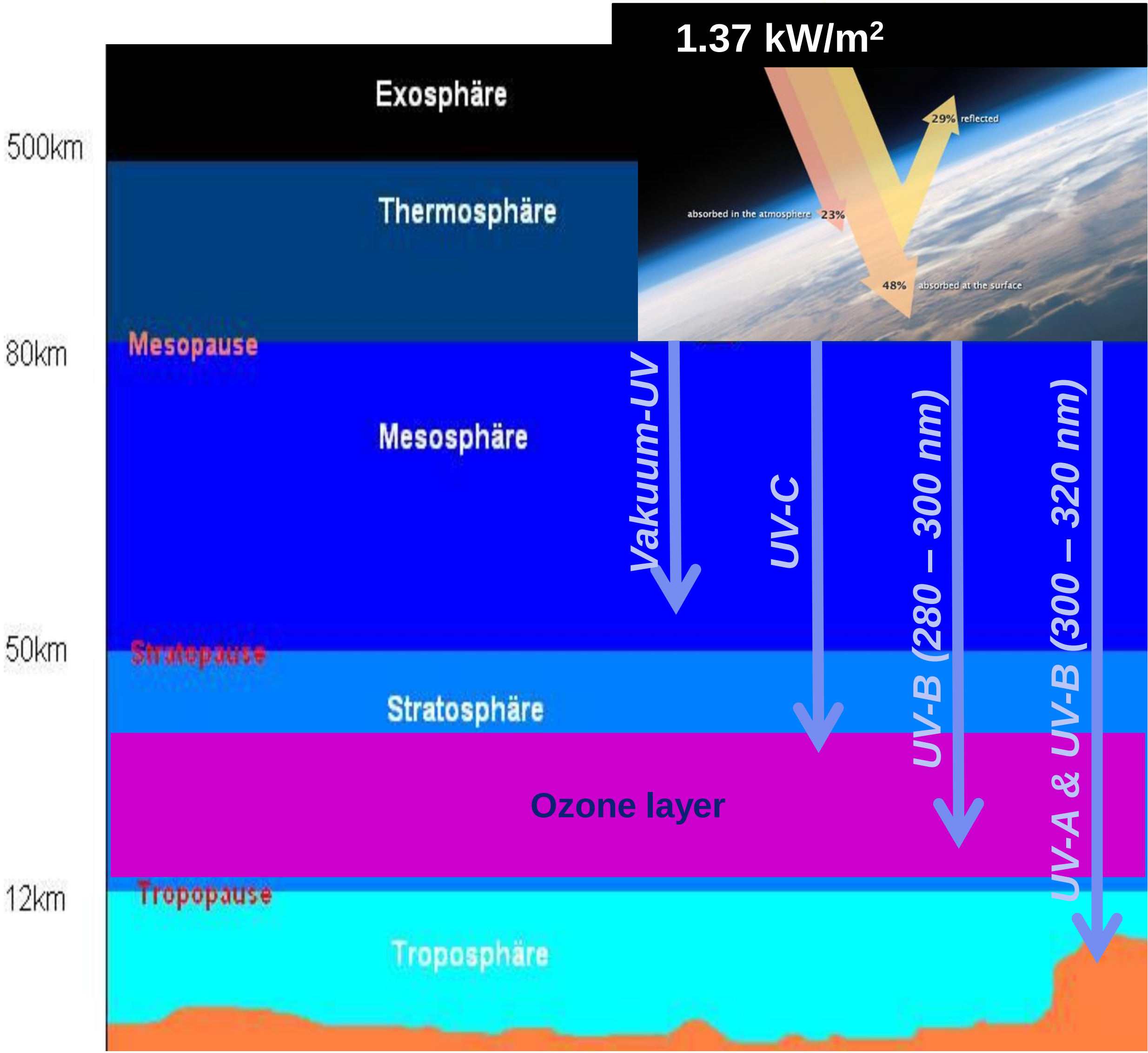
- Photolysis of water
- Cleavage of N_2 and O_2
- Ozone formation

UV-C (200 - 280 nm) &
UV-B (280 - 300 nm)

- Ozone cleavage

UV-B (300 - 320 nm) &
UV-A (320 - 380 nm)

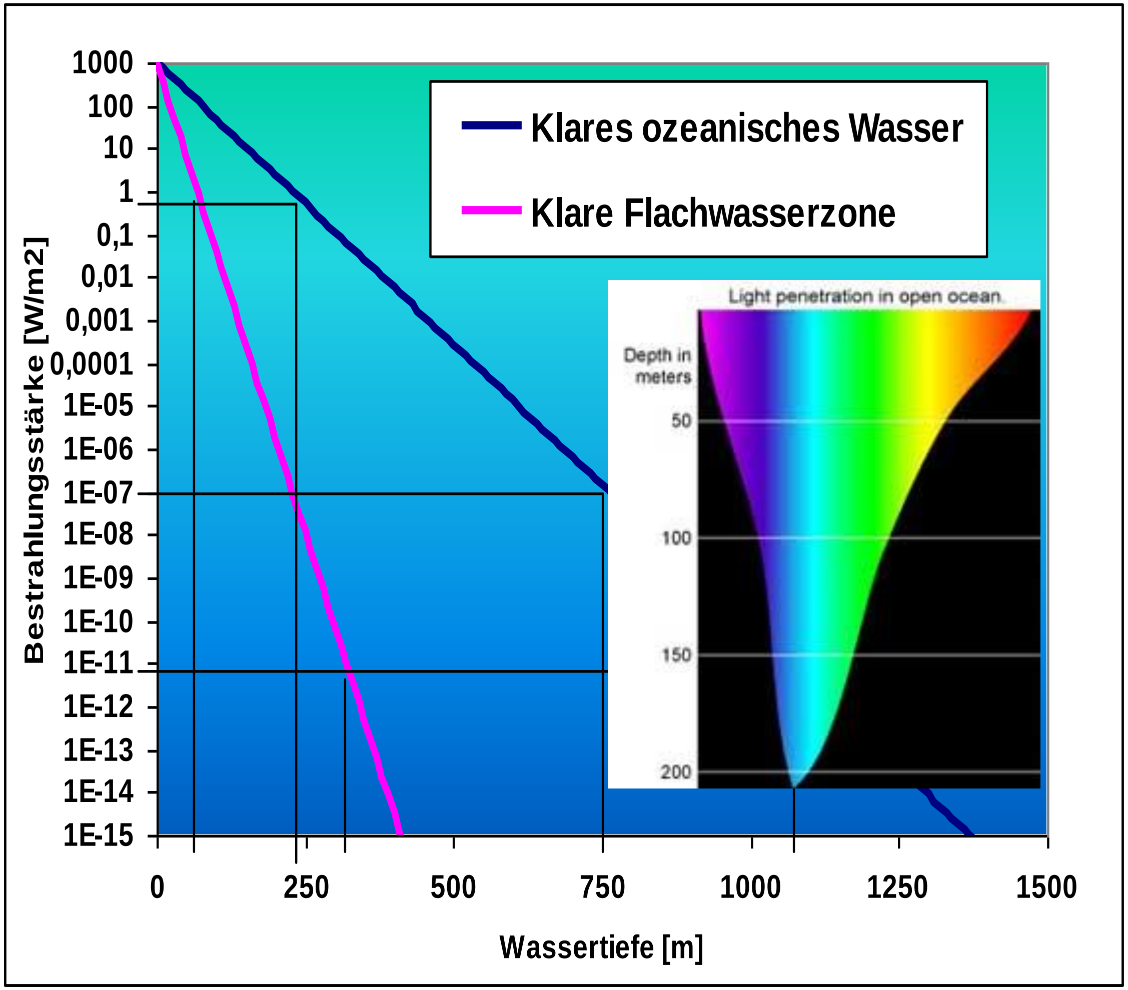
- Photochemical decline of air pollutants
- Ozon formation in presence of NO_x
- Disinfection at photo-catalytically active sites



3. Matter Radiation Interaction

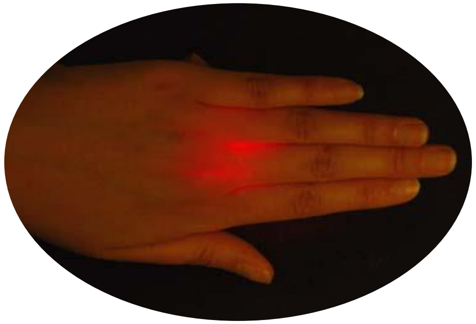
Into Water

- Power density @ surface:
  1000 W/m²
- Photosynthesis feasible:
  1 – 10 W/m²
- Phototaxis of crustacea:
  10^{-7} – 10^{-8} W/m²
  (Full moon ~ 5 x 10^{-3} W/m²)
- Light perception:
  Deep sea fish 10^{-11} W/m²
  Comparison: Scotopic vision
  Homo sapiens: 10^{-7} W/m²
  Perception limit at 10^{-12} W/m²
  (~ star of 6th magnitude)



UV radiation solely penetrates surface layer!

3. Matter Radiation Interaction



Into Biomatter

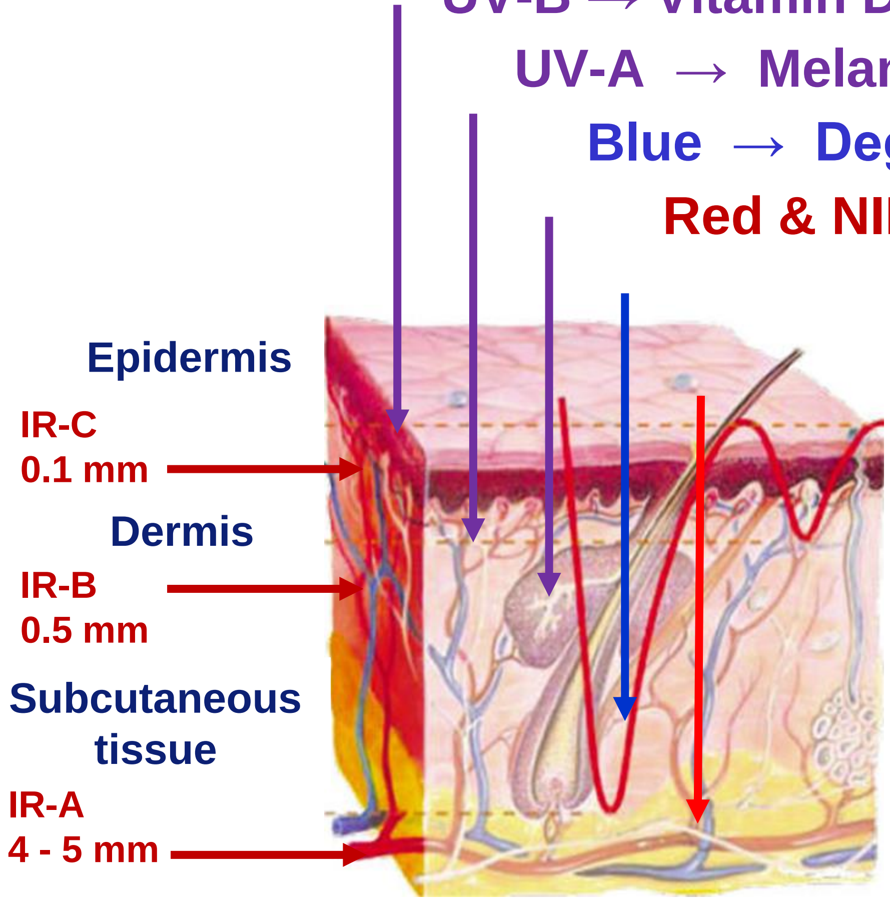
UV-C → Genetic damages

UV-B → Vitamin D formation

UV-A → Melanin oxidation

Blue → Degradation of bilirubin, NO formation

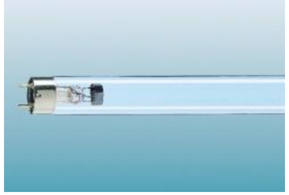
Red & NIR → Vasodilatory effect



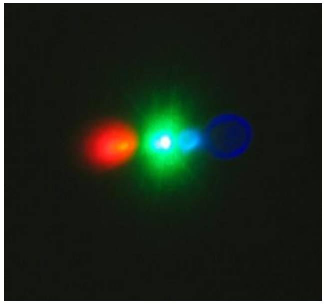
- Red and NIR radiation is able to penetrate epidermis, dermis, and subcutaneous tissue (up to ~ 5 mm)
- UV radiation impact is limited to surfaces (up to ~ 50 µm)
- VUV radiation is even heavily absorbed by water and air

3. Matter Radiation Interaction - Sources

Overview

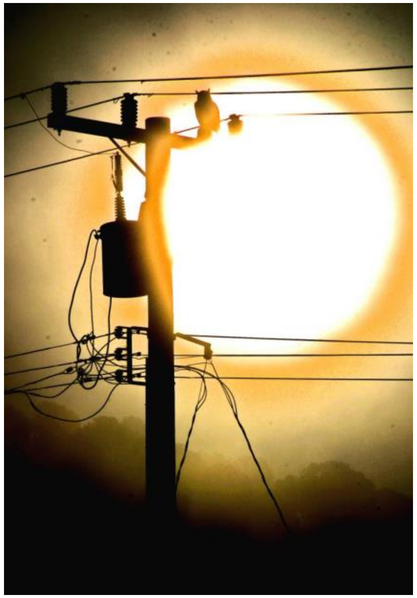


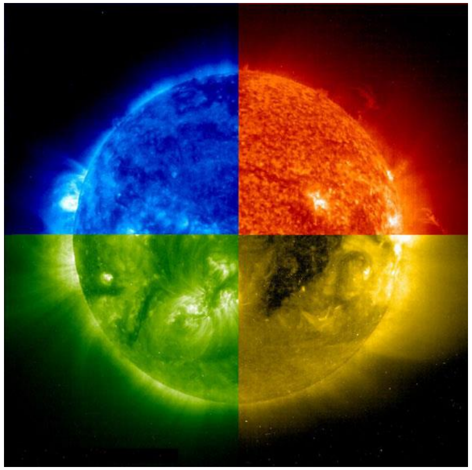
Solar radiation	> 300 nm	
Hg discharge lamps		
• low pressure	185, 254 nm	+ phosphor → 300 - 800 nm
• amalgam	185, 254 nm	
• medium pressure	200 – 400 nm	
Xe/(Hg) discharge lamps	230 – 800 nm	
D_2 discharge lamps	110 – 400 nm	
Excimer lasers		
• ArF*	193 nm	
Excimer discharge lamps (Dielectric Barrier Discharges: DBD)		
• Xe_2*	172 nm	+ phosphor → 190 - 800 nm
• KrCl*	222 nm	
• XeBr*	282 nm	
• XeCl*	308 nm	
Solid state lasers		
• Al_2O_3:Cr	694 nm	
• Al_2O_3:Ti	800 nm	
• YAG:Nd	1064 nm	
(Al,Ga)N LEDs	210 – 370 nm	
(In,Ga)N LEDs	370 – 550 nm	



3. Matter Radiation Interaction - Sources

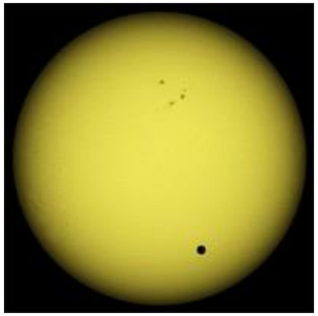
The Sun – Gravity Center and Heat & Light Source of the Solar System





3. Matter Radiation Interaction - Sources

Photosynthesis: Almost All Energy Consumed by Living Organisms Stems from Solar Energy (Exception: Thermophiles in Deep Sea)



Energy source in solar system: The sun

Luminosity (radiation flux): $3.83 \cdot 10^{26}$ W

Annual radiation power: $1.24 \cdot 10^{34}$ J (at present)

Habitable zone:

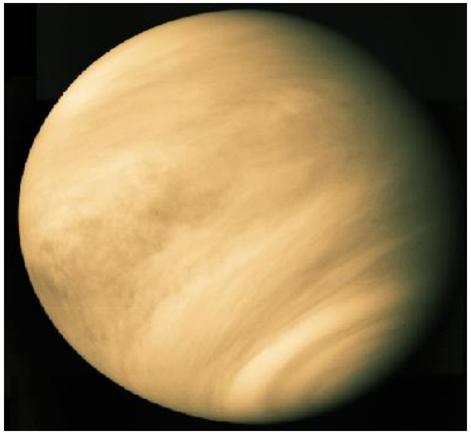
Venus (early stage of solar system), earth (today), mars (late phase...)

Planet	Perihelion- and aphelion-distance in astronomic units (149.6 Mio km)	Solar radiation maximum und minimum (W/m²)
Mercury	0.3075 – 0.4667	14446 – 6272
Venus	0.7184 – 0.7282	2647 – 2576
Earth	0.9833 – 1.017	1413 – 1321
Mars	1.382 – 1.666	715 – 492
Jupiter	4.950 – 5.458	55.8 – 45.9
Saturn	9.048 – 10.12	16.7 – 13.4
Uranus	18.38 – 20.08	4.04 – 3.39
Neptune	29.77 – 30.44	1.54 – 1.47

3. Matter Radiation Interaction - Sources

Photosynthesis: The energetic base of the biosphere, i.e. Mn^{n+} catalysed water splitting, $2\ H_2O \rightarrow 4\ H^+ + 4\ e^- + O_2\uparrow$

Venus



$2.61\ kW/m^2$
Albedo = 0.76
$\rightarrow T_E = 232\ K$
$96\%\ CO_2 + 3\%\ N_2 + SO_2 + H_2O + Ar$ (ppm)
93 bar → $T_{eff} = 740\ K$

Earth

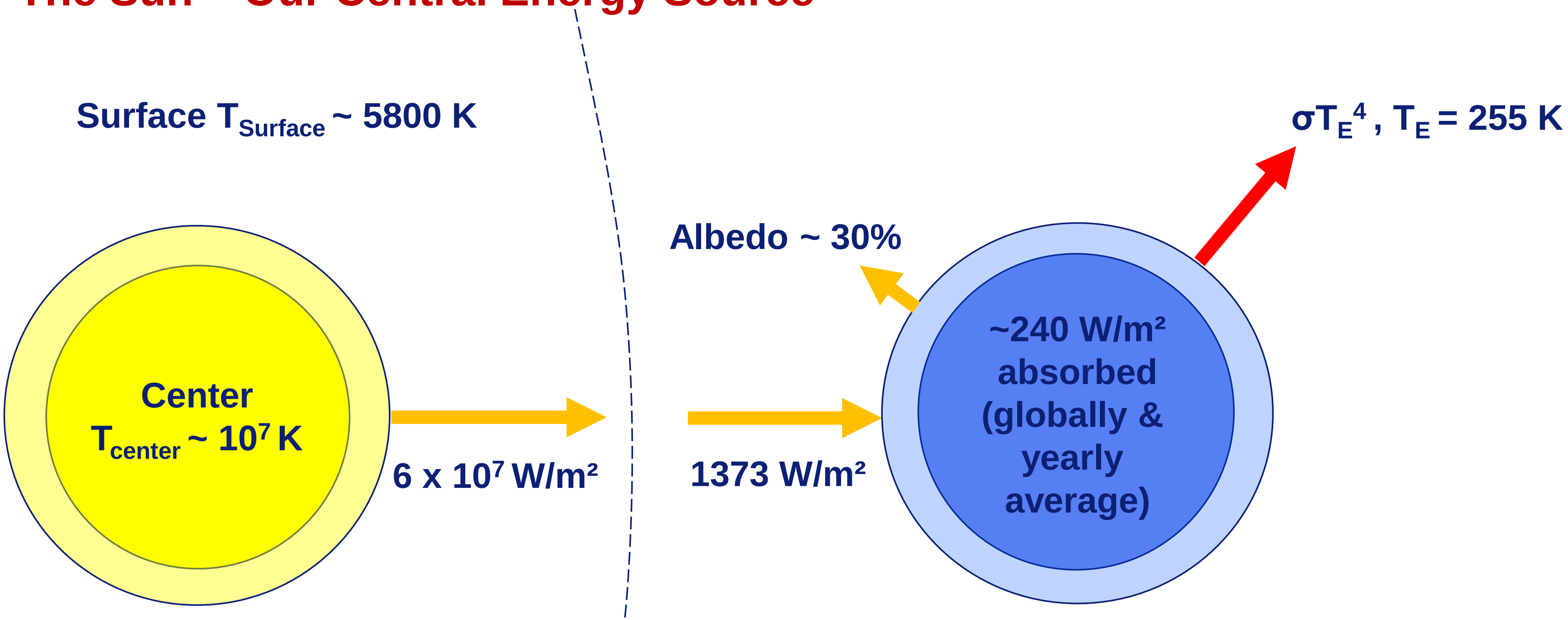
$1.37\ kW/m^2 = 1.56 \cdot 10^{18}\ kWh/a$
Albedo = 0.30
$\rightarrow T_E = 255\ K$
$78\%\ N_2 + 21\%\ O_2 + 0.9\%\ Ar + CO_2 + H_2O + CH_4$ (ppm)
1 bar → $T_{eff} = 288\ K$
Life = aquatic chemistry
Water → $2\ H_2$ and O_2 → energy!

Mars

$0.59\ kW/m^2$
Albedo = 0.15
$\rightarrow T_E = 213\ K$
$95\%\ CO_2 + 3\%\ N_2 + 1.5\%\ Ar + H_2O$ (ppm)
5.6 mbar → $T_{eff} = 225\ K$

3. Matter Radiation Interaction - Sources

The Sun – Our Central Energy Source

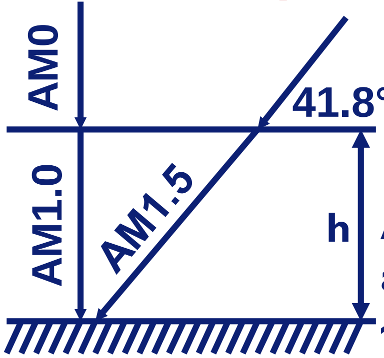


Radiant power	$3.8 \cdot 10^{26}$ W	$1.3 \cdot 10^{17}$ W
Energy flux	$1.24 \cdot 10^{34}$ J/a	$4.1 \cdot 10^{24}$ J/a

For comparison: **Global energy consumption 2015 ~ $5.2 \cdot 10^{20}$ J/a**

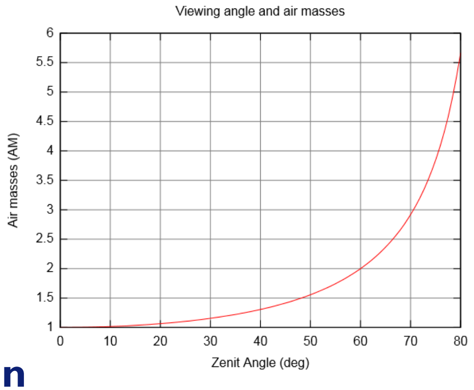
3. Matter Radiation Interaction - Sources

The solar spectrum (global radiation)



Altitude of atmosphere ~ 8 km for an isobaric column (h = p/g·ρ)

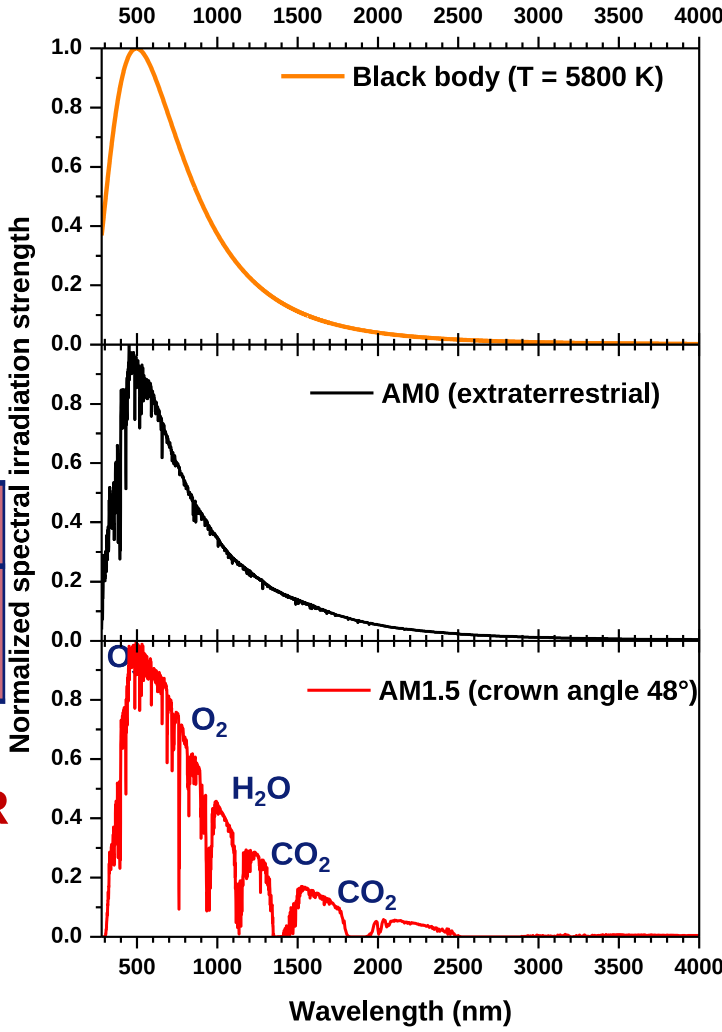
Surface of Earth



<400	400-500	500-600	600-700	>700
37.8 W/m² 5.3%	130.4 W/m² 18.2%	144.6 W/m² 20.2%	134.0 W/m² 18.7%	269.2 W/m² 37.6%

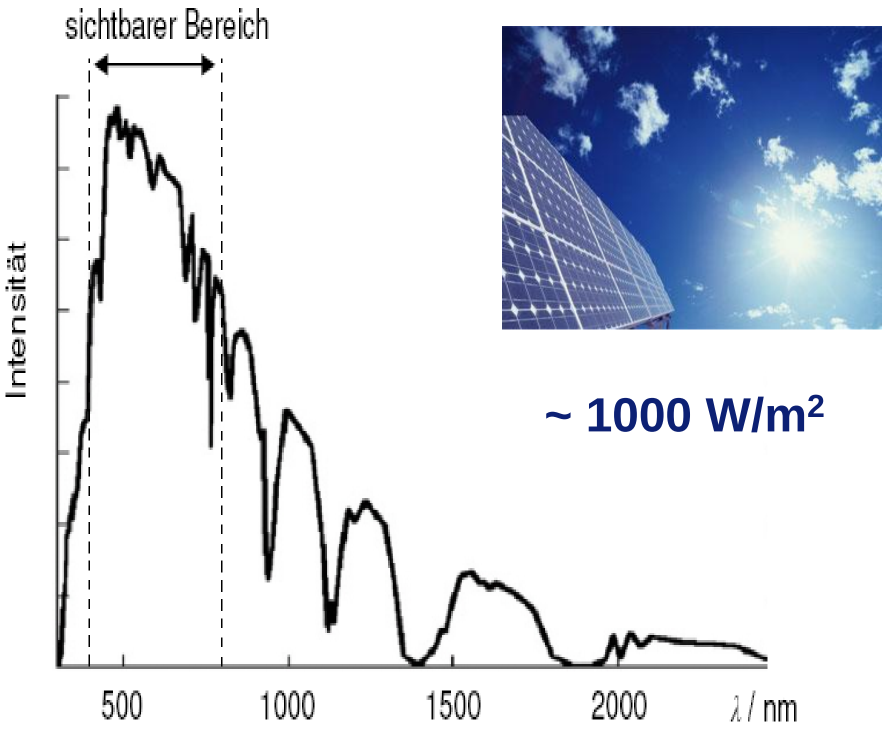
~ 5% UV **~ 55% VIS** **~ 40% IR**

Solar spectrum depends on daytime & season, air pressure, humidity, clouds, dust, and so on



3. Matter Radiation Interaction - Sources

Direct radiation

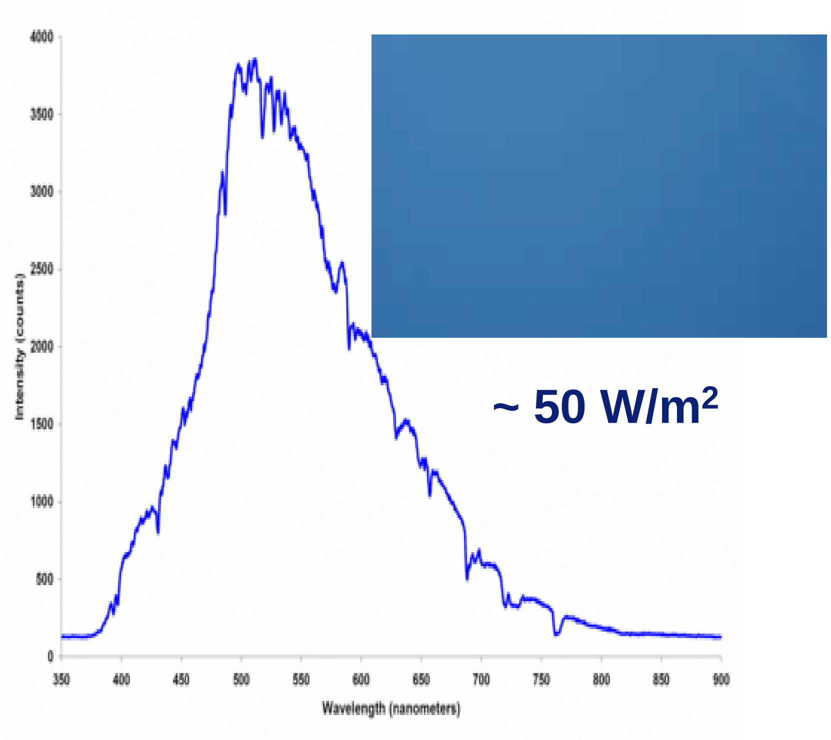


~ 1000 W/m²

Colour temperatur ~ 5500 - 6500 K

50 W/m² UV and 0.1 W/m² UV-B

Diffuse radiation „Blue sky“



~ 50 W/m²

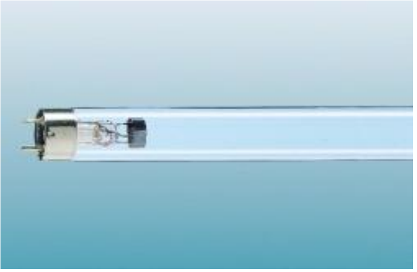
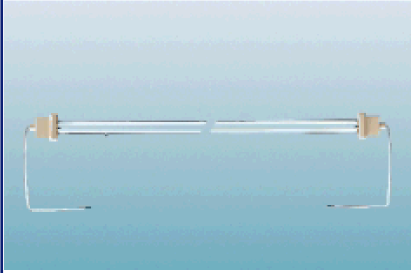
~ 10600 K

Almost no UV!

3. Matter Radiation Interaction - Sources

Hg vapour discharge lamps - Overview

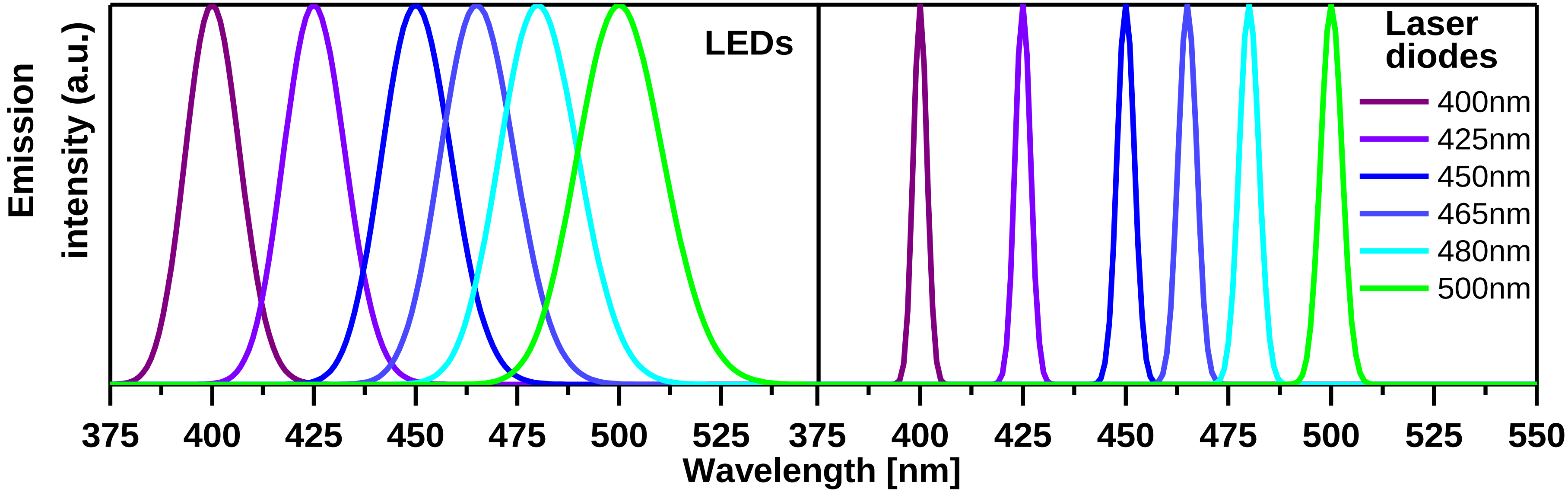
Hg lamp invented 1904 for Rachitis therapy

	Low Pressure Hg	Amalgam	Medium Pressure Hg
			
UV-C wavelength	254 nm	254 nm	200 - 280 nm
Typical lamp power	4 ... 100 W	100 ... 300 W	1 ... 17 kW
Lamp efficiency	< 40%	30 ... 35%	10 ... 15%
GAC factor	85%	85%	80%
UV-C power per length	0.2 W / cm	0.7 W / cm	15 W / cm
Wall temperature	40 °C	100 °C	600 - 800 °C

Spectra can be modified by additional filling gases and phosphors

3. Matter Radiation Interaction - Sources

LEDs and laser diodes



„LED platform“

465 nm LEDs	Illumination
410 nm LEDs	Full conversion
365 nm LEDs	Black light
265 nm LEDs	Disinfection

„Laser diode platform“

940 nm	Remote control
785 nm	CD
655 nm	DVD
405 nm	Blue ray DVD

3. Matter Radiation Interaction - Sources

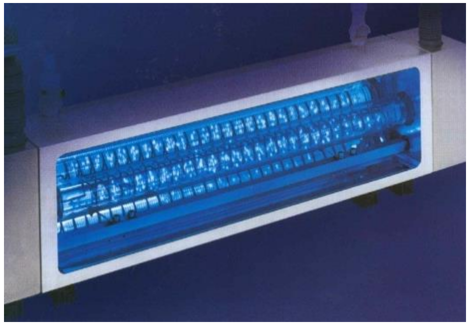
Devices using a Dielectric Barrier Excimer Discharge (either O_2 or Xe)

Ozone generator (Wedeco AG)

Exhaust treatment (Siemens AG)

UV Radiation sources (Xenon)

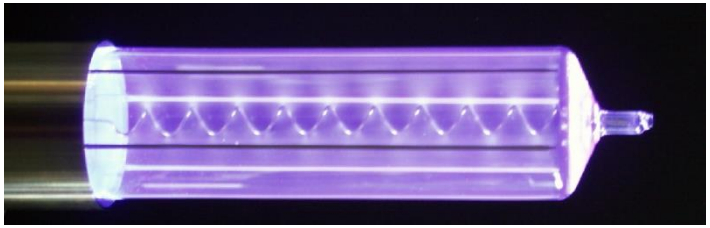
Heraeus Noblelight



Triton

Flat lamp for LCD Backlighting (Osram AG)

Osram Xeradex



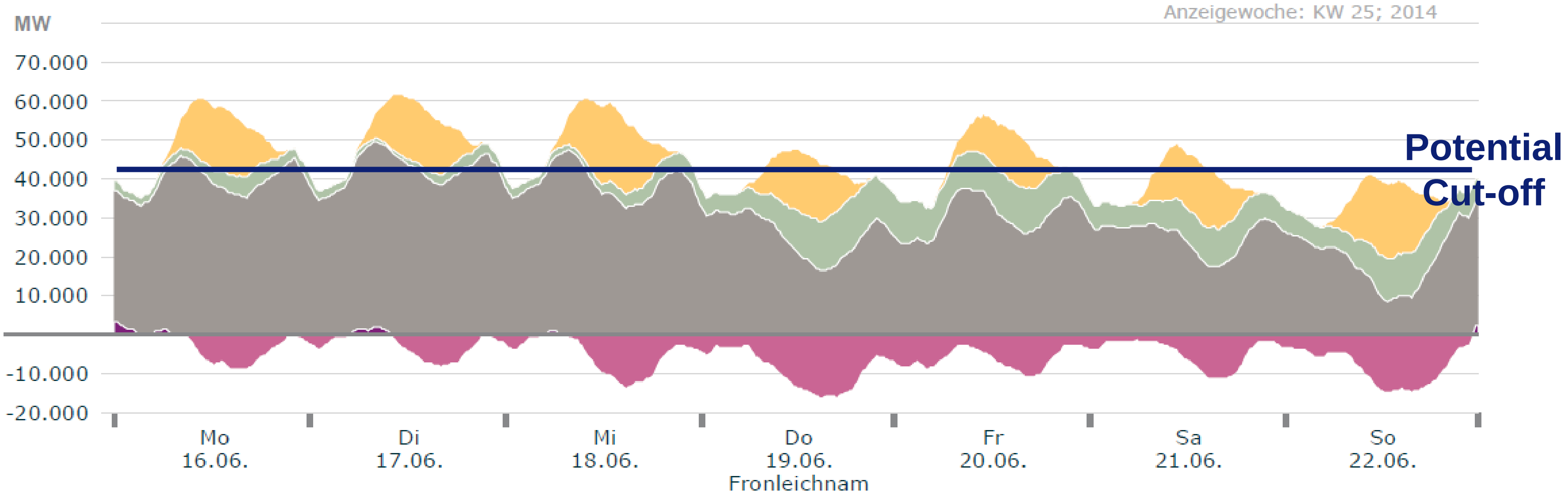
4. Photovoltaic Materials

Solar and wind energy market is strongly growing

Situation in Germany

Year	Installed peak power
2011	18 GW solar
	28 GW wind
2014	36 GW solar
	34 GW wind
2020	~50 GW solar
	~40 GW wind

Some days at noon conventional power was not necessary anymore power production spikes will be increased due to growth in PV!



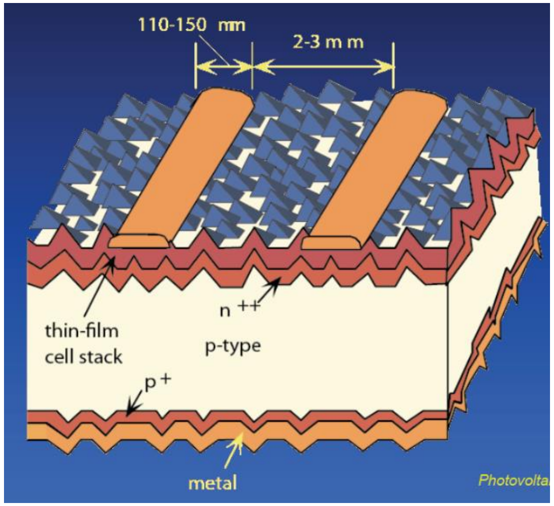
Potential Cut-off

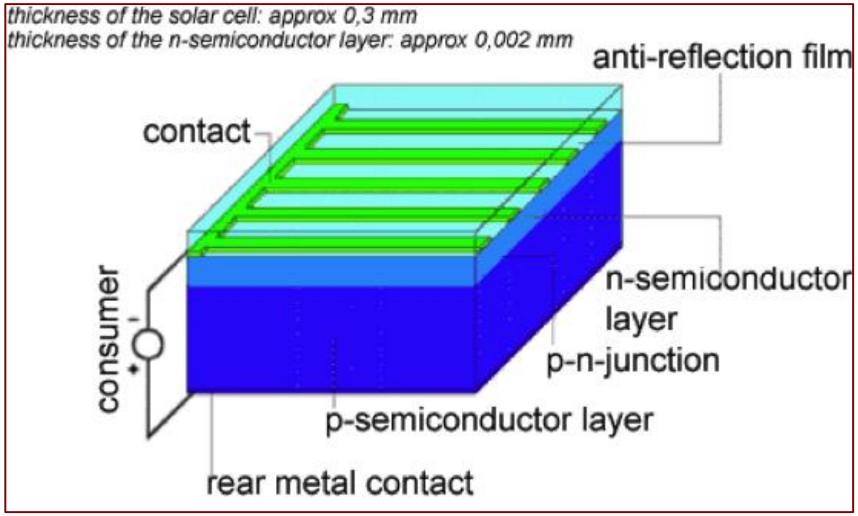
Cut-off PV solar energy production by photocatalysis to store energy is of large interest!

4. Photovoltaic Materials

Solar Cells from 1954 till today

**First practical photovoltaic cell:
Chapin, Fuller, Pearson at
Bell Labs, 1954: 6% efficiency**



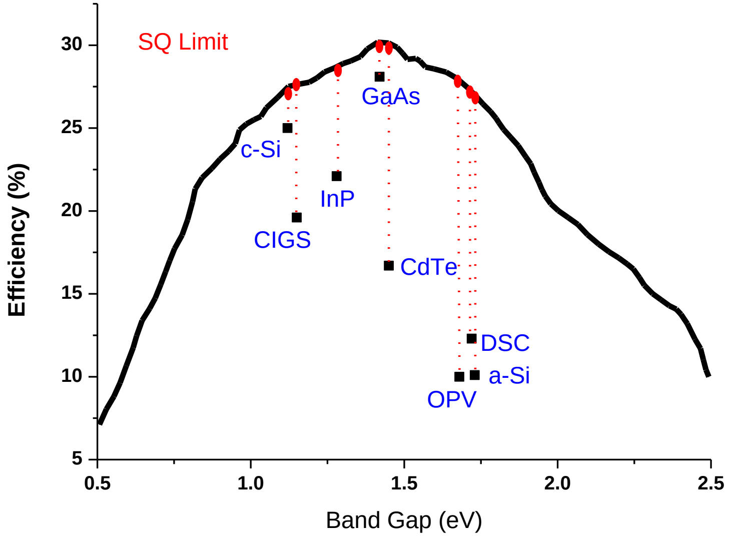

thickness of the solar cell: approx 0,3 mm
thickness of the n-semiconductor layer: approx 0,002 mm

4. Photovoltaic Materials

Solar cell generations by materials

c-Si (crystalline) cells	**1st generation cells**
(thin film) CdTe, GaAs, Cu(In,Ga)S_2, a-Si	**2nd generation cells**
Dye cells, organic cells, perovskite cells	**3rd generation cells**

Main problem: Shockley-Queisser* (SQ) Limit → PV efficiency < 30%



Optimal band gap: 1.34 eV!

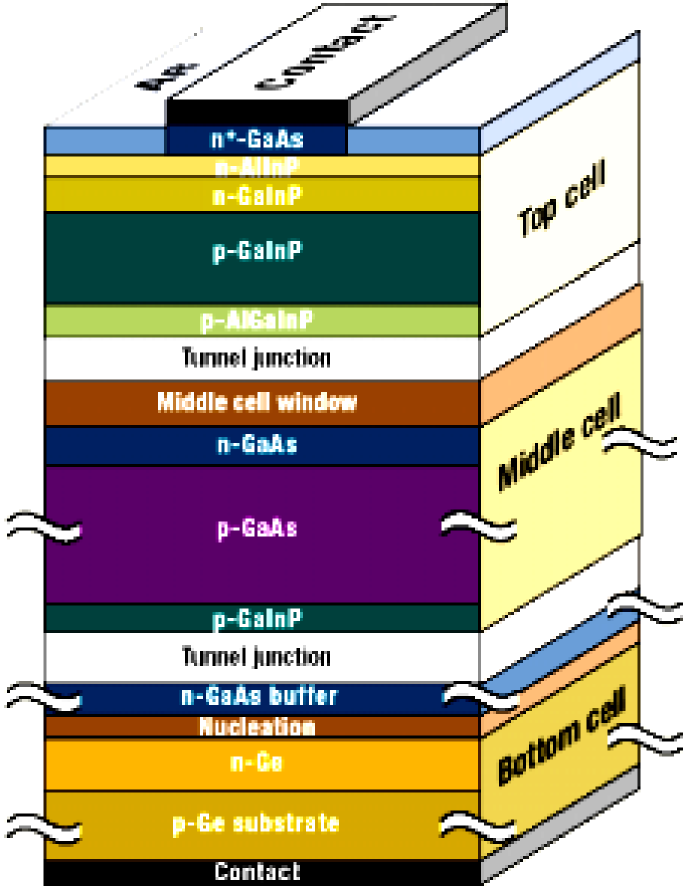
Reference:

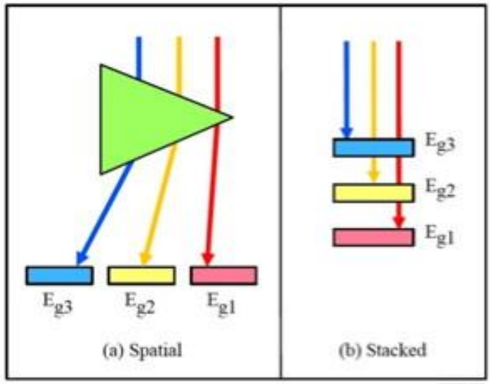
- **Prince, *JAP* 26 (1955) 534**
- **Loferski, *JAP* 27 (1956) 777**
- ***W. Shockley, H.J. Queisser, *JAP* 32 (1961) 510**

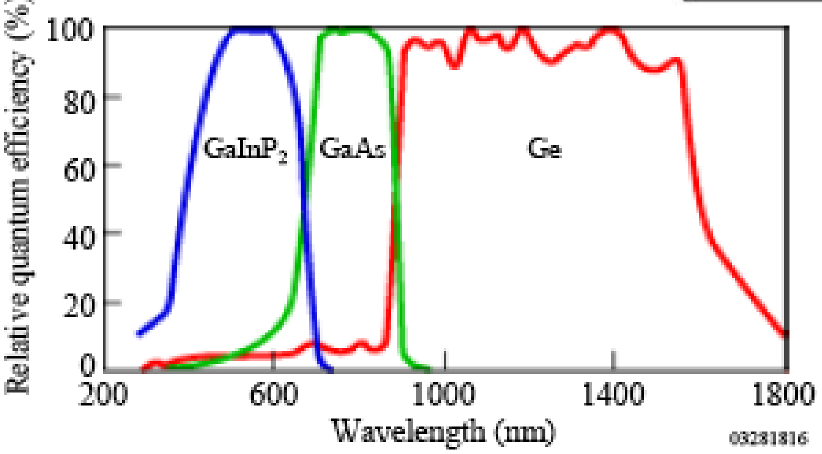
4. Photovoltaic Materials

How to circumvent SQ limit and other losses?

Photon management: Multi band gap, multi-junction photovoltaics







$GaInP_2$ E_g = 1.8 - 1.9 eV

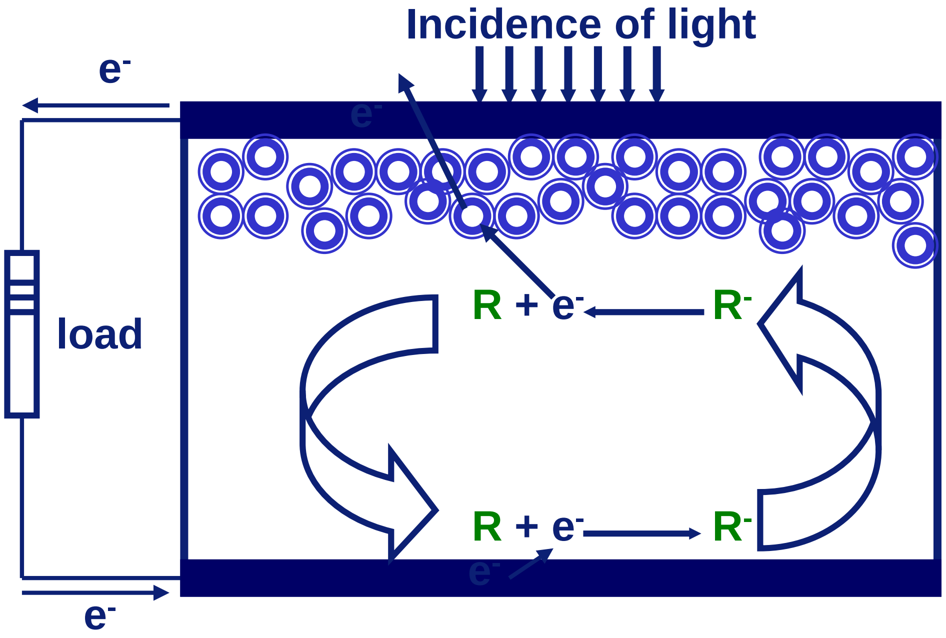
4. Photovoltaic Materials

Material challenges and development routes

Semiconductor	SQ limit	Challenges	Possible solutions
c-Si	25%	Absorption strength	Light in-coupling foils
a-Si	10%	SQ limit	Down/Up-converter
GaAs	28%	Toxicity	?
$Cu(In,Ga)S_2$	20%	stability, price	Coatings, solid solut.
CdTe	17%	Toxicity	?
$APbX_3$ (perovskites) $A = CH_3NH_3^+$, … $X = Cl^-, Br^-, I^-$	30%	Stability, hydrolysis	Encapsulation

4. Photovoltaic Materials

Dye Sensitised Cells (Grätzel Cells): Inventor Prof. Michael Grätzel



Glass substrate with SnO_2:F (0.5 µm)

TiO_2-nano particle membrane (5 - 10 µm)

Electrolyte solution with redox mediator

Glass substrate with SnO_2:F (0.5 µm)
and Pt-coating (2 µm)

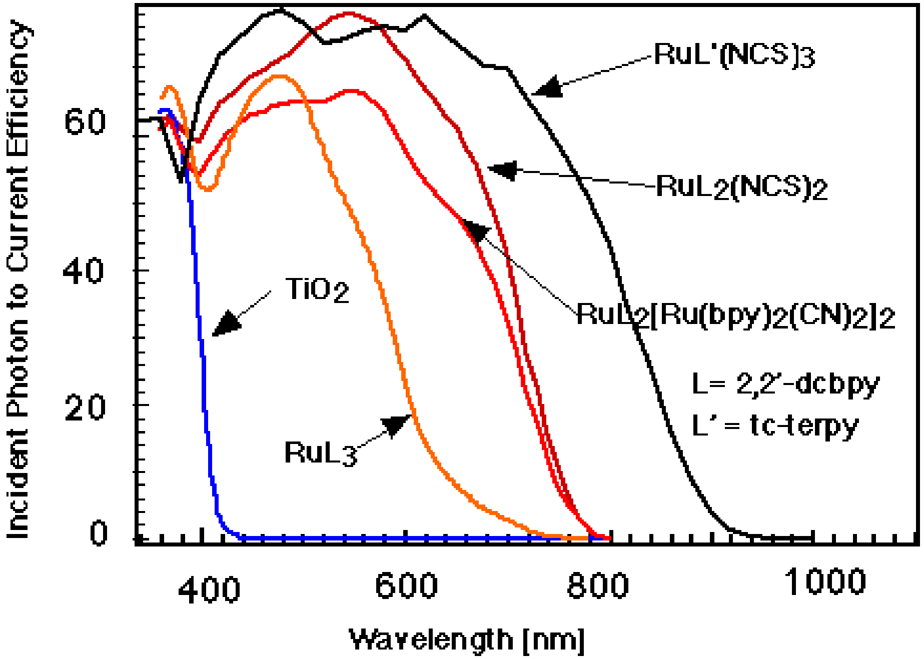
TiO_2 is the catalyst for the charge separation, but does not absorb visible light

4. Photovoltaic Materials

Dye Sensitised Cells (Grätzel Cells)

Photosensitisers

Absorption spectra of TiO_2 and octahedral Ru^{2+}-complexes



Advantages of Ru^{2+}-chelating complexes

- Reversible Ru^{2+}/Ru^{3+} redox pair
- Electronic low-spin configuration (anti-bonding orbitals are unoccupied)
- Chelating effect (entropic effect)

⇒ kinetically very stable (slow ligand exchange reaction)

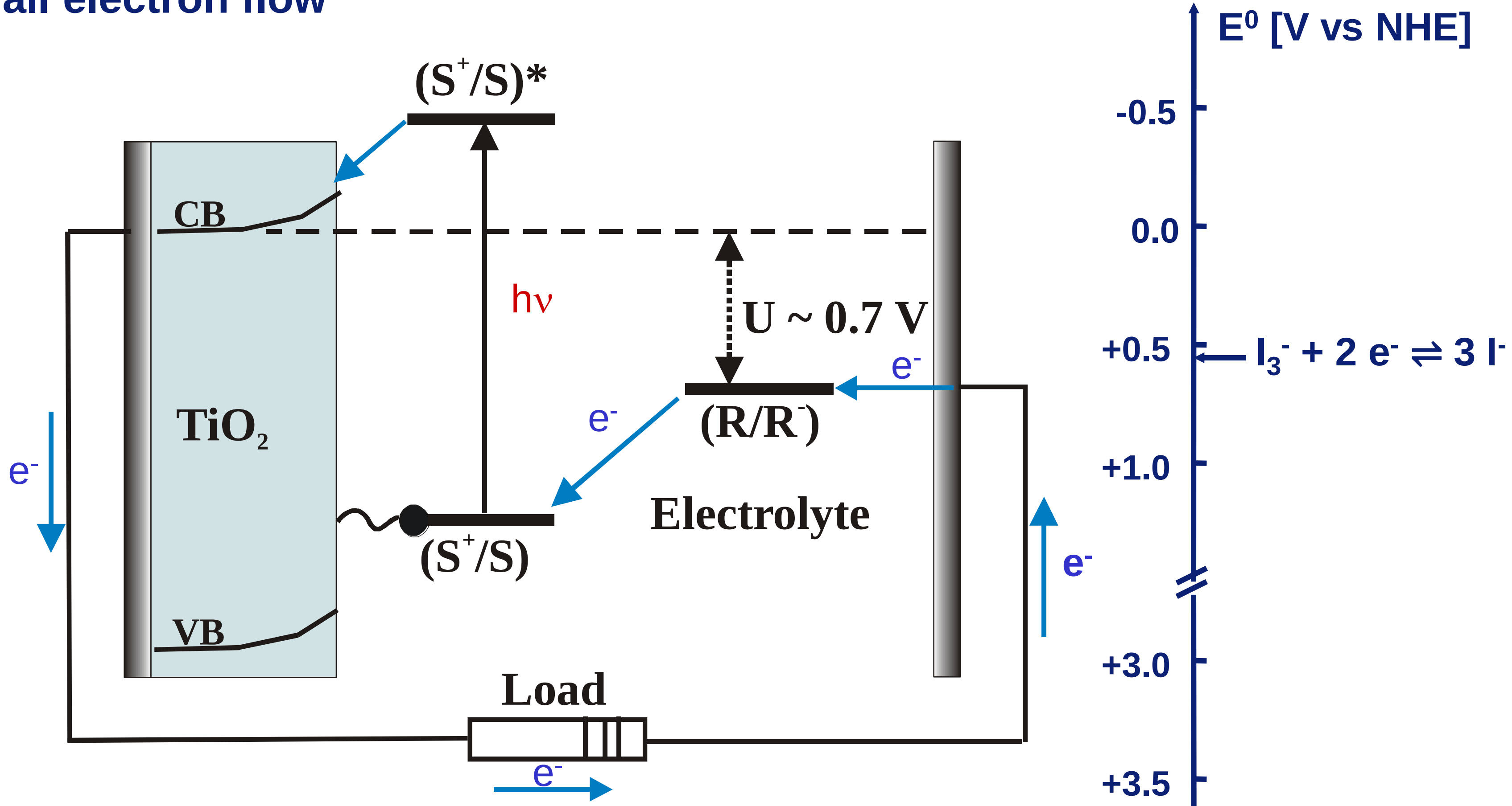
- Allowed MLCT transitions at relative low energies

⇒ intense absorption bands in the visible range of the spectrum

4. Photovoltaic Materials

Dye Sensitised Cells (Grätzel Cells)

Overall electron flow



4. Photovoltaic Materials

Photovoltaic Energy Conversion Requires Strong Absorption of Light and Efficient Charge Carrier Separation

Solar cell type	absorption process	charge carrier separation
pn-semiconductor	band to band	by an electrostatic field at the pn-junction
Graetzel	MLCT on $[RuL_2X_2]$	electron transfer to n-TiO_2 + oxidation of I^- to ½ I_2
„Chloroplast“	π-π* on chlorophyll	electron transfer to $NADP^+$ + oxidation of O^{2-} to ½ O_2

- Energy conversion efficiency of best practice Graetzel Cells is about 10%
- Lifetime is a problem due to cell sealing and electrolyte leakage

5. Photochemical Water Splitting

World wide energy demand and production

Global annual photosynthetical produced biomass ~ $3.0 \cdot 10^{21}$ J = 700 Gt (efficiency η ~ 0.15%)

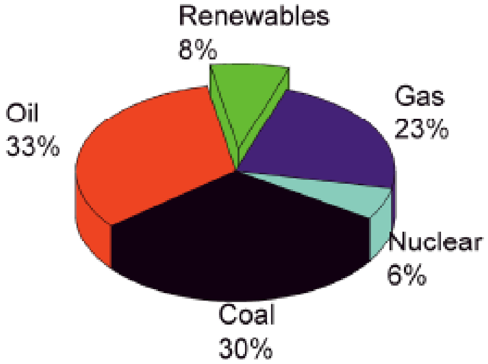
$$CO_2 + H_2O \xrightarrow{[Mn_4Ca]\text{-Cluster}} (CH_2O)_x + O_2$$

~ 95 TW

World energy consumption	Y2010	~ 14 TW
	Y2050	~ 25 TW
	Y2100	40-50 TW

Potential

Biomass	5-7 TW
Wind	14 TW
Solar	100000 TW



Conclusion: Energy consumption of human society must be supported by distributed harvesting of solar energy on the long term!

→ Solar thermal processes

→ Photovoltaics

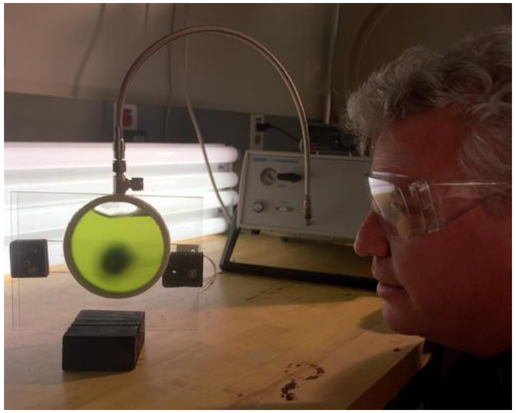
→ Photochemistry (artificial photosynthesis)

Challenges: Efficiency + Scalability + Lifetime

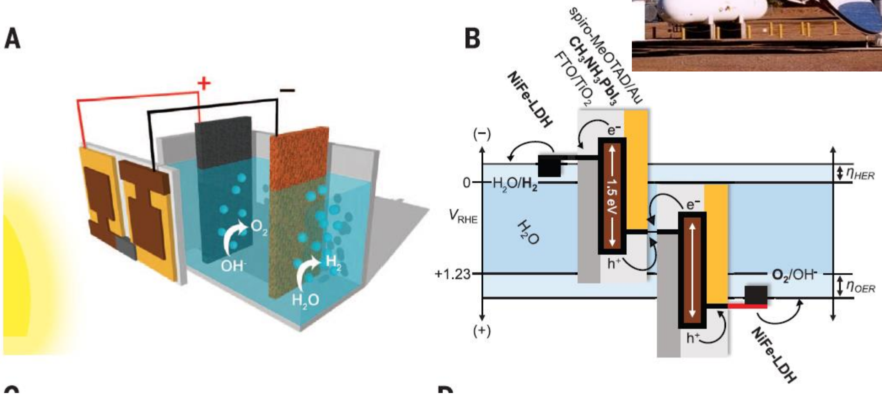
5. Photochemical Water Splitting

Pathways towards water cleavage

$2\ H_2O(g) \rightarrow O_2(g) + 2\ H_2(g)$



- Photosynthesis
  - Plants
  - Algae
- Thermolysis
- Electrolysis
- Photolysis
- Photocatalysis



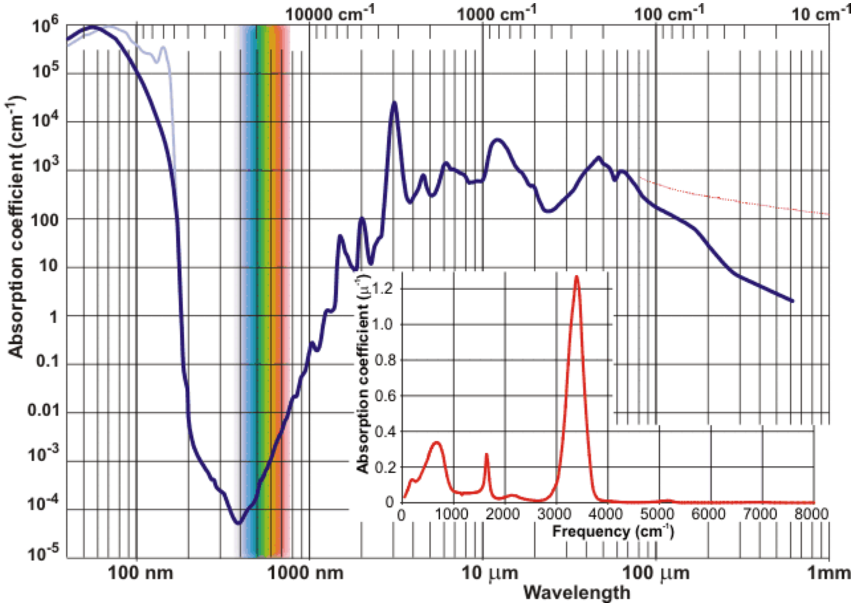
5. Photochemical Water Splitting

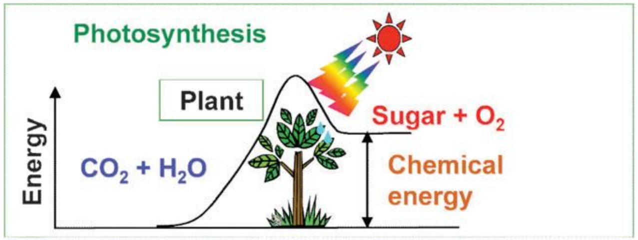
Energy Balance

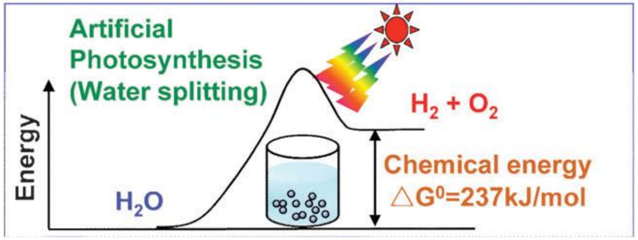
$$\begin{tikzcd}
2\,H_2O(g) \arrow[r, shift left, "+\ 2x\ 237\ \text{kJ/mol}"] \arrow[d, shift right, "-\ 2x\ 138\ \text{kJ/mol}"'] & O_2(g)\ +\ 2\,H_2(g) \arrow[l, shift left, "-\ 2x\ 237\ \text{kJ/mol}"] \\
2\,H_2O(l) \arrow[u, shift right, "+\ 2x\ 138\ \text{kJ/mol}"'] \arrow[r, "+2120\ \text{kJ/mol}", "{=530\ \text{kJ/mol per O-H bond}}"'] & 2\,O(g)\ +\ 4\,H(g) \arrow[u, "-2x\ 436\ \text{kJ/mol}"', "-498\ \text{kJ/mol}\ +"]
\end{tikzcd}$$

Photolysis of water without any photocatalyst requires VUV or EUV Radiation (10 – ~200 nm)

→ Stratosphere and Mesosphere





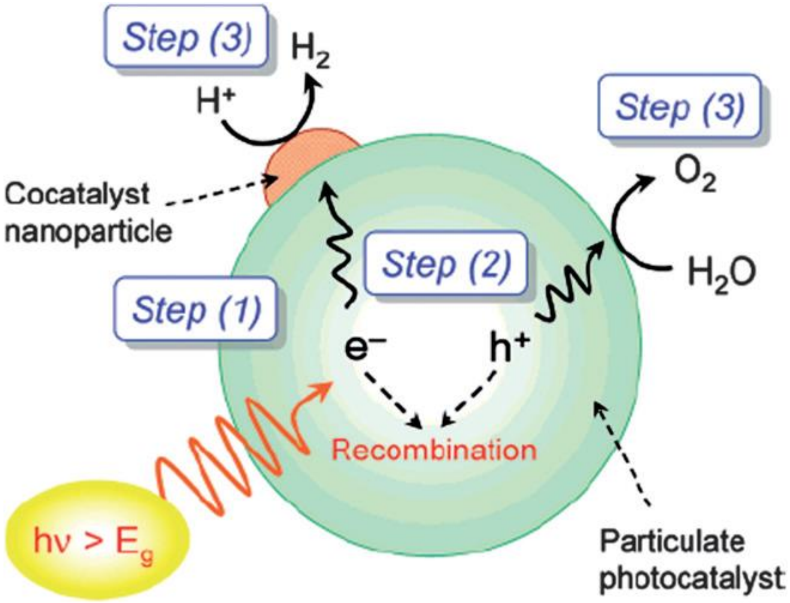


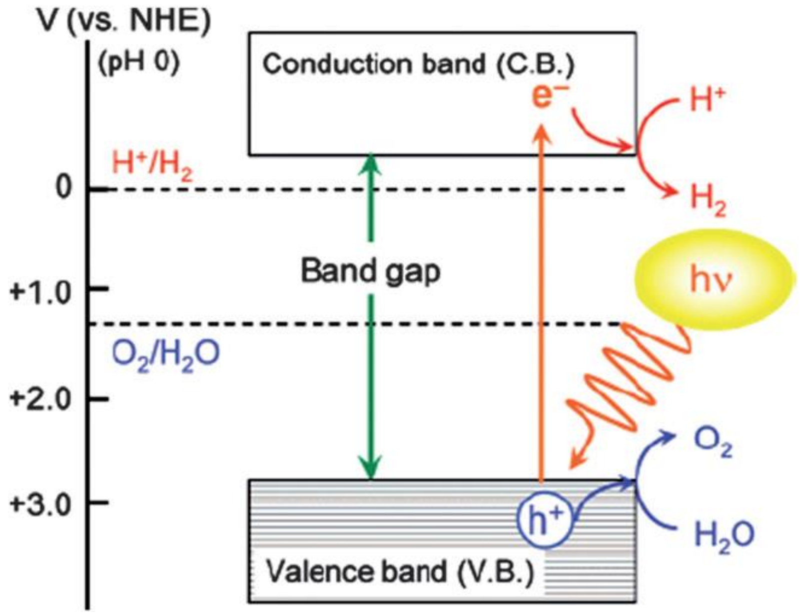
5. Photochemical Water Splitting

Photocatalytic Process by Using Semiconductors

- **First system explored in 1971 by A. Fujishima and K. Honda (Nature 238 (1972) 38) → TiO_2 with Pt as a co-catalyst**

- **In general water splitting is possible at around 1000 nm (1.23 eV), in real systems voltage is higher > ~1.8 V**

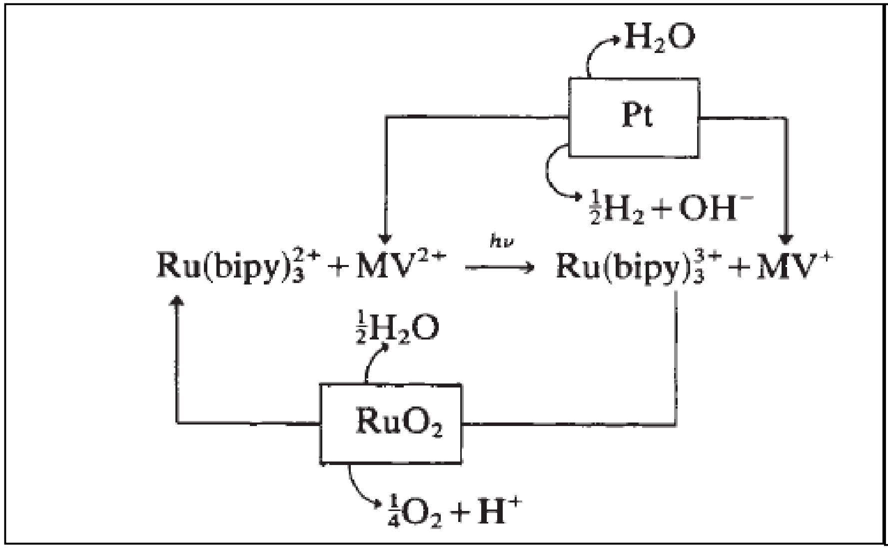


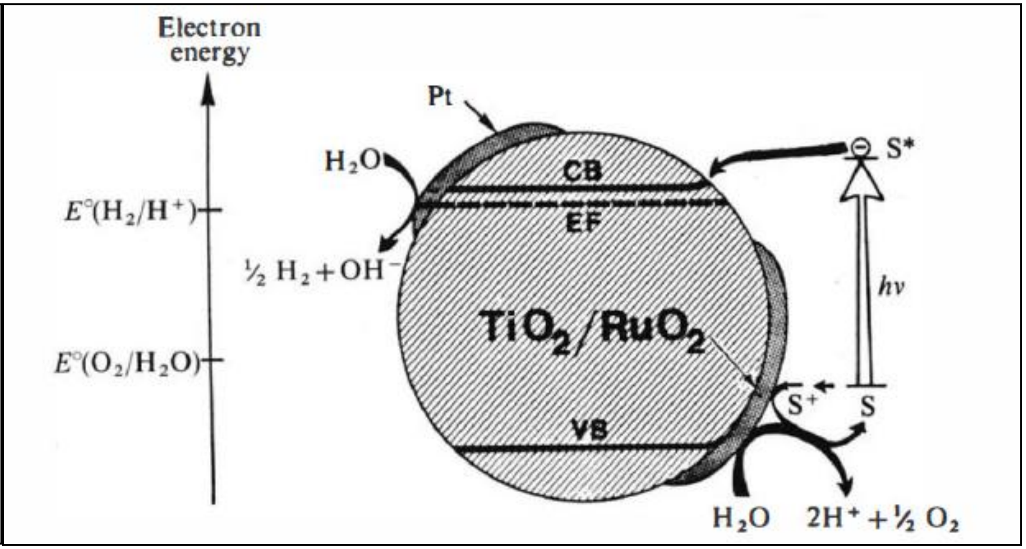


5. Photochemical Water Splitting

Photocatalytic Process by Using Semiconductors and a Sensitizer

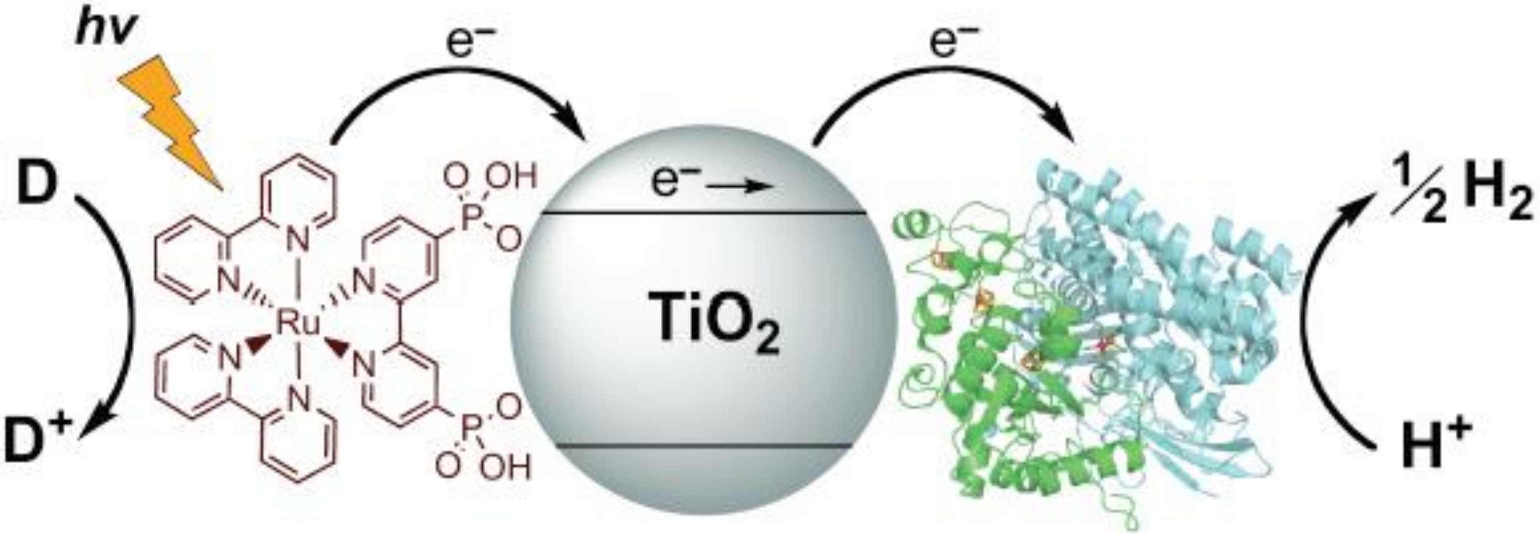
- First system using a sensitizer presented in 1981 by M. Graetzel (Nature 289 (1981) 158)
- → TiO_2 with Pt and RuO_2 as co-catalysts and $[Ru(bpy)_3]^{2+}$ and methylviologen as sensitizers (antennae)
- Synthesis of Pt nanoparticles from H_2PtCl_6 and citrate





5. Photochemical Water Splitting

Solar Hydrogen Generation

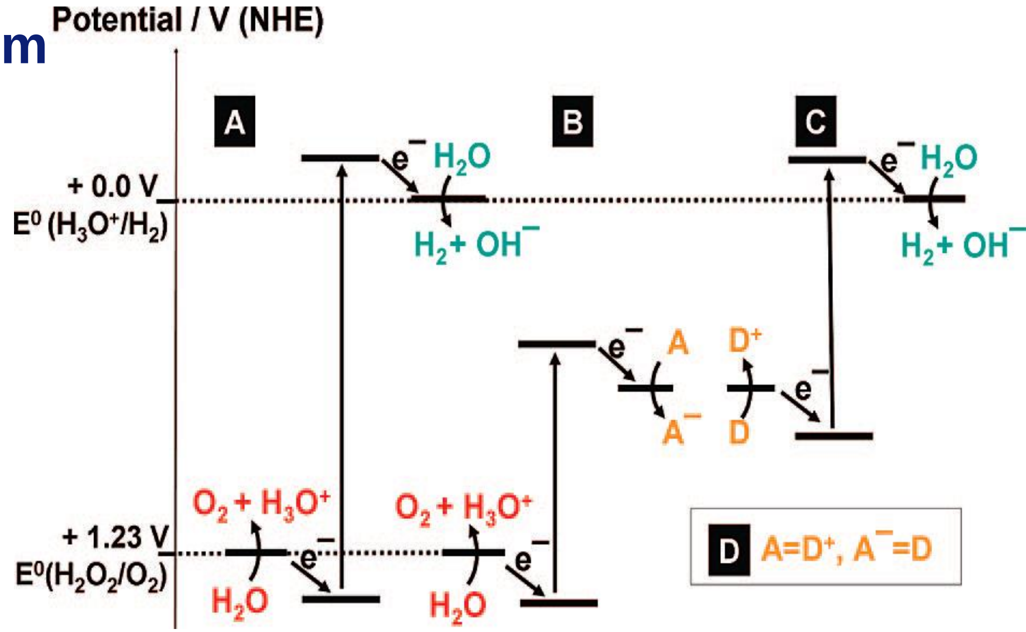


Schematic representation of visible light-driven H_2 production with D [NiFeSe]-H attached on ruthenium-dye sensitized TiO_2 nanoparticles, in the presence of a sacrificial electron donor D.

Visible light irradiation (λ > 420 nm) excites the $Ru(bipy)_3$ photo-sensitizer, which injects electrons into the conduction band of TiO_2 and on to the hydrogenase, resulting in H^+ reduction.
Ref.: F.A. Armstrong, E. Reisner et al., Chemical Society Reviews 108 (2008) 2439

5. Photochemical Water Splitting

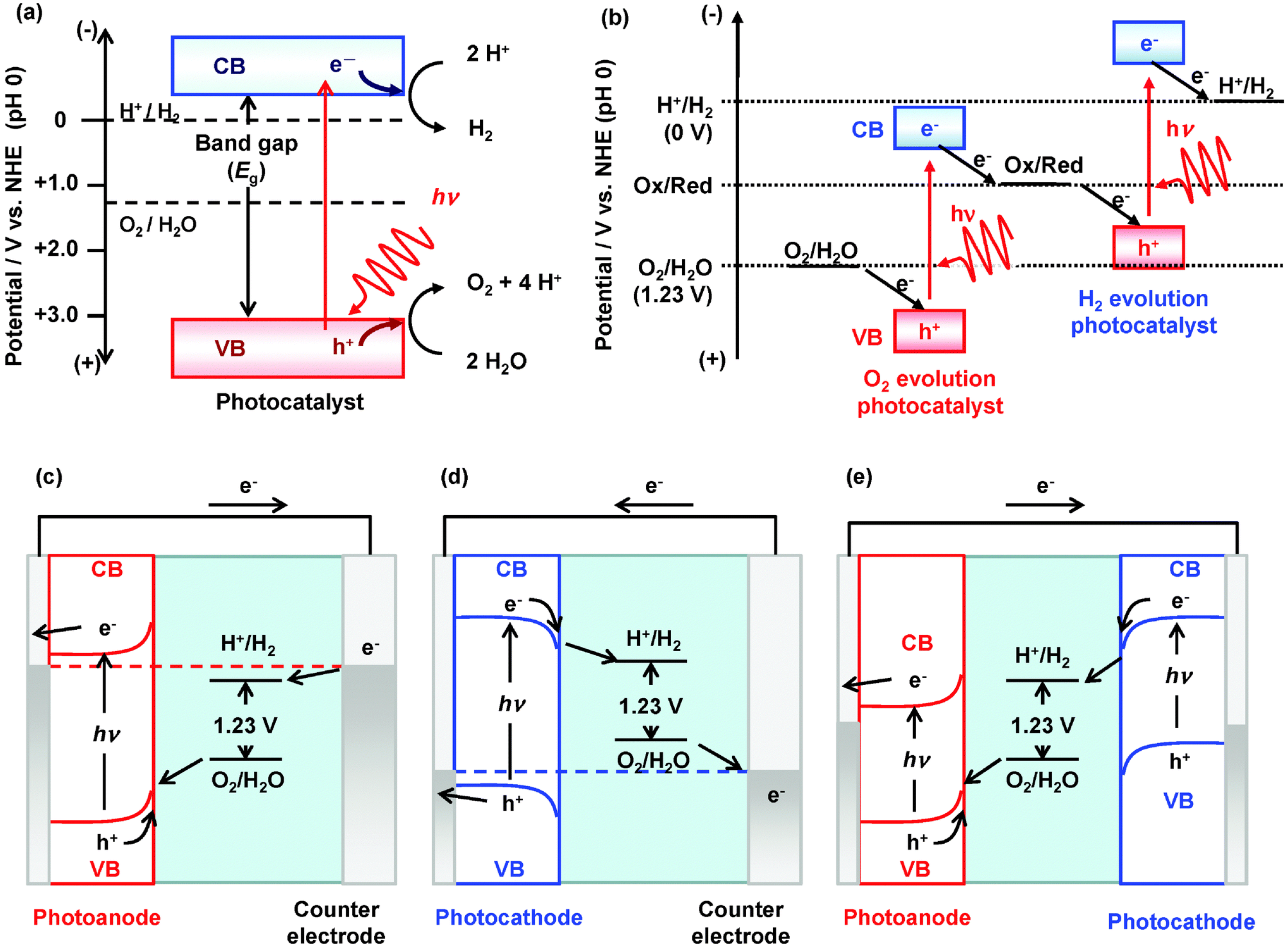
Photocatalytic Process by Using Semiconductors - Approaches



- A: single semiconductor system
- B: single semiconductor system with electron acceptor → O_2
- C: single semiconductor system with electron donor → H_2
- D: combination of B and C (tandem system)
- Additionally: Powders in solution (→ detonating gas formation)

5. Photochemical Water Splitting

Photocatalytic Process by Using Semiconductors - Approaches

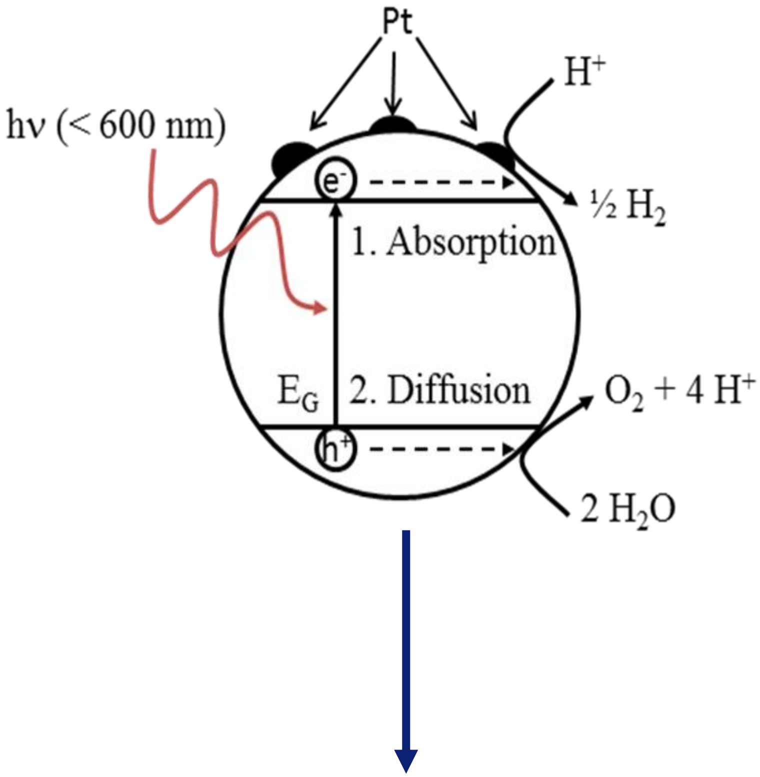


5. Photochemical Water Splitting

From Powder to Ceramics for a Light Splitting Tandem Cell

- Top structure (UV - Blue)
  - Water splitting by an inorganic & stable photocatalyst
  - Conductive ceramic is required
  - Structured Platin deposition

- Bottom structure (Green – NIR)
  - Photovoltaic unit
  - Options: Modification by up-converter and/or down-converter



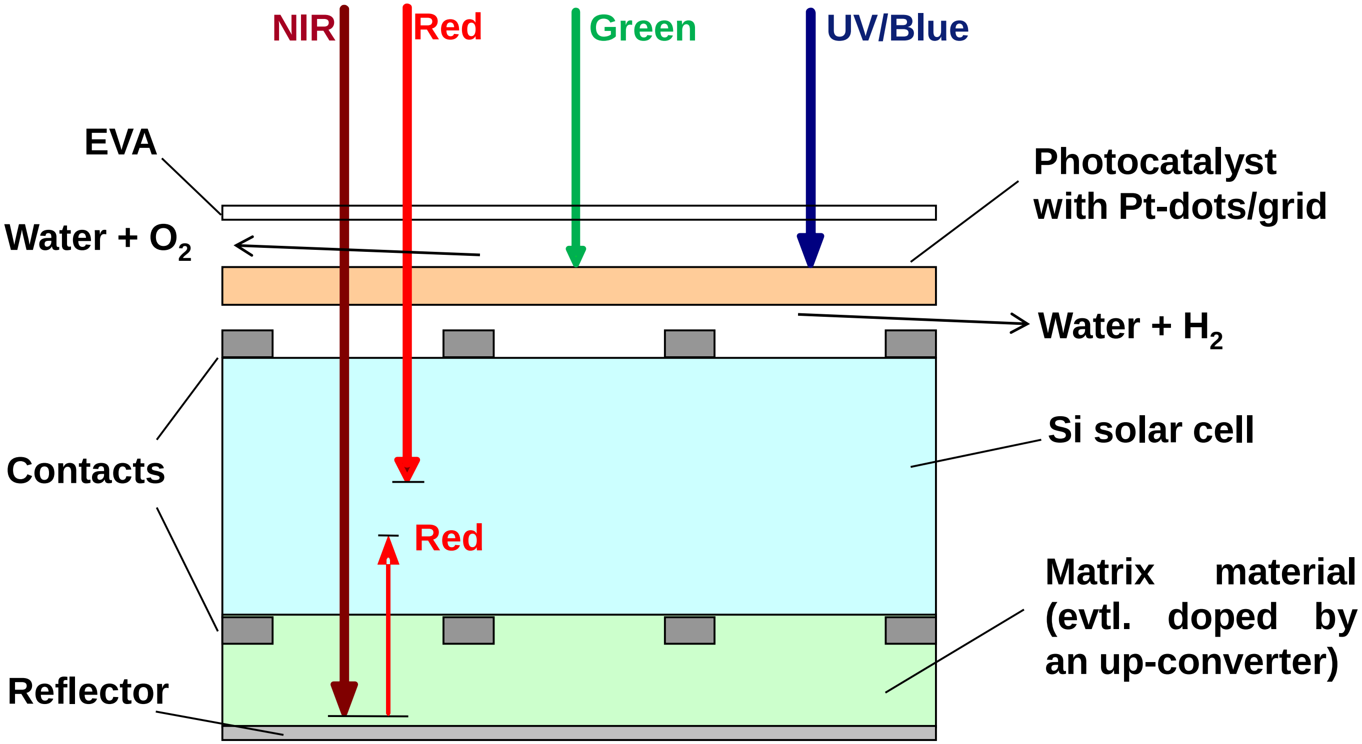
$2\,OH^- + 2\,h^+ \rightarrow 2\,OH^{\cdot} \rightarrow H_2O_2 \rightarrow H_2O + ½\,O_2$

Pt-dots/grid

$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$ (pH↑)

5. Photochemical Water Splitting

Light Splitting Tandem Cell: PV Unit & Photocatalytical Unit



Advantages

Cooling of the PV unit

Less thermalisation

Less damage of the PV unit by UV to blue radiation

Ref.: T. Jüstel et al., German Patent Application, Energy Conversion System, DE102014107268

5. Photochemical Water Splitting

Requirements on the Photocatalyst

- **Stability**
  The most photochemically stable semiconductors in aqueous solution are oxides, but their band gaps are either too large for efficient light absorption (~3 eV), or their semiconductor characteristics are poor.

- **Efficiency (band gap)**
  For reasonable solar efficiencies, the band gap must be less than 2.2 eV, unfortunately, most useful semiconductors with band gaps in this range are photochemically unstable in water.

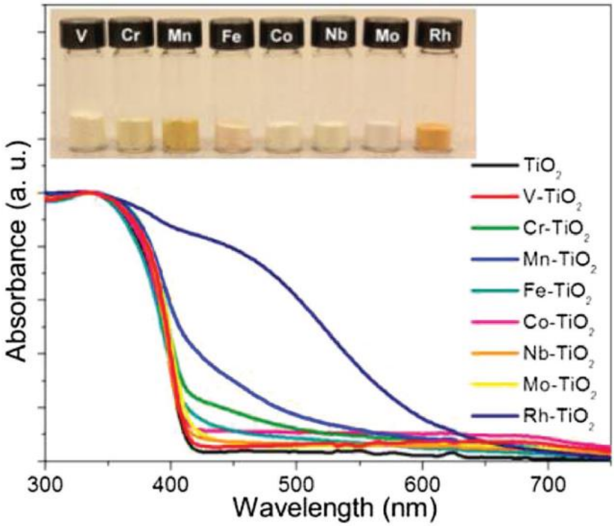
- **Energetics**
  In contrast to metal electrodes, semiconductor electrodes in contact with liquid electrolytes have fixed energy levels where the charge carriers enter the solution. So even though a semiconductor electrode may generate sufficient energy to effect an electrochemical reaction, the energetic position of the band edges may prevent it from doing so. For spontaneous water splitting, the oxygen and hydrogen reactions must lie between the valence and conduction band edges, and this is almost never the case.

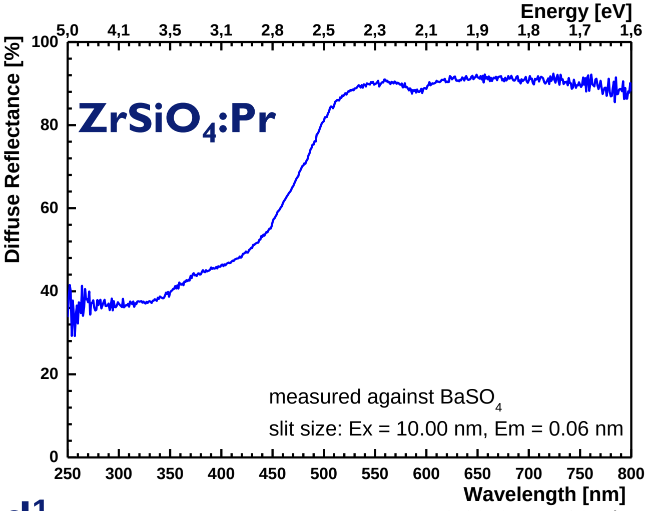
5. Photochemical Water Splitting

Photocatalyst Stability

Oxide	Band gap [eV]	Colour
$ZrSiO_4$	6.5	white
ZrO_2	5.0	white
$CaWO_4$	4.1	white
ZnS	3.8	white
$KTaO_3$	3.4	white
ZnO	3.3	white
$SrTiO_3$	3.2	white
TiO_2	3.0	white
CeO_2	2.8	yellow
WO_3	2.7	yellow
$BiVO_4$	2.4-2.5	yellow
CdS	2.3	orange
Fe_2O_3	2.0	red
InN	1.9	red

Doping by Ce^{3+}, Pr^{3+}, Tb^{3+} **MMCT**
Eu^{2+} $[Xe]4f^7$ – $[Xe]4f^65d^1$



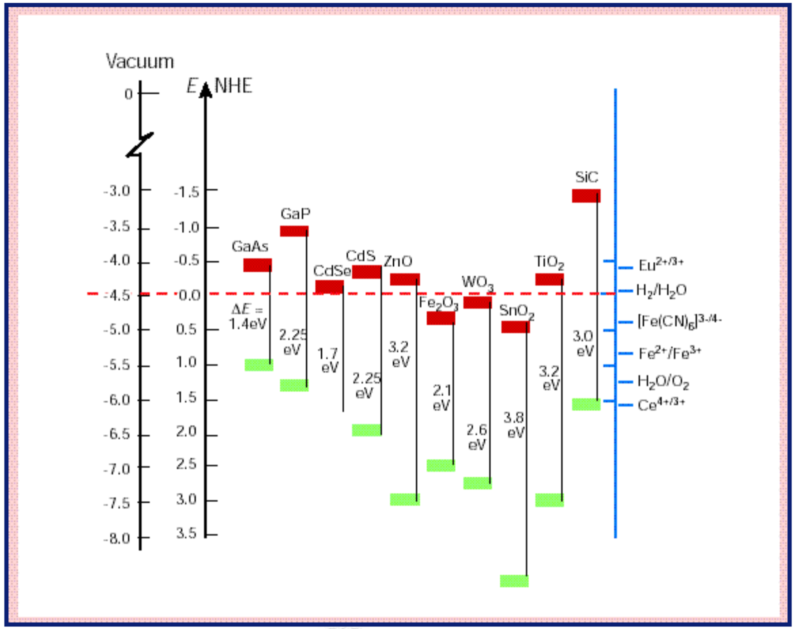


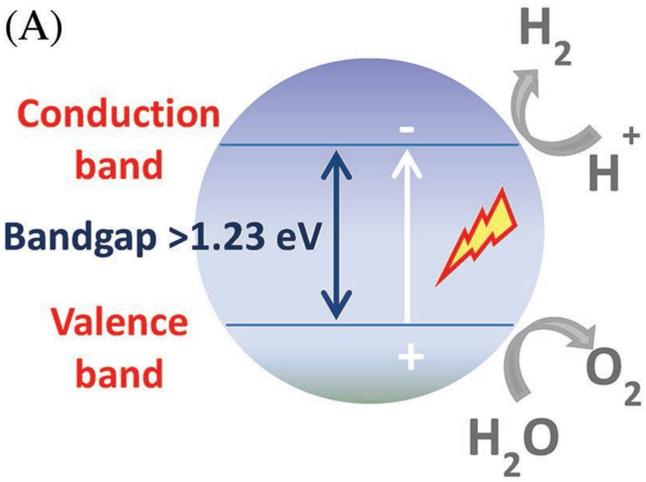
LOT# UVC-2010-DE-ZS011b

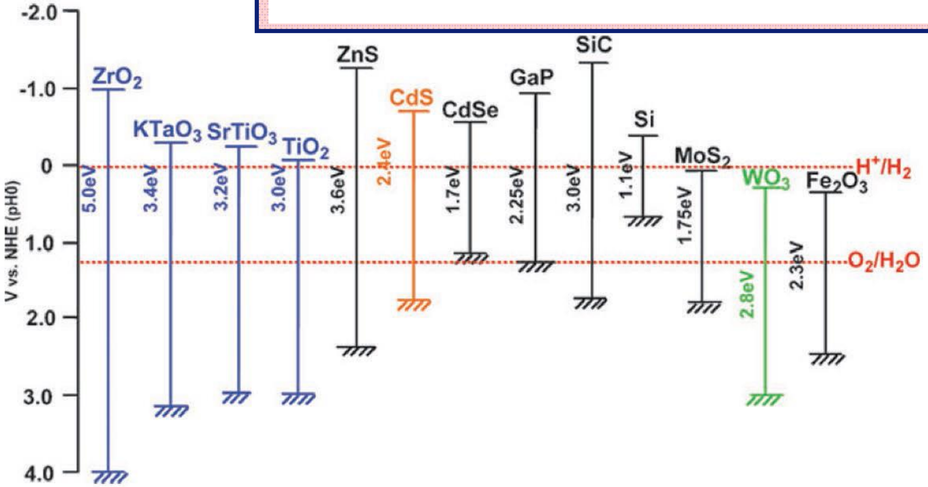
5. Photochemical Water Splitting

Photocatalyst Efficiency and Energetics

Band gap	**2.0 – 3.0 eV**
VB	**~ -6.0 V below vacuum level**
CB	**~ -4.0 V below vacuum level**

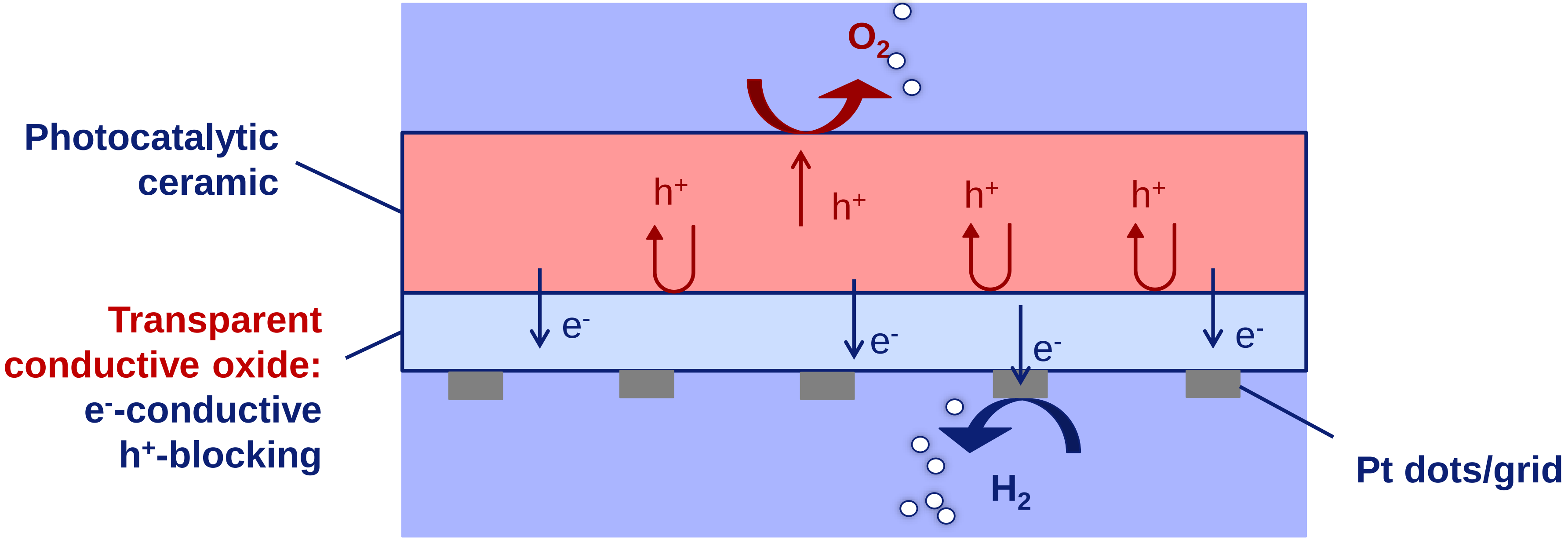






5. Photochemical Water Splitting

Final Goal: Develop photocatalytic unit, comprising a hole blocking layer



Technology already applied in

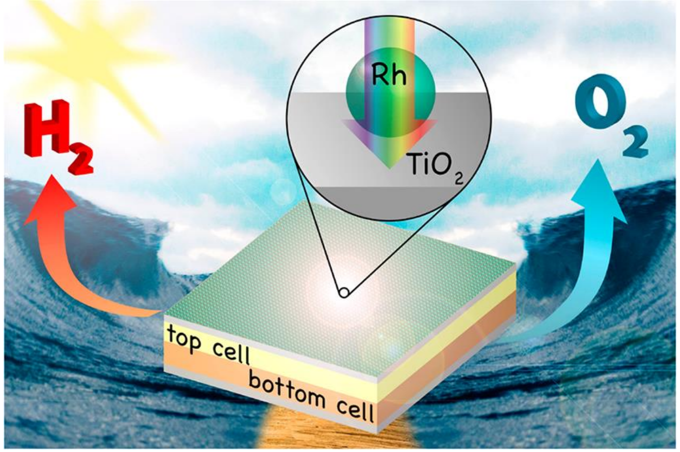
- OLEDs and PLEDs
- Inverted Polymer Solar Cells
- Other photocatalysts
- …..

Deposition methods

- Sol-gel method
- Spin-coating
- Sputtering (RF-MS)
- …..

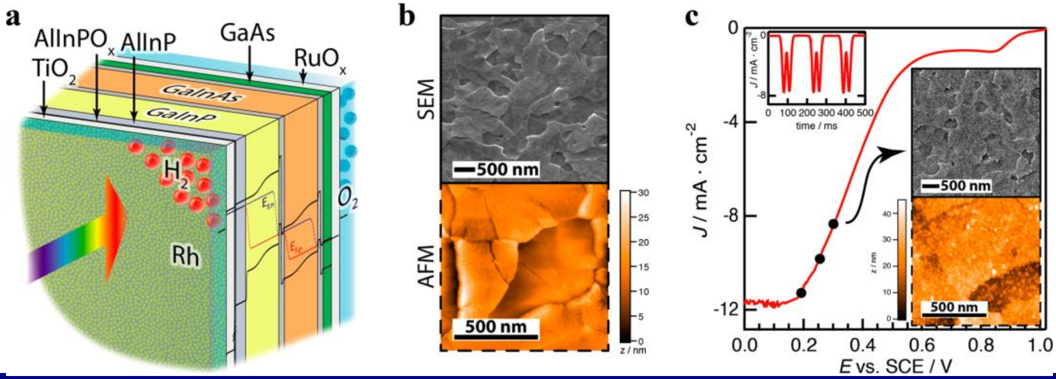
5. Photochemical Water Splitting

Recent Embodiment



- Charge carrier separation and e^- / h^+ conduction by epitactically grown AlInP, AlInPO layers
- Rh onto TiO_2 as photocathode
- RuO_x onto GaAs as photoanode
- Problem: Relief of evolving pH gradient

Ref.: ACS Energy Lett. 3 (2018) 1795-1800



6. Lighting Towards Ultimate Efficiency

About 20% of the produced electrical energy is used for lighting (source: NASA)

Even more than 25 years after Germany's reunification East and West Berlin can be diminished by lighting

1961	Construction of the Berlin Wall
1989	End of the Berlin Wall "The wind of change"
1990	Germany's reunification
1993	Blue LED: (In,Ga)N
1996	White LED: YAG "The light of change"
2014	White LED > 300 lm/W & Nobel price
2021	LED dominate lighting business

6. Lighting Towards Ultimate Efficiency

Historical Development

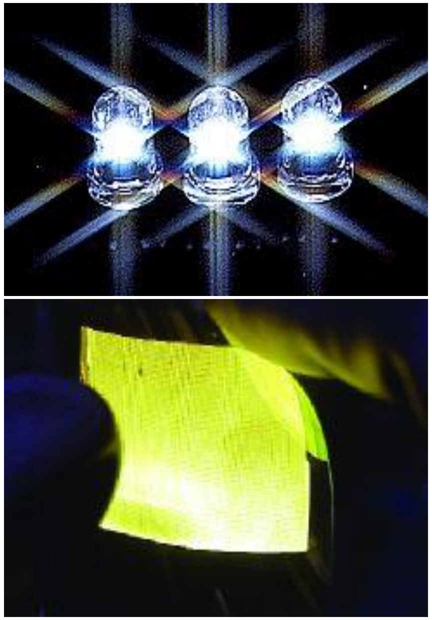
10000 B.C. **19th century** **20th century** **21st century**

First there was open fire...

...then the fire was tamed...

...put into a glass bulb...

...and made more efficient...



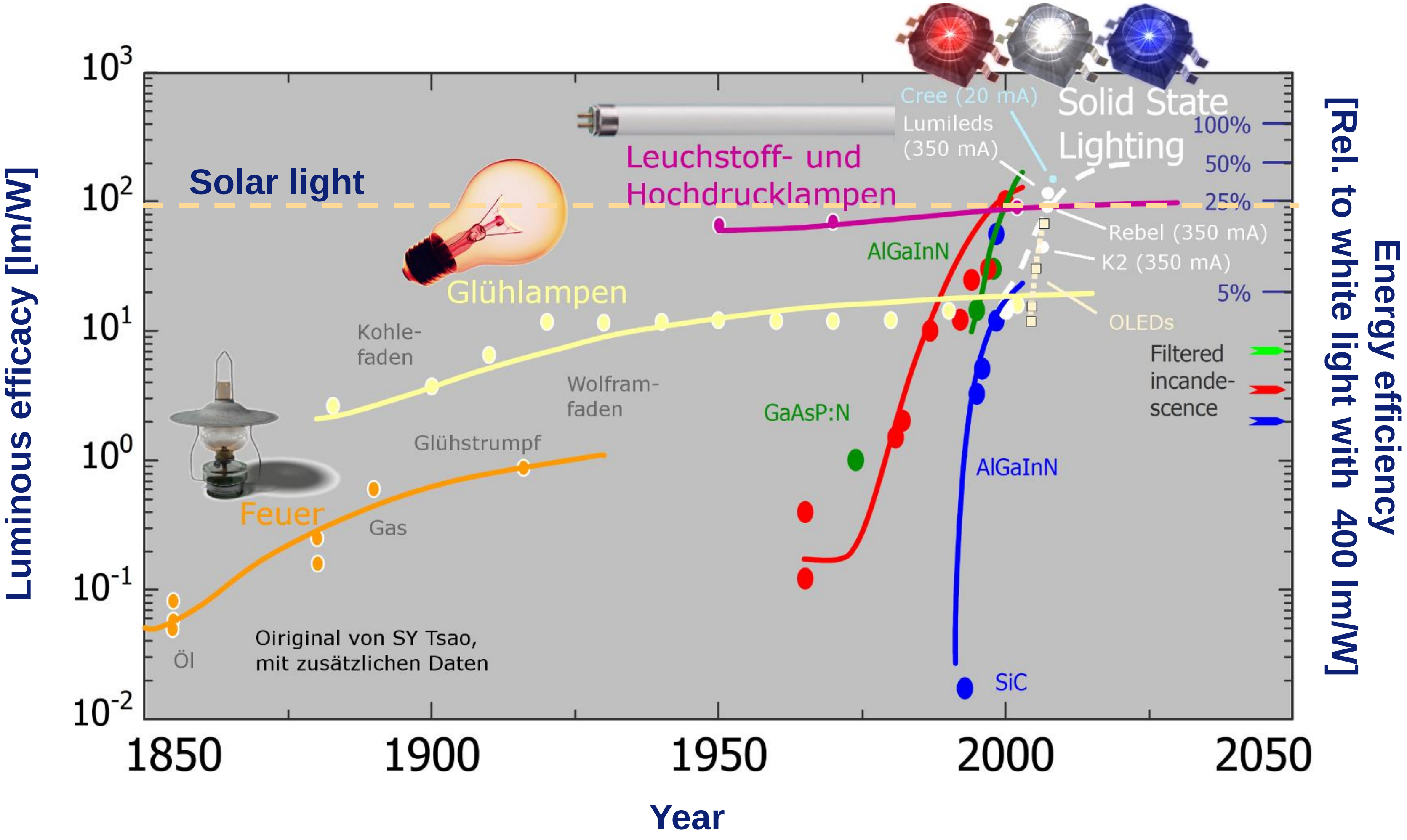
...then the fire vanished and light only prevailed !

From chemical light sources

to electrical light sources

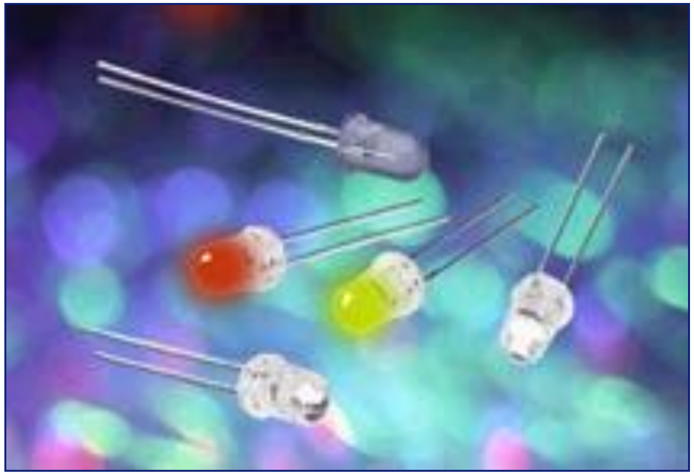
6. Lighting Towards Ultimate Efficiency

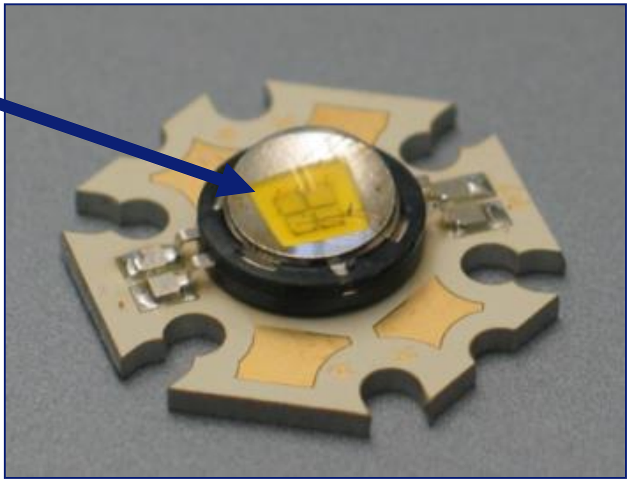
Historical Development: Luminous Efficacy and Energy Efficiency



6. Lighting Towards Ultimate Efficiency

Historical Development: Colours and Power Density





Luminescent screen

1970

(Ga,As)P

< 0.1 W

< 1.0 lm

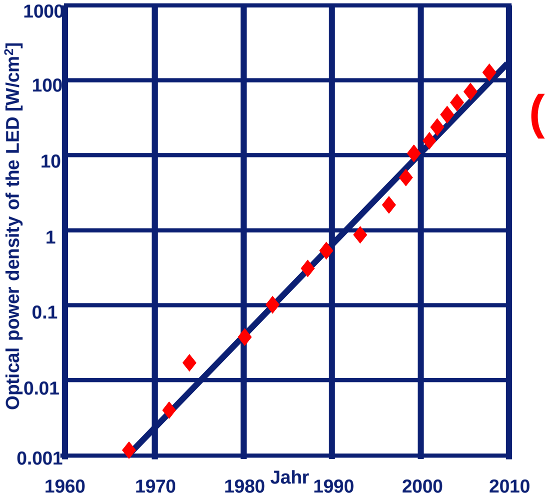
< 10 lm/W

< 120 °C

< 100 W/cm^2

> 120 K/W

yellow, red, NIR



Development of the optical power density of LED light sources (source: fairchildsemi.com)

2019

(Al,In,Ga)P, (In,Ga)N, (Al,Ga)N

1 - 10 W

> 100 lm

up to 303 lm/W

120 – 200 °C

100 – 200 W/cm^2

2 – 12 K/W

UV-A/B/C, all colors, NIR

6. Lighting Towards Ultimate Efficiency

Power Saving Potential by LEDs

Source: DOE SSL R&D Multi-Year Program Plan

Electric lighting consumes worldwide

2,600,000,000,000,000 Wh (2600 TWh) p.a.

(~20% of total global electricity production)

LED energy saving potential: 1500 TWh

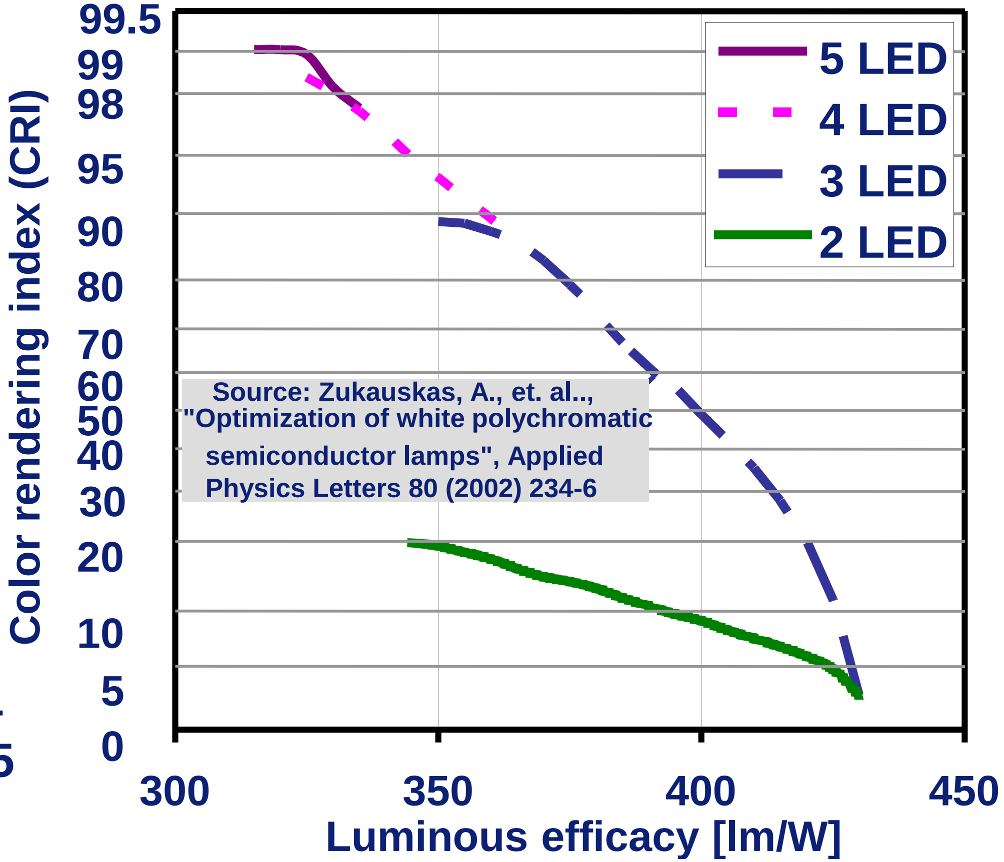
➜Reductions in power plants:
  - **200 nuclear power plants or**
  - **200 fossil power plants**

Ref.: IEA, International Energy Agency

6. Lighting Towards Ultimate Efficiency

Multichip LED Lamps

- Narrow band emitter e.g. LEDs
  - $\lambda_{1/2}$ = 30 nm
  - Several colored LEDs
- Theoretical maximum
  - 430 lm/W for
  - CCT = 4870 K
  - CRI = 3 (!)
- Feasible values
  - ~ 350 lm/W for CRI 90, n = 3 - 4
  - max. 320 lm/W for CRI 99, n = 5
- Problems
  - Thermal stability of the LEDs
  - LED efficiency
    - Red and blue high
    - Green and yellow moderate → Phosphors!



Source: Zukauskas, A., et. al.., "Optimization of white polychromatic semiconductor lamps", Applied Physics Letters 80 (2002) 234-6

BREAKING BARRIERS

Cree leads the industry in LED efficacy and innovation. We were the first company to hit these industry-leading performance milestones and we're not stopping!

6. Lighting Towards Ultimate Efficiency

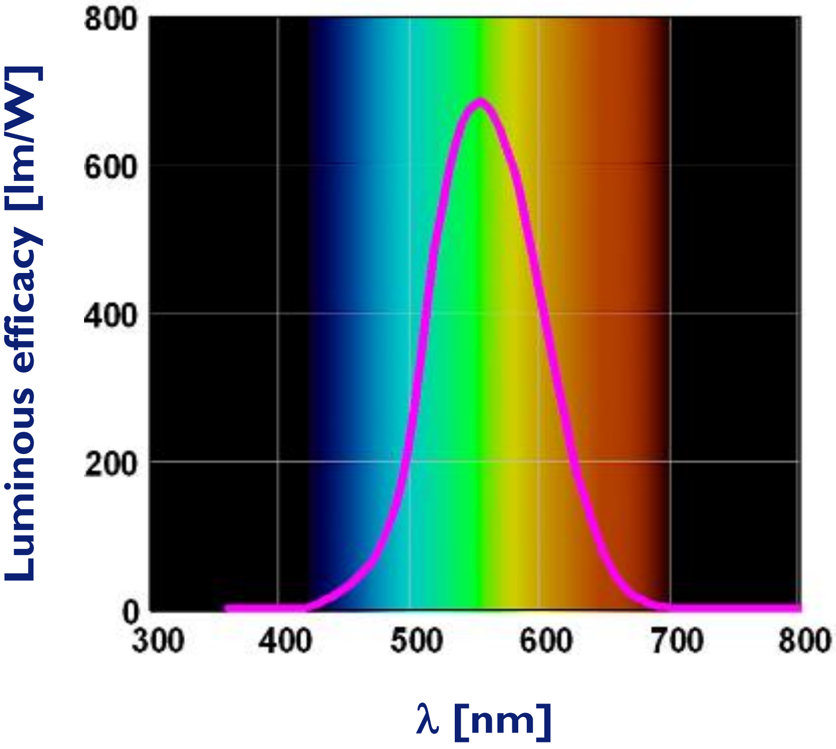
Luminous Efficacy of Light Sources

- Strong dependence on emission spectrum

- Optimum is at 555 nm
  - V(λ) = 683 lm/W (100%)

- Lumen output
  - 1000 lm at 555 nm requires 1.5 W
  - Incandescent bulb ~ 80 W, i.e. 12.5 lm/W

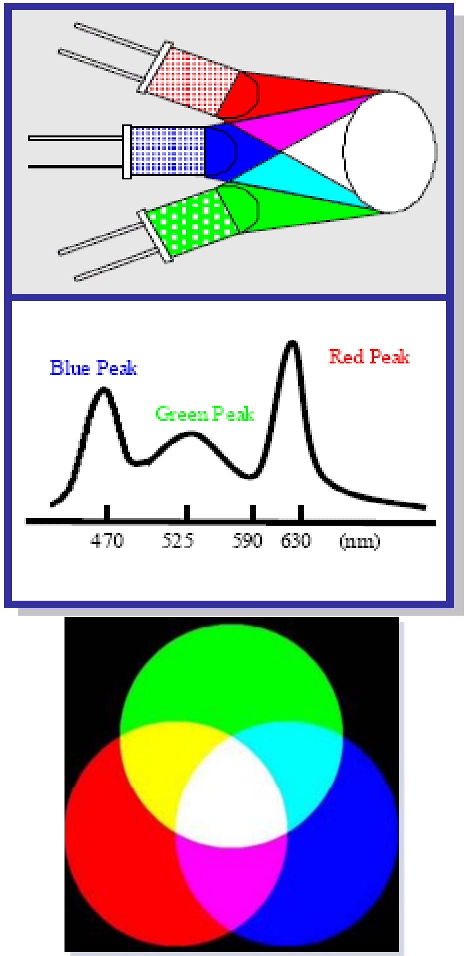
- Blue and red radiation
  - V(λ) < 70 lm/W (10%)



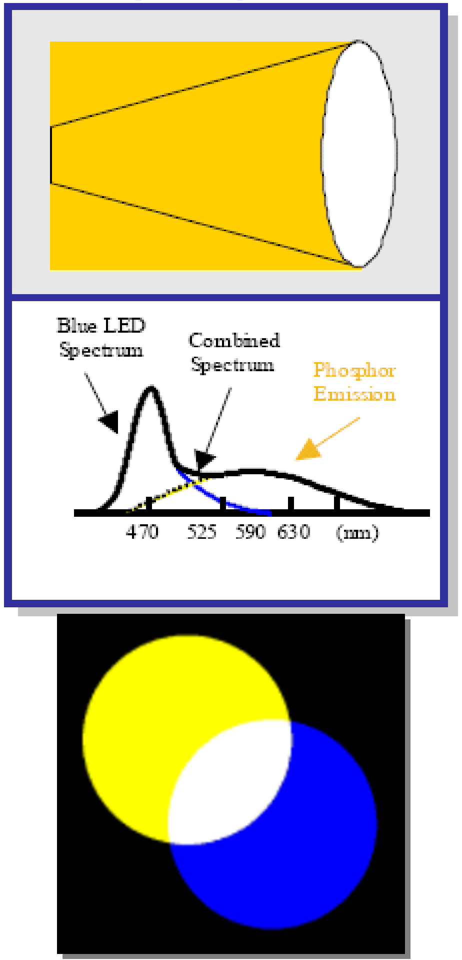
6. Lighting Towards Ultimate Efficiency

General Approaches

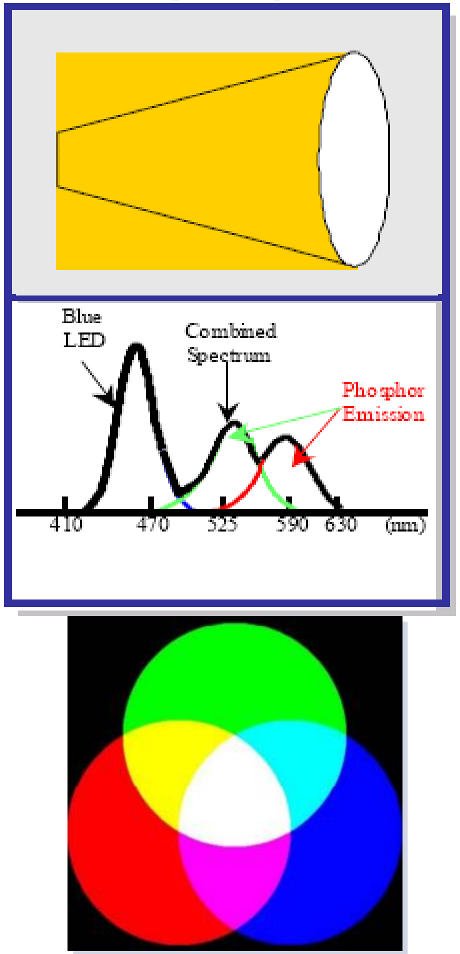
Red + Green + Blue LEDs



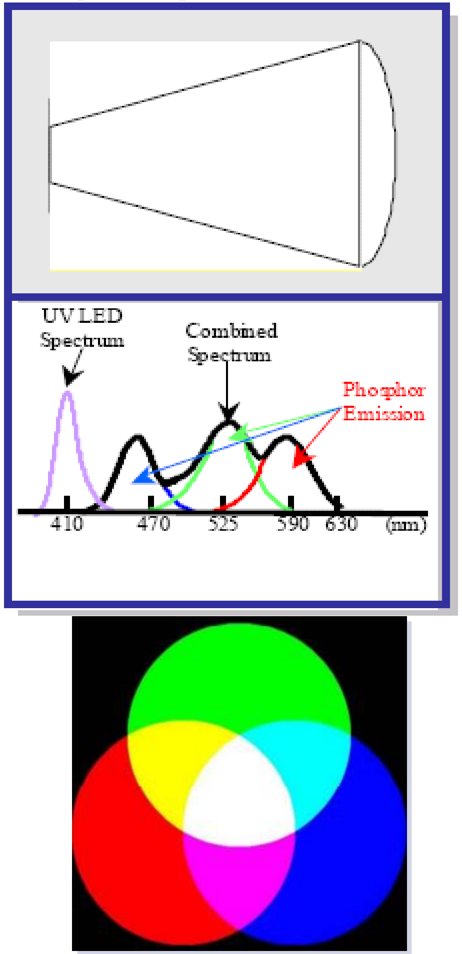
Blue LED + yellow phosphor



Blue LED + yellow + red phosphor

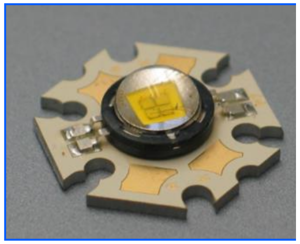


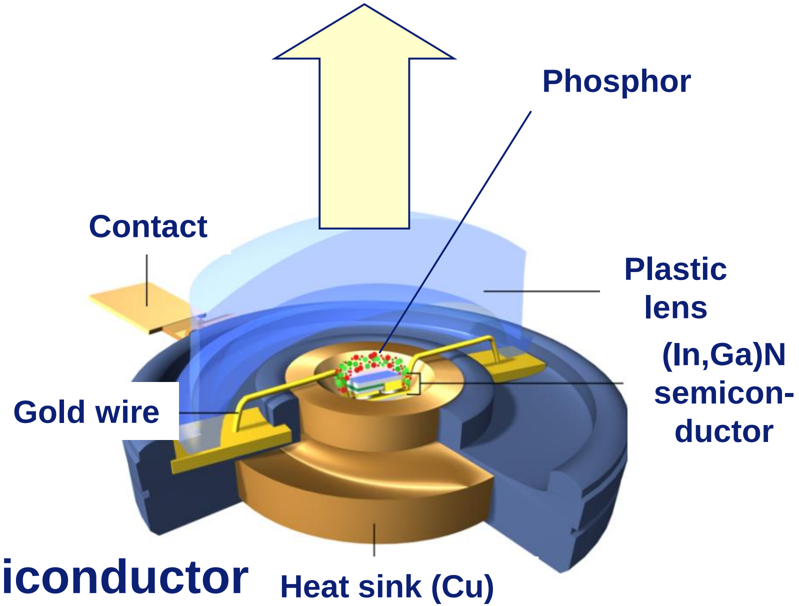
UV LED + RGB phosphor blend

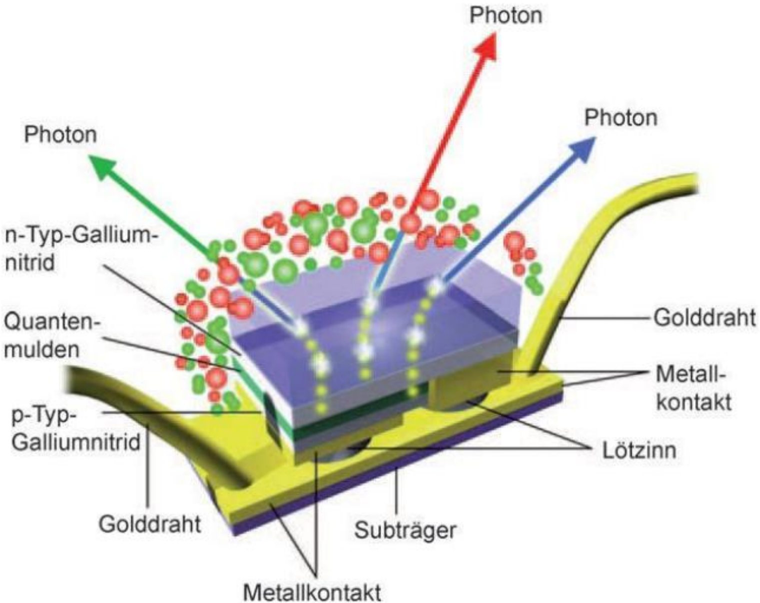


6. Lighting Towards Ultimate Efficiency

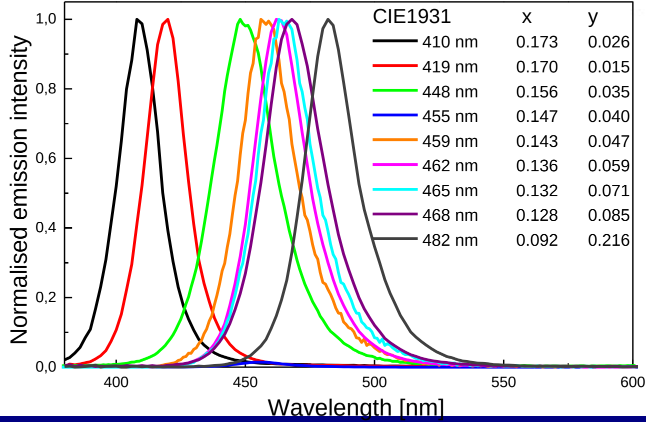
“Phosphor Converted” (pc) LED



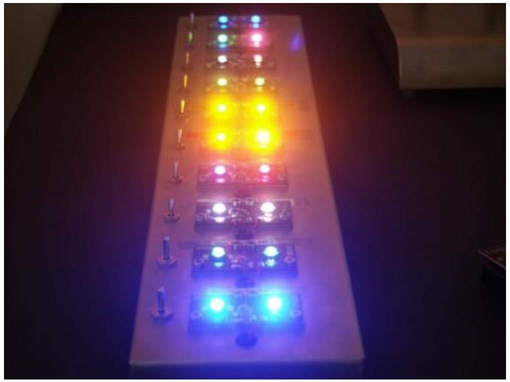


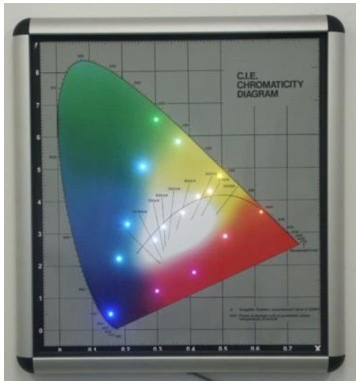


$In_{1-x}Ga_xN$ Semiconductor



CIE1931	x	y
410 nm	0.173	0.026
419 nm	0.170	0.015
448 nm	0.156	0.035
455 nm	0.147	0.040
459 nm	0.143	0.047
462 nm	0.136	0.059
465 nm	0.132	0.071
468 nm	0.128	0.085
482 nm	0.092	0.216





6. Lighting Towards Ultimate Efficiency

Micropowders or Ceramics

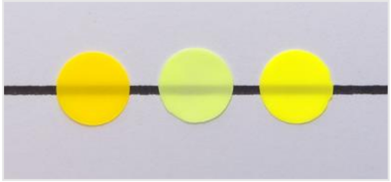
Aluminates → Ce^{3+}

$(Y,Gd,Tb)_3Al_5O_{12}$:Ce

$Lu_3(Ga,Al)_5O_{12}$:Ce

Sulphides → Eu^{2+}

(Ca,Sr)S:Eu

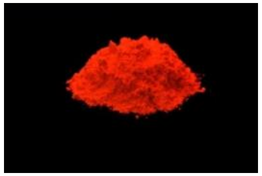


Oxides → Eu^{2+} or Ce^{3+}

$CaSc_2O_4$:Ce,Mg

$(Ca,Sr,Ba)_2SiO_4$:Eu

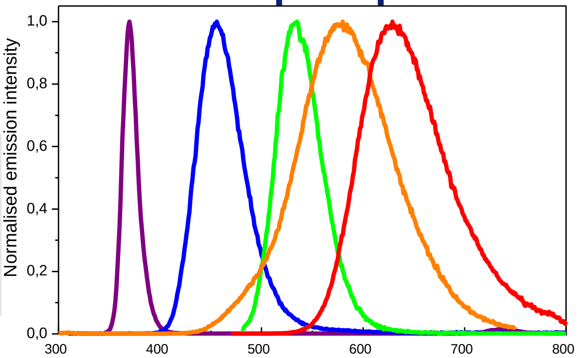
$(Ca,Sr,Ba)_3SiO_5$:Eu

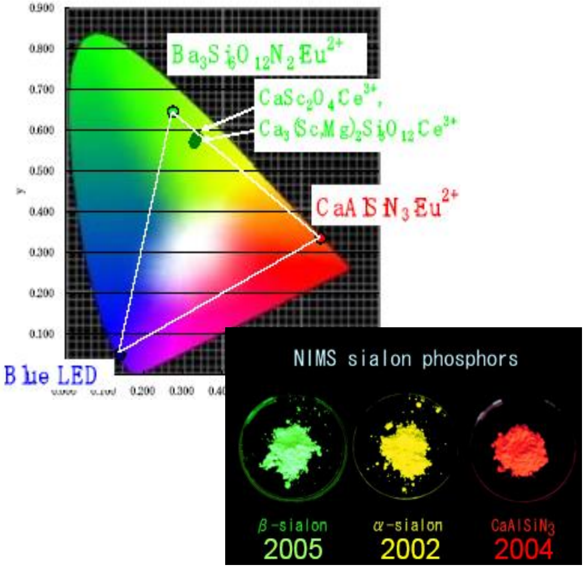


(Oxy)Nitrides → Eu^{2+} or Ce^{3+}

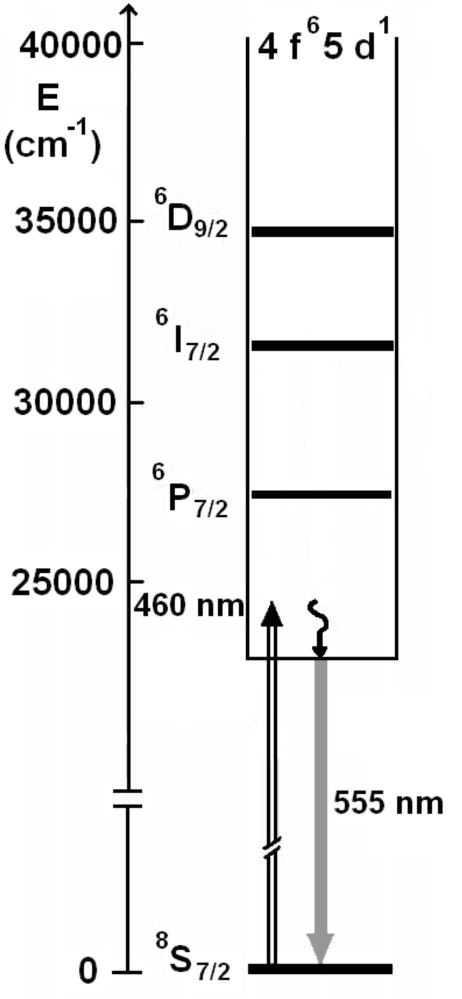
$(Sr,Ca,Ba)_2Si_5N_8$:Eu	„2-5-8“
$(Sr,Ca,Ba)Si_2N_2O_2$:Eu	„1-2-2-2“
$(Ca,Sr)AlSiN_3$:Eu	„1-1-1-3“
$La_3Si_6N_{11}$:Ce	„3-6-11“
$Ba_3Si_6O_{12}N_2$:Eu	
$\alpha,\beta\text{-}Si_{3-x}Al_xN_{4-x}O_x$:Eu	SiAlON

Typical spectra of Eu^{2+} phosphors



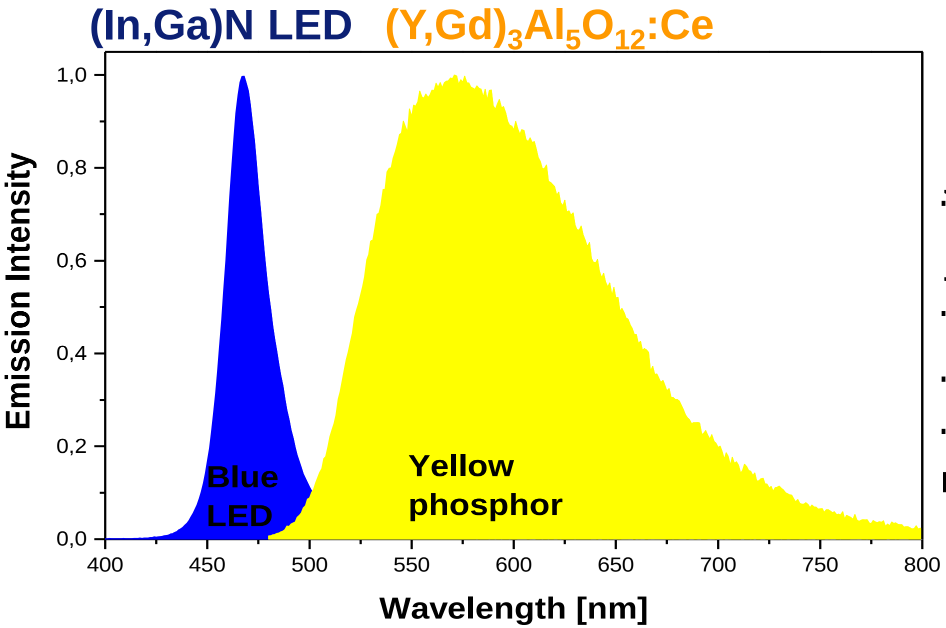


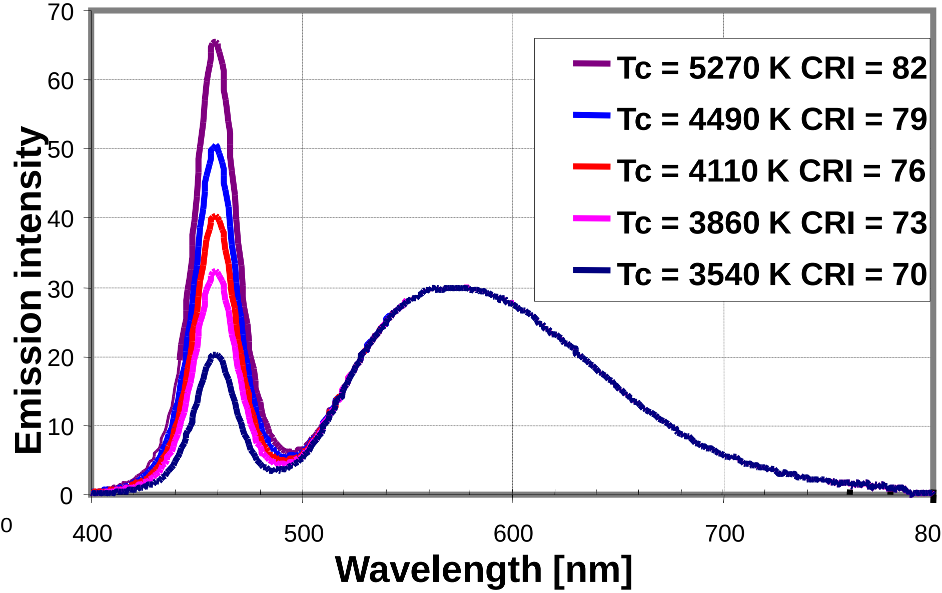
Simplified energy level scheme of Eu^{2+}



6. Lighting Towards Ultimate Efficiency

1st Generation pcLEDs: Wall Plug efficiency (WPE) >> Discharge lamps





Status quo cool white phosphor converted LEDs @ 2021

Yellow phosphors

garnets: $(Y,Gd,Tb)_3Al_5O_{12}:Ce^{3+}$

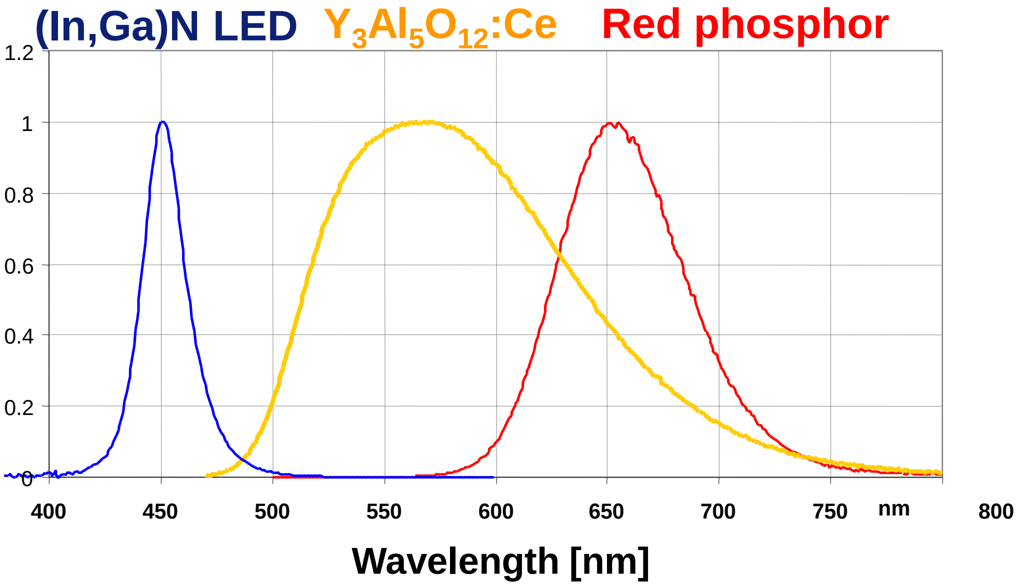
ortho-silicates: $(Ca,Sr,Ba)_2SiO_4:Eu^{2+}$

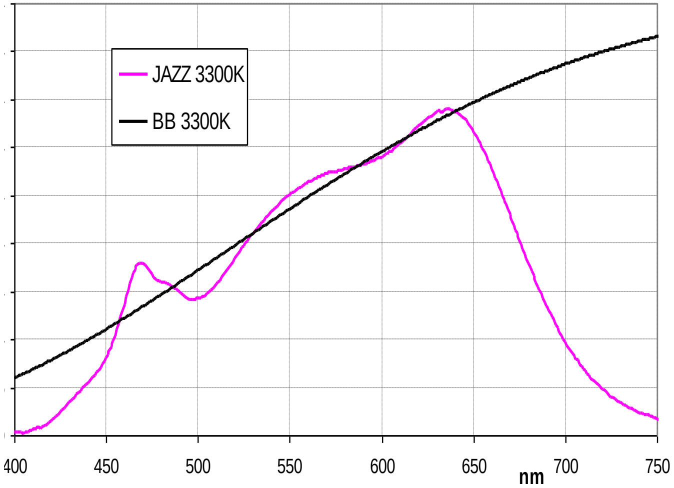
- LE 300 lm/W (WPE > 80%)
- CRI 70 - 80
- CCT > 5000 K

Element	Y	Gd	Ce	Al	O	$(Y_{0,77}Gd_{0,2}Ce_{0,03})_3Al_5O_{12}$
Molar Mass (g/mol)	88,91	157,25	140,12	26,98	16,0	639,243
Coefficient	2,31	0,6	0,09	5	12	
Mass fraction	32%	15%	2%	21%	30%	100%

6. Lighting Towards Ultimate Efficiency

2nd Generation pcLEDs: Enhancement of CRI and reduction of CCT





Status quo warm white phosphor converted LEDs @ 2019

- Red phosphor Eu^{2+} activated
- LE 80 - 150 lm/W
- CRI 85 – 95
- CCT 2500 - 4000 K

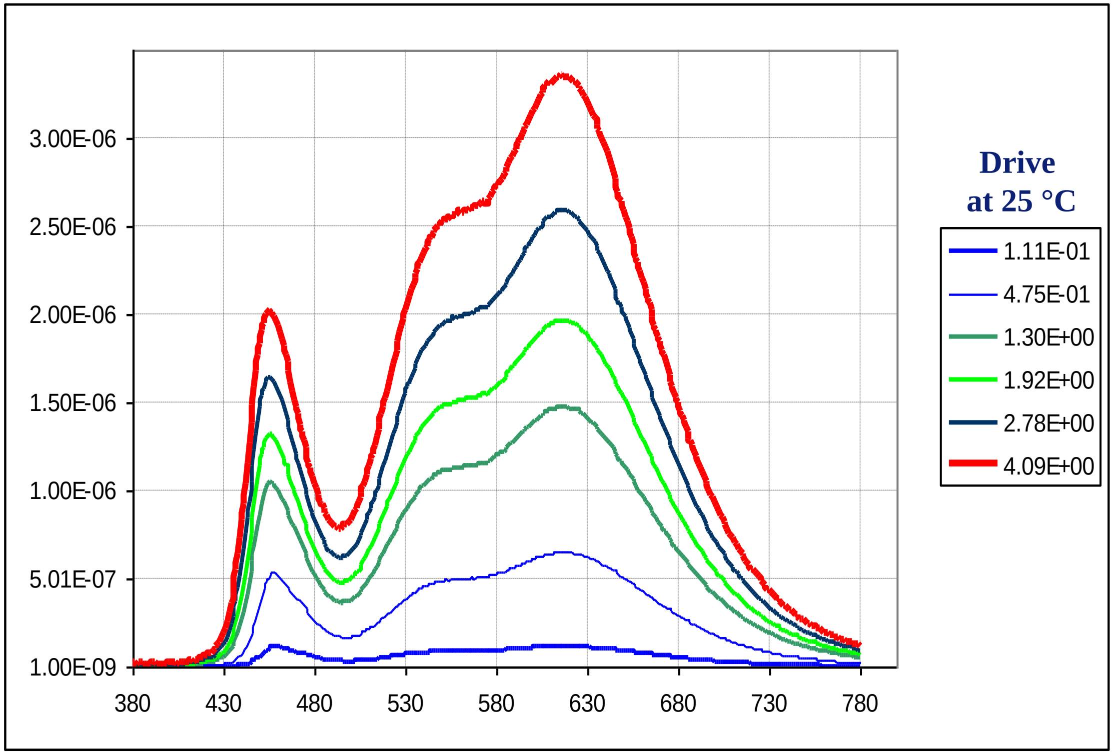
Phosphor	Molar Mass (g/mol)	Coeffi-cient for Eu^{2+}	Mass fraction Eu^{2+}
$Ca_{0,5}Sr_{0,45}Eu_{0,05}S$	99,14	0,05	8%
$(Sr_{0,95}Eu_{0,05})_2Si_5N_8$	434,12	0,1	4%
$Ca_{0,5}Sr_{0,45}Eu_{0,05}AlSiN_3$	168,14	0,05	5%

Ref.: R. Mueller-Mach, G.O. Mueller, P.J. Schmidt, T. Jüstel, Red Deficiency Compensating Phosphor LED, Light Emitting Device, US Patent 2003/0006702

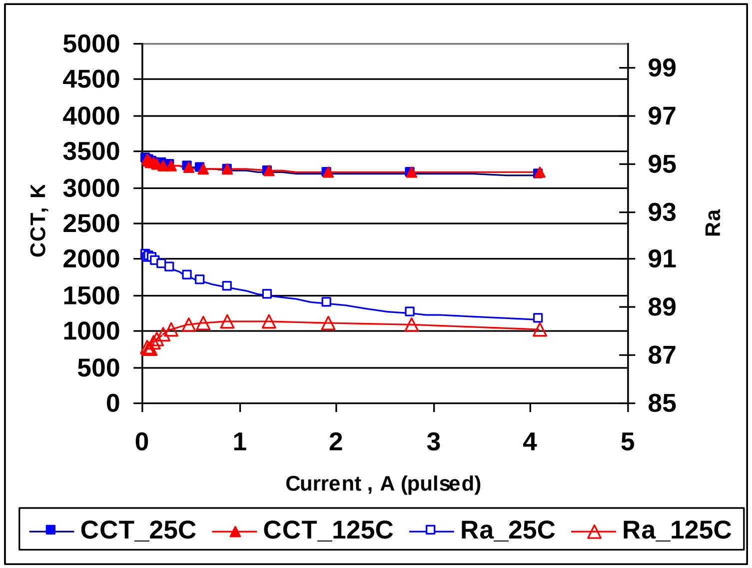
6. Lighting Towards Ultimate Efficiency

First all nitride LED demonstrated in 2005 (QY > 0.9, QY_{rel}(200 °C) > 0.95)

(In,Ga)N LED + $SrSi_2N_2O_2$:Eu + $Sr_2Si_5N_8$:Eu **or $(Sr,Ca)AlSiN_3$:Eu or α-SiAlONes**

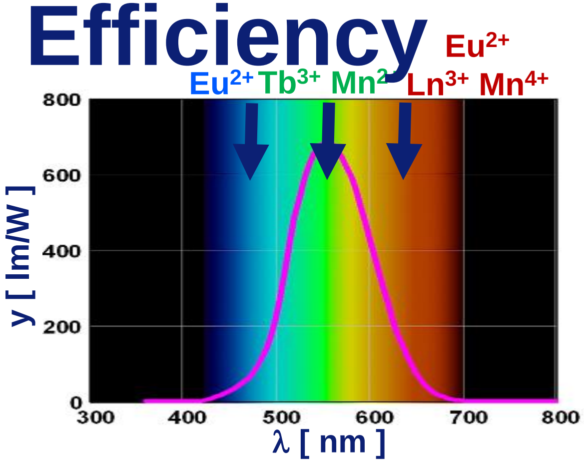


Colour rendering index CRI > 88
Excellent colour point consistency with drive is achieved



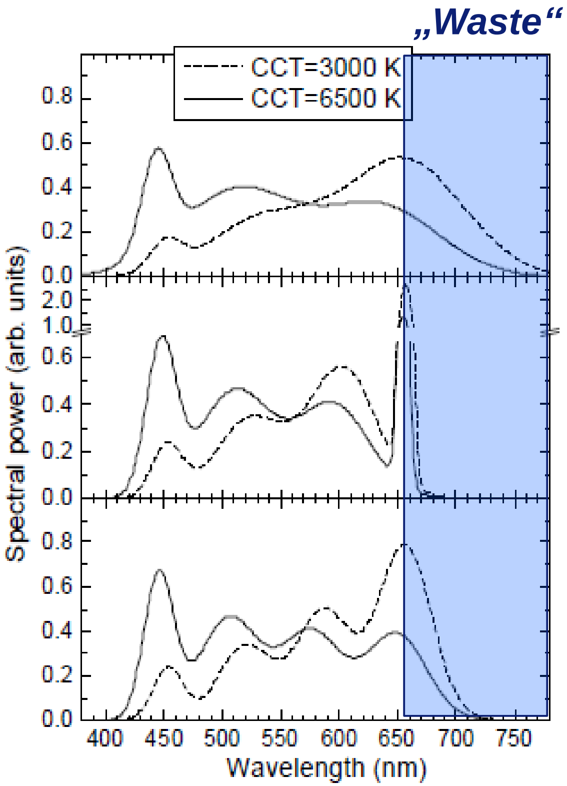
Ref.: R. Mueller-Mach, G.O. Mueller, M.R. Krames, H. Höppe, F. Stadler, W. Schnick, T. Jüstel, P.J. Schmidt, Highly efficient all nitride phosphor converted white light emitting diode, Phys. Stat. Sol. A 202 (2005) 1727

6. Lighting Towards Ultimate Efficiency



Red band emitter cause reduction in lum. efficacy

1. Spectral interaction due to re-absorption
2. Reduction in lumen equivalent



Band width [nm]	Position (nm)	LE (lm/W)	Red LED Phosphor
90 - 120	635	257	(Ca,Sr)S:Eu $(Ca,Sr,Ba)_2Si_5N_8$:Eu $(Ca,Sr)AlSiN_3$:Eu
20 – 30	655	278	$Mg_2TiO_4:Mn^{4+}$
20 – 30	620	320	Ln^{3+} activated (Ln = Eu, Sm, Pr) Mn^{4+} activated
50 – 60	655	269	Eu^{2+}- activated
50 – 60	620	300	Eu^{2+}- activated

Ref.: A. Zukauskas et al., Appl. Phys. Lett. 93 (2008) 051115

6. Lighting Towards Ultimate Efficiency

Requirements to an „ideal“ red LED phosphor

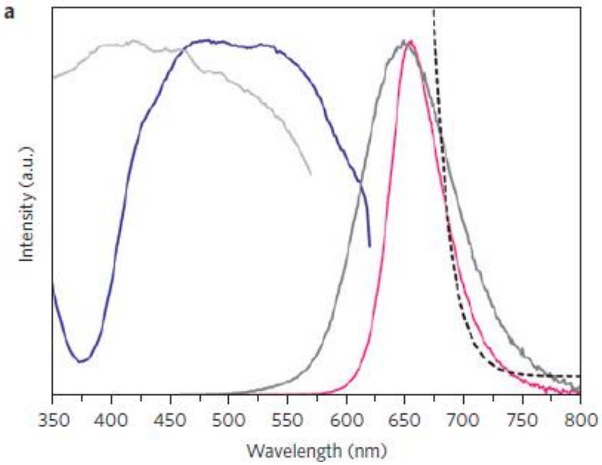
- Narrow FWHM ~ 20 - 60 nm
- Emission peak at ~ 630 nm
- QY (excitation at 450 nm) > 90%
- Absorption at 450 nm > 50%
- $T_{1/2}$ > 200 °C
- Decay time < 10 ms
- No saturation up to 100 W/mm^2 (good linearity)
- High (photo)chemical and thermal stability

Activator	Spectral range [nm]	Lumen equivalent [lm/W_{opt}]	Decay time τ	QY [%]	Absorption at 450 nm
RE-Ions					
Eu^{2+}	360 - 700	50 – 550	~ 1 µs	high	strong
Eu^{3+}	590 - 710	200 – 360	~ 1 ms	high	weak
Sm^{2+}	670 - 770	< 100	~ 1 µs	high	moderate
Sm^{3+}	560 - 710	240 – 260	0.5 ms	moderate	weak
Pr^{3+}	590 - 680	100 – 220	0.1 ms	moderate	weak
TM-Ions					
Mn^{2+}	500 - 650	100 - 550	5-15 ms	high	weak
Mn^{4+}	620 - 680	80 – 230	1-10 ms	high	moderate
Cr^{3+}	680 - 750	< 100	1-10 ms	high	moderate

6. Lighting Towards Ultimate Efficiency

Narrow band red emitter $Sr[LiAl_3N_4]:Eu^{2+}$

Claimed as next generation LED-phosphor material”

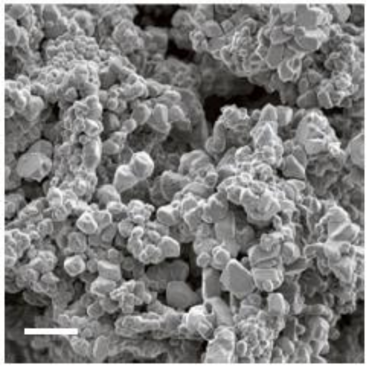


Synthesis

$LiAlH_4 + (1\text{-}x)\ SrH_2 + x\ EuF_3 + 2\ AlN + N_2$

$\rightarrow (Sr_{1-x}Eu_x)[LiAl_3N_4] + 3x\ HF + (3\text{-}x)\ H_2$

RF-Furnace, 1000 °C



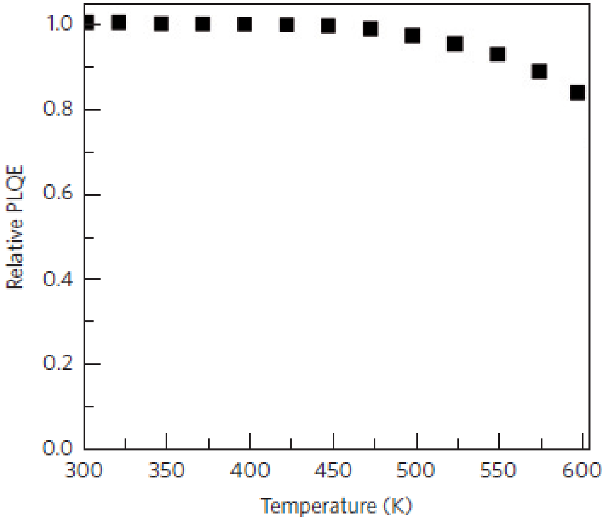
Optical Properties

λ_{max} = 651 nm for 5% Eu^{2+}

FWHM = 1180 cm^{-1} (~ 60 nm)

QY(200 °C) > 95% rel. to QY(RT)

Decay time of Eu^{2+} ~ 1.1 µs



Problems: Excitation @ 410 nm → photoionisation and strong re-absorption of YAG:Ce/LuAG:Ce PL

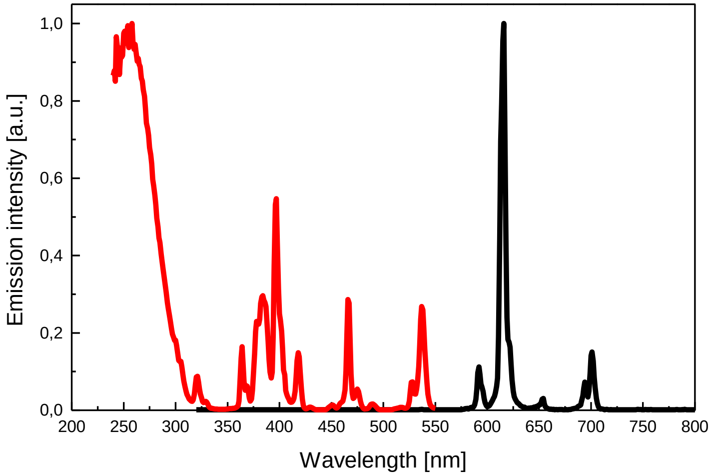
Ref.: W.S. Schnick et al., Nature Materials (2014) 1-6

6. Lighting Towards Ultimate Efficiency

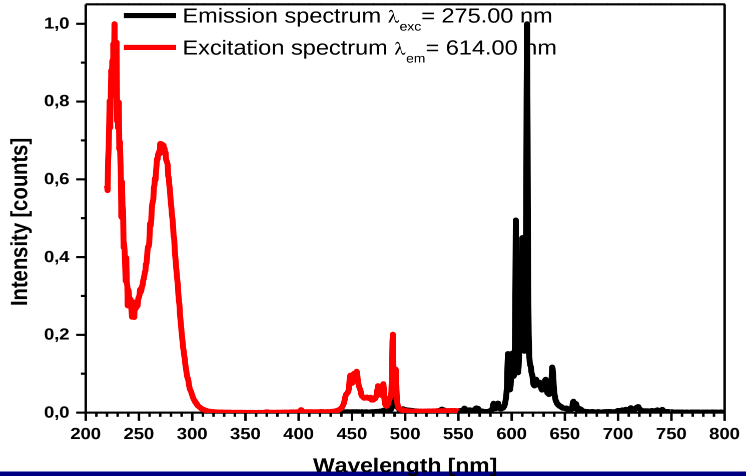
Remaining Options

Red emitter	LE [lm/$W_{opt.}$]	QY at RT
Eu^{3+}	220 – 360	high
Pr^{3+}	200 – 220	moderate
Mn^{4+}	5 – 200	high

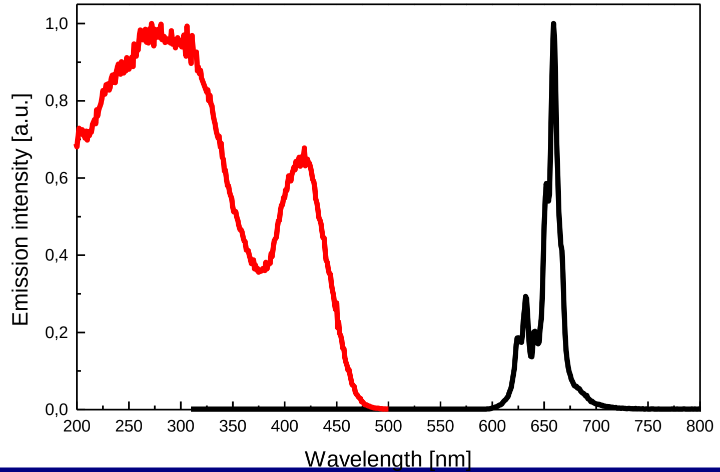
$La_2W_3O_{12}$:Eu



$LuTaO_4$:Pr



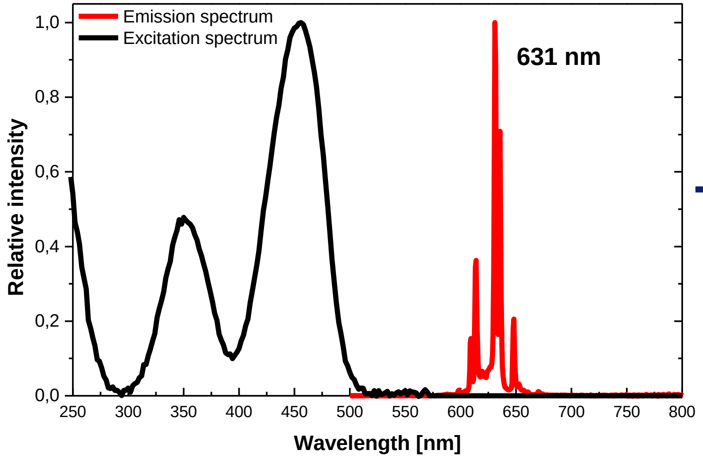
$Mg_4GeO_{5.5}F$:Mn



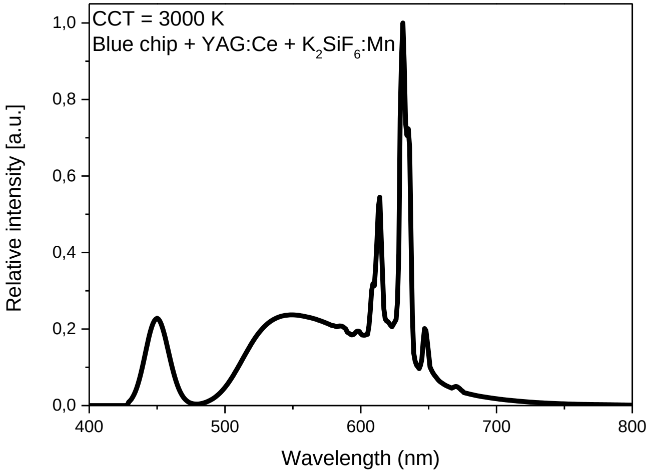
6. Lighting Towards Ultimate Efficiency

Red line emitter → Mn^{4+}

K_2MF_6:Mn (M = Si, Ge, Ti)



Warm white pcLED



LED Chip	Blue	420 – 480 nm
Converter	Yellow	$(Y,Gd,Tb,Lu)Al_5O_{12}$:Ce
	Red	Mn^{4+}- phosphor
Typical yellow/red blend	$Tb_3Al_5O_{12}$:3%Ce + $K_2[MF_6]$:Mn^{4+} (M = Si, Ge, Sn, Ti, Zr)	
Problems	Absorption strength, linearity, and stability of Mn^{4+}	
	$MnF_4 \rightarrow MnF_3 + ½ F_2$	

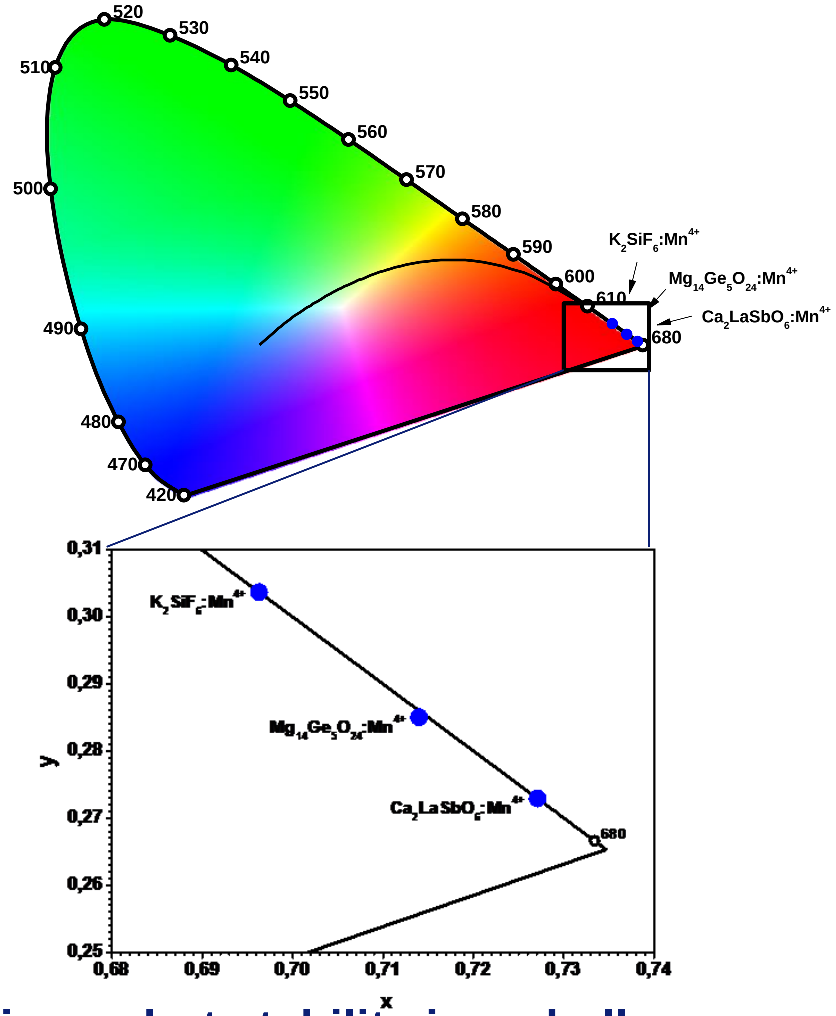
Ref.: A. Srivastava et al., GE, US Patent US2006/0169998

6. Lighting Towards Ultimate Efficiency

Red line emitter → Mn^{4+}

Phosphor	LE [lm/W]	Peak λ_{em} [nm]
$K_2SiF_6:Mn^{4+}$	196	631.0
$K_2TiF_6:Mn^{4+}$	192	631.8
$K_2GeF_6:Mn^{4+}$	191	632.0
$Mg_{14}Ge_5O_{24}:Mn^{4+}$	80	658
$K_2Ge_4O_9:Mn^{4+}$	46	663*
$Rb_2Ge_4O_9:Mn^{4+}$	38	667*
$Ca_2YNbO_6:Mn^{4+}$	15	680
$Ca_2LaSbO_6:Mn^{4+}$	7	699
$LaScO_3:Mn^{4+}$	7	703

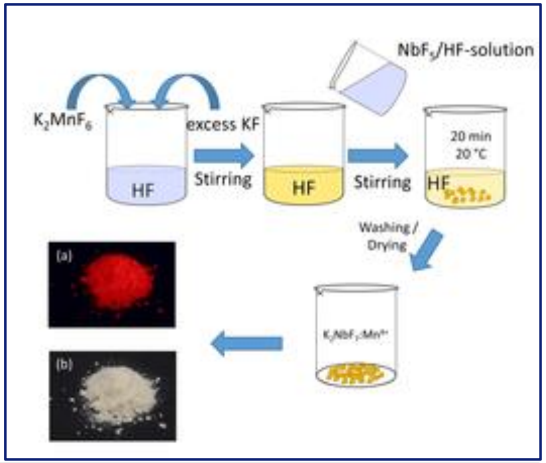
Ref.: F. Baur, T. Jüstel, J. Luminescence 177 (2016) 354



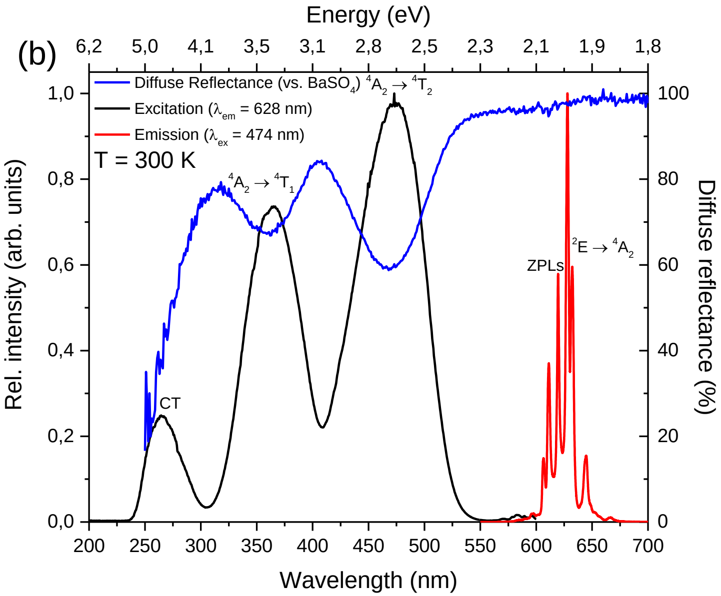
Fluorides → Rather high luminous efficacy, but stability is a challenge
Oxides → Very stable, but low luminous efficacy

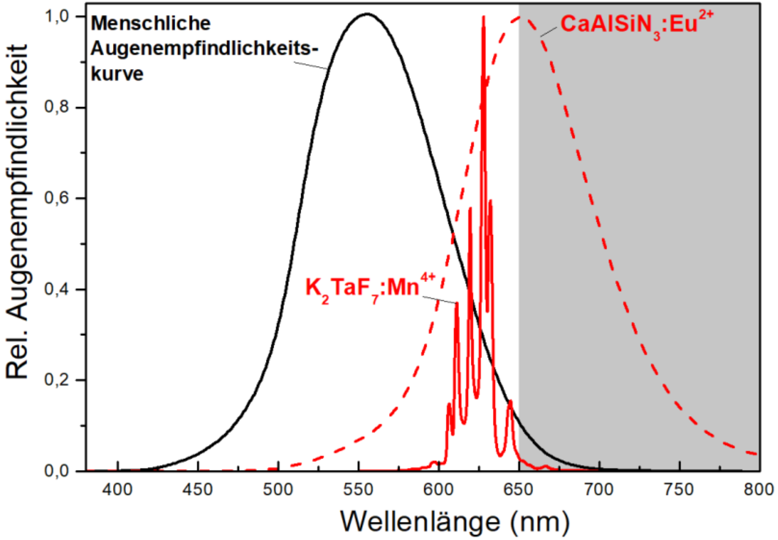
6. Lighting Towards Ultimate Efficiency

Red line emitter → $K_2(Nb,Ta)F_7:Mn^{4+}$



λ_{max} = 628 nm
LE = 228 lm/W
CIE1931: x = 0.690; y = 0.310



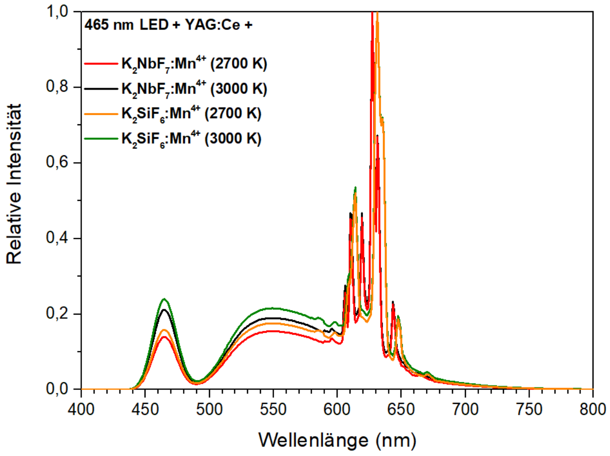


Ref.: T. Jansen, F. Baur, T. Jüstel, Red Emitting $K_2NbF_7:Mn^{4+}$ and $K_2TaF_7:Mn^{4+}$ for Warm-White LED Applications, J. Luminescence 192 (2017) 644

6. Lighting Towards Ultimate Efficiency

Red line emitter → $K_2(Nb,Ta)F_7:Mn^{4+}$ with superior luminous efficacy (LE)

Blue LED + YAG:Ce +	CCT [K]	LE [lm/W_{opt}]	CRI
$K_2NbF_7:Mn^{4+}$	3000	346	95
	2700	345	95
$K_2TaF_7:Mn^{4+}$	3000	345	95
	2700	345	94
$Na_3AlF_6:Mn^{4+}$	3000	345	95
	2700	344	95
$K_2SiF_6:Mn^{4+}$	3000	339	95
	2700	297	95
$Mg_{14}Ge_5O_{24}:Mn^{4+}$	3000	254	83
	2700	241	78
$Y_2Mg_3Ge_3O_{12}:Mn^{4+}$	3000	255	84
	2700	242	79
$CaAlSiN_3:Eu^{2+}$	3000	272	93
	2700	260	95



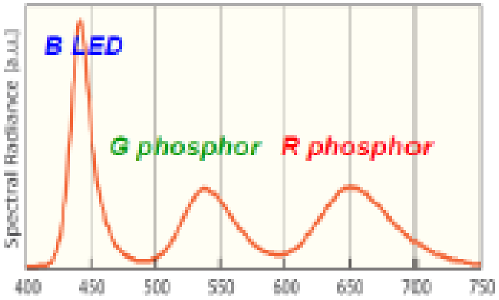
A 2700 K LED comprising YAG:Ce and $K_2TaF_7:Mn^{4+}$ shows a 15% higher LE than an LED comprising YAG:Ce and $K_2SiF_6:Mn^{4+}$

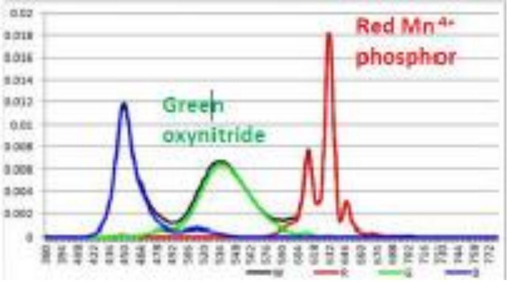
6. Lighting Towards Ultimate Efficiency

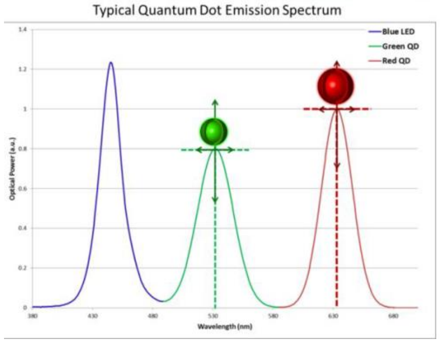
The Quest for a Narrow Band Red Emitter

$Eu^{2+} \rightarrow Mn^{4+}$ or CdSe / InP QDots

Material	Peak at [nm]	FWHM [nm]	Pros	Cons
(Sr,Ca)S:Eu	615 - 650	60 - 70	Rather narrow band	Low chemical stability
$(Sr,Ba)_2Si_5N_8$:Eu	585 - 625	80 - 100	Reliability	IR spillover
$(Ca,Sr)AlSiN_3$:Eu	610 – 655	80 – 90	Reliability	IR spillover
$SrLiAl_3N_4$:Eu	650	50 nm	Narrow band	Self absorption, some IR spillover
K_2SiF_6:Mn	631	Lines < 2 nm	Very narrow band, low stab.	Moderate absorption
CdSe QDots	Tunable green to red	30 – 50	Narrow band	Reliability, Reabsorption
InP QDots	Tunable green to red	45 – 65	Narrow band	Reliability, Reabsorption
Direct red LEDs	Tunable red	25 – 35	No Stokes loss Narrow band	Strong TQ, more complex
$K_2(Ta,Nb)F_7$:Mn	628	Lines < 2 nm	Very narrow band, stability?	Moderate absorption



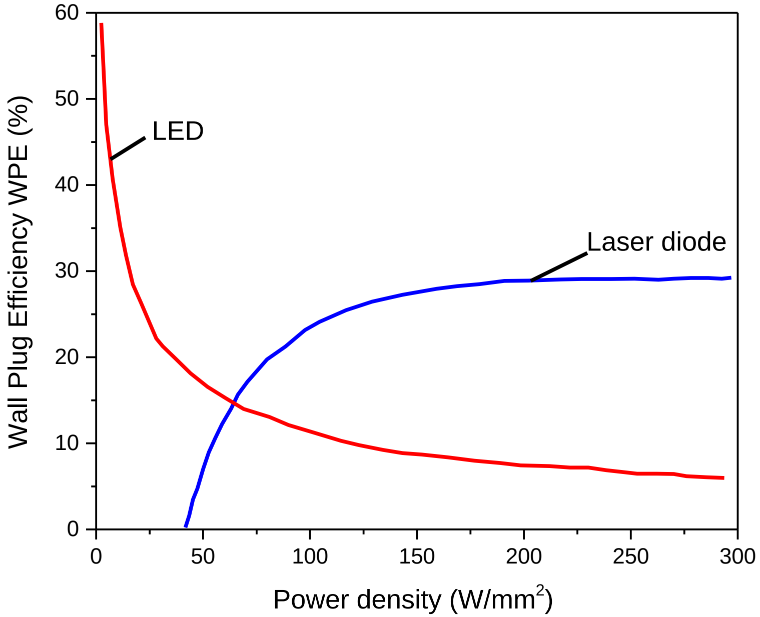




Modified from GE, PGS2016, Newport Beach, CA, USA

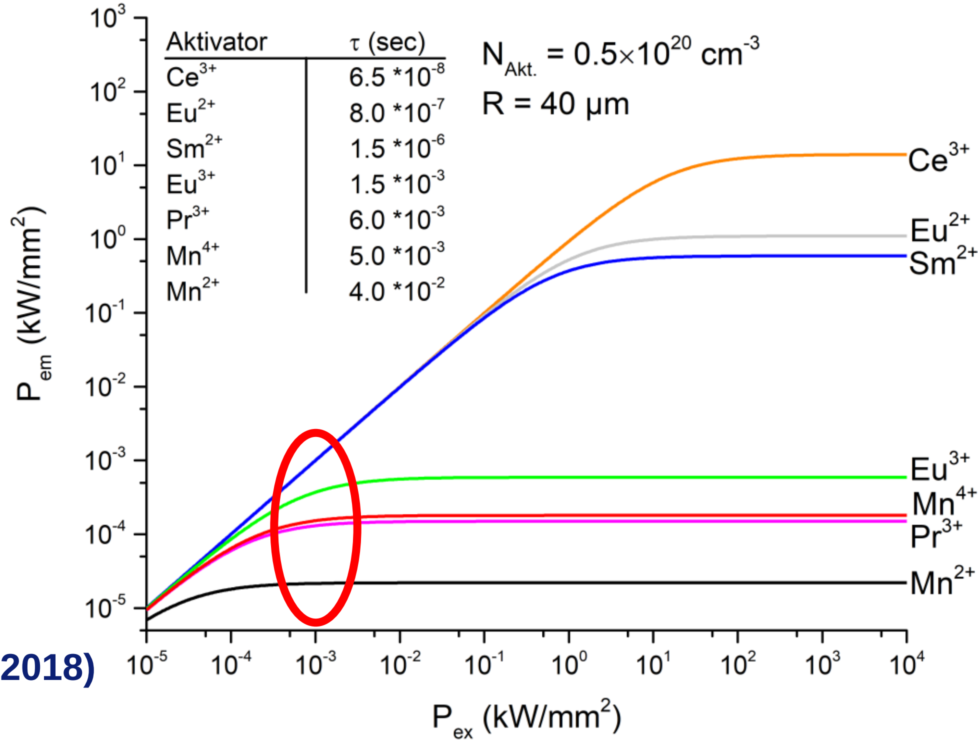
6. Lighting Towards Ultimate Efficiency

Red line emitter → Remaining problem: Saturation at ~ 1 W/mm²



Brils Modell*: $P_{em,max} = Nact\, E_{h\nu} C_{extraction}\, R/\tau_r$

$$\eta = \frac{P_{em}}{P_{abs}} = \frac{\eta_0}{1 + \left(P_{abs}\,\eta_0 / P_{em,max}\right)}$$

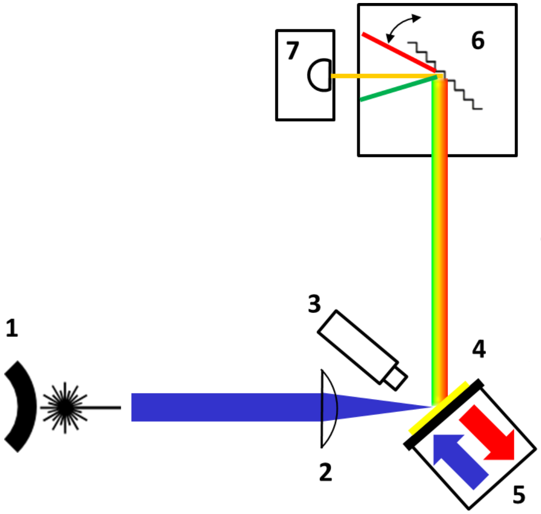


Aktivator	τ (sec)
Ce^{3+}	6.5 *10^{-8}
Eu^{2+}	8.0 *10^{-7}
Sm^{2+}	1.5 *10^{-6}
Eu^{3+}	1.5 *10^{-3}
Pr^{3+}	6.0 *10^{-3}
Mn^{4+}	5.0 *10^{-3}
Mn^{2+}	4.0 *10^{-2}

$N_{Akt.} = 0.5\times10^{20}$ cm^{-3}
R = 40 µm

Ref.: Dissertation WWU Münster, Thomas Jansen (2018)
***A. Bril, Physica 15 (1949) 361-379**

6. Lighting Towards Ultimate Efficiency



1 - Laserdiode
2 - Fokussierlinse (Fleckdurchmeser: 11 µm)
3 - Infrarotkamera (7.5 … 14 µm)
4 - Probe
5 - Kühlung (Ag-Probenhalter)
6 - Emissionsmonochromator
7 - Detektor

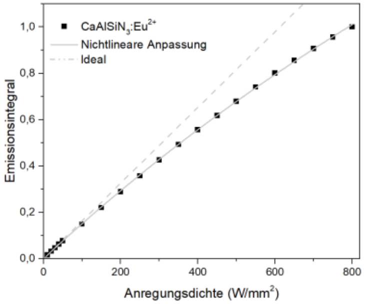
Saturation by photoioinsation

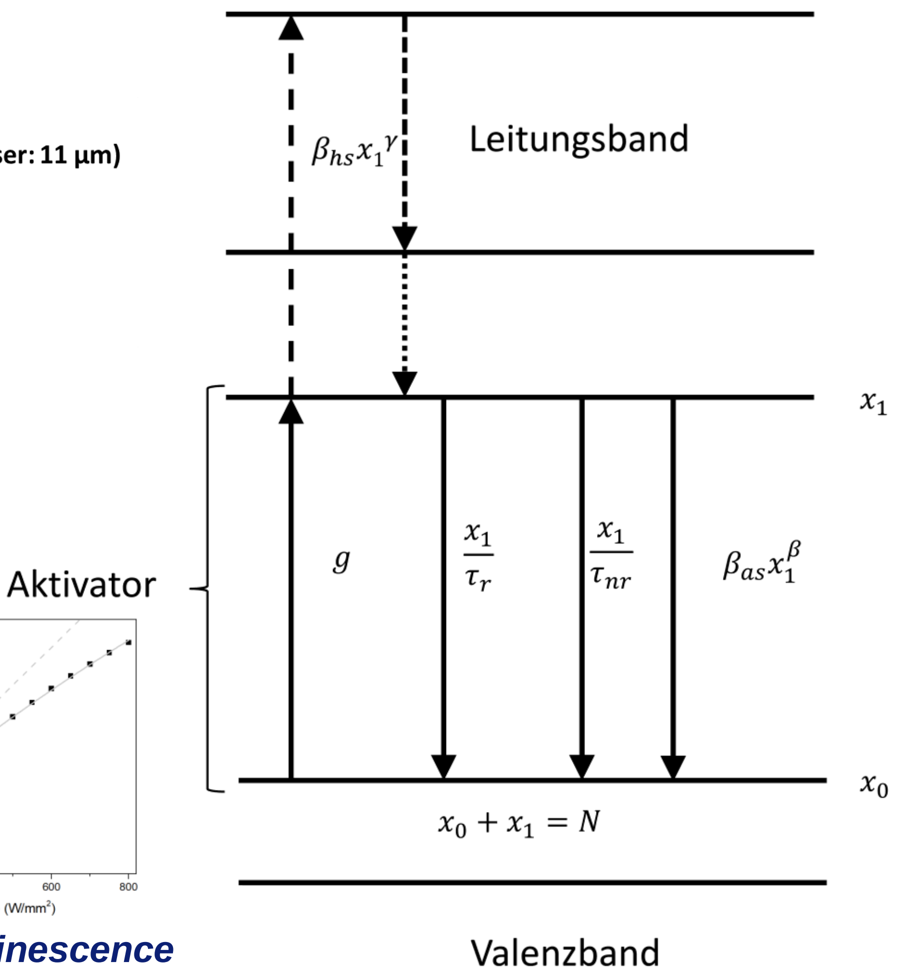
E_g

$(Sr_{1,6}Ca_{0,4})SiO_4:Eu^{2+}$

$(Ca,Sr)AlSiN_3:Eu^{2+}$

$(Sr,Ba)_2Si_5N_8:Eu^{2+}$





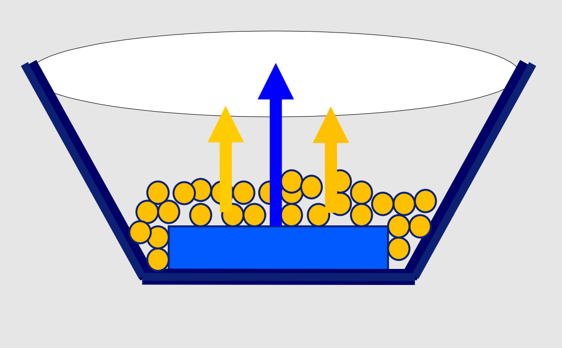
T. Jansen, D. Böhnisch, T. Jüstel, On the Photoluminescence Linearity of Eu^{2+} based LED Phosphors upon High Excitation Density, ECS J. Solid State Sci. Technol. 5 (2016) R91

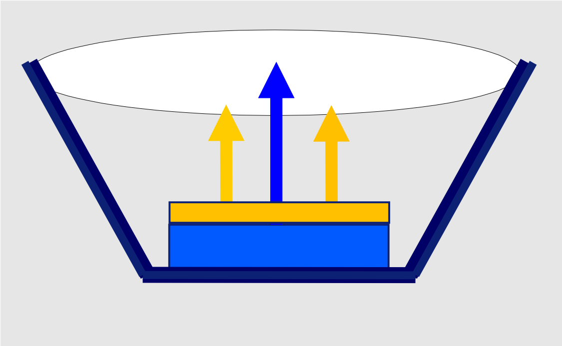
6. Lighting Towards Ultimate Efficiency

Morphology of converter: µ-powders → Nanopowders or ceramics

Blue (In,Ga)N LED + YAG:Ce µ-powder (many products, industrial standard)

Blue (In,Ga)N LED + (Y,Lu)AG:Ce ceramic body (Philips: Lumiramic, Osram: c^2, Schott)



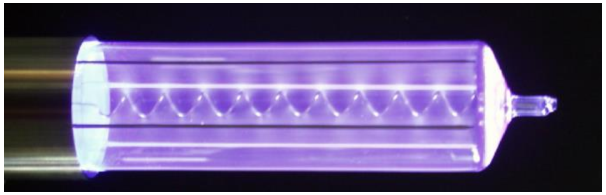


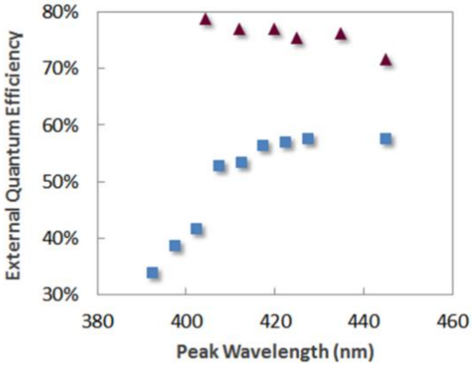
→ $(Y,Gd)_3Al_5O_{12}$:Ce	(Y,Gd)AG
→ $SrSi_2N_2O_2$:Eu	SSONE
→ $Ba_2Si_5N_8$:Eu	BSSNE
→ $CaAlSiN_3$:Eu	eCAS

7. Summary and Outlook

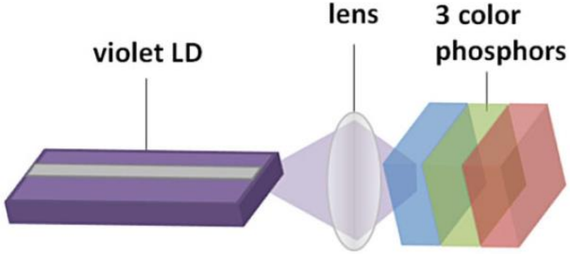
21st Century Light/Radiation Sources

Parameter	Xe Excimer Discharge	LED	Laser Diode (LD)
Power density	1-10 W/cm^2	100-1000 W/cm^2	> 1000 W/cm^2
Spectral range	170 - 700 nm	210 - MIR	210 - MIR
Life time	> 10000 h	> 30000 h	> 10000 h
Application areas	*Plasma displays*	*Illumination*	*Projection*
	Disinfection	*Photopolym.*	*Data transfer*
	Purification	*Photomedicine*	*Photomedicine*
	Photochemistry	*Agriculture*	*Signalling*
	Lithography	*Automotive*	*Automotive*
		Aviation	*Photophysics*





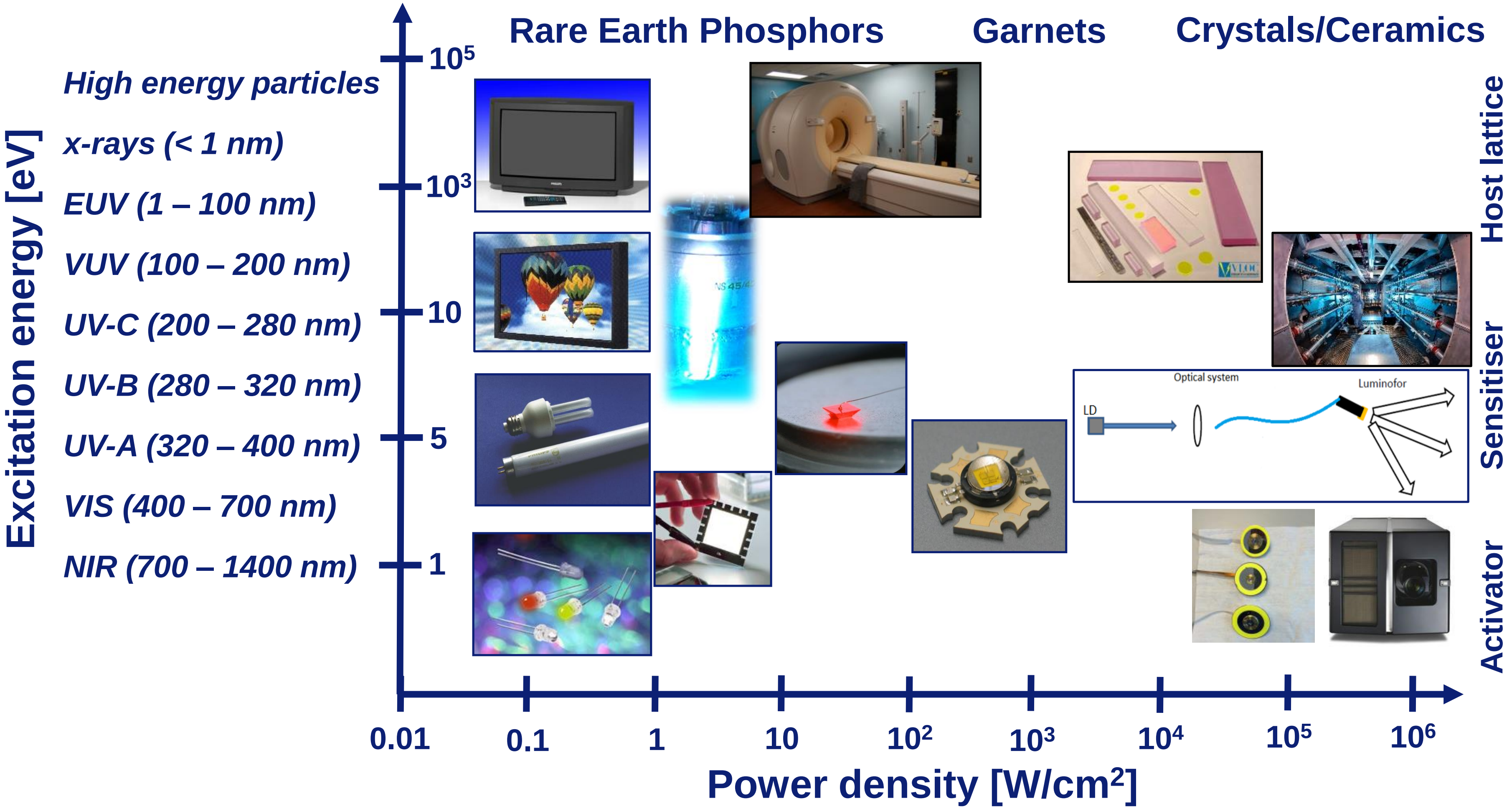
Wi-Fi	Li-Fi
10^9 Hz	10^{14} Hz
7 Gb/s	3 Tb/s



Ref.: C. Hurni et al., Applied Physics Letters 106, 031101 (2015)

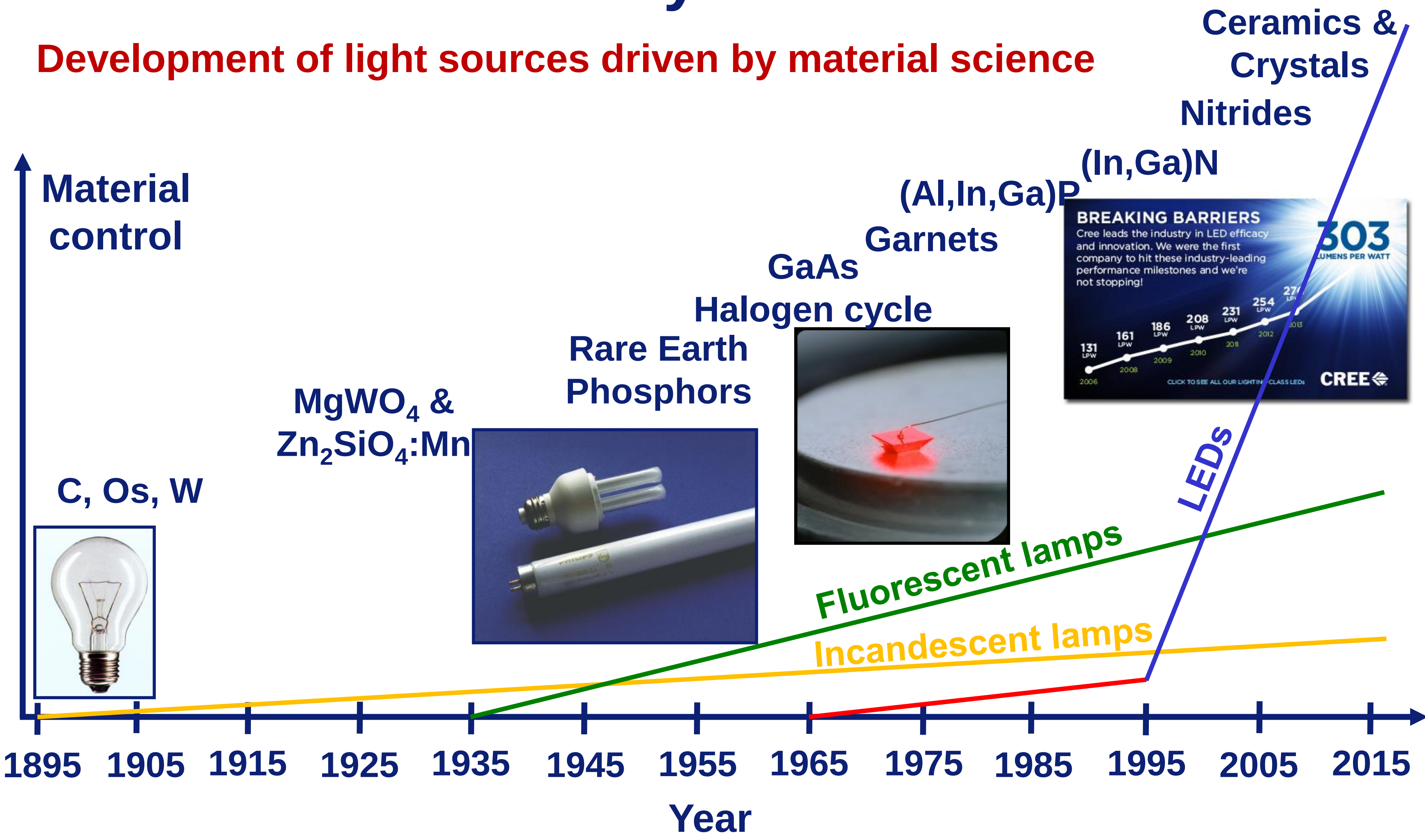
7. Summary and Outlook

Increase of energy density drives search for novel materials



7. Summary and Outlook

Development of light sources driven by material science



Material control

C, Os, W

$MgWO_4$ & Zn_2SiO_4:Mn

Rare Earth Phosphors

Halogen cycle

GaAs

Garnets

(Al,In,Ga)P

(In,Ga)N

Nitrides

Ceramics & Crystals

BREAKING BARRIERS

Cree leads the industry in LED efficacy and innovation. We were the first company to hit these industry-leading performance milestones and we're not stopping!

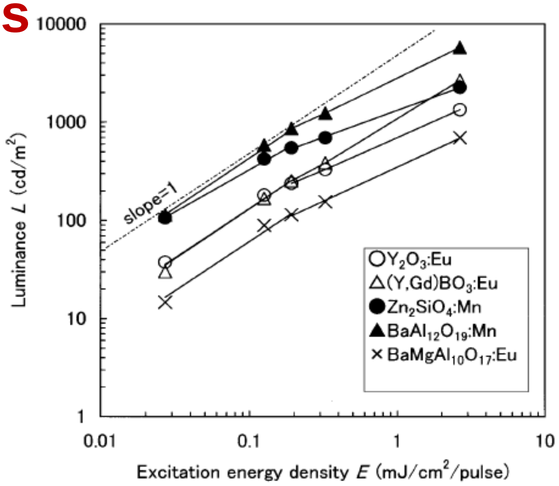
7. Summary and Outlook

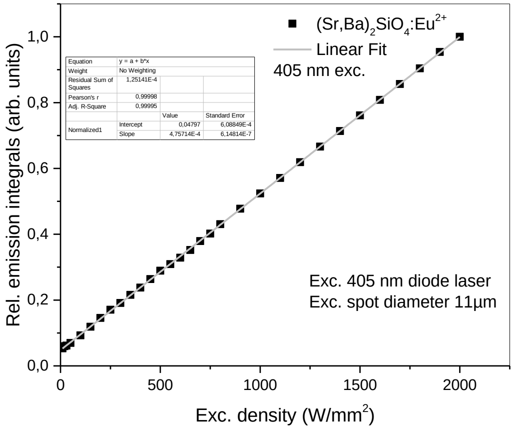
Demands on converter materials & photo catalysts

⇒ **Materials with**
- **High thermal quenching temperature**
- **Reduced (photo)chemical aging**
- **Increased linearity and thus absorption strength**
- **Reduced tendency for photoionisation**

⇒ **Rigid host materials with high thermal conductivity, little thermal expansion, low defect density and optimised e^-/h^+ mobility**

⇒ **Future activities**
- **Development of suitable analytical tools and spectroscopy**
- **Link CF- and JO-theory to predict intens. of 4f-4f transitions**
- **Find rigid hosts for VUV, UV-C or, x-ray excitation**
- **Develop core-shell particles & translucent ceramics**
- **Photochemistry with excimer lamps, LEDs, and Laser**
- **Photochemical processes for nanoscale coatings**



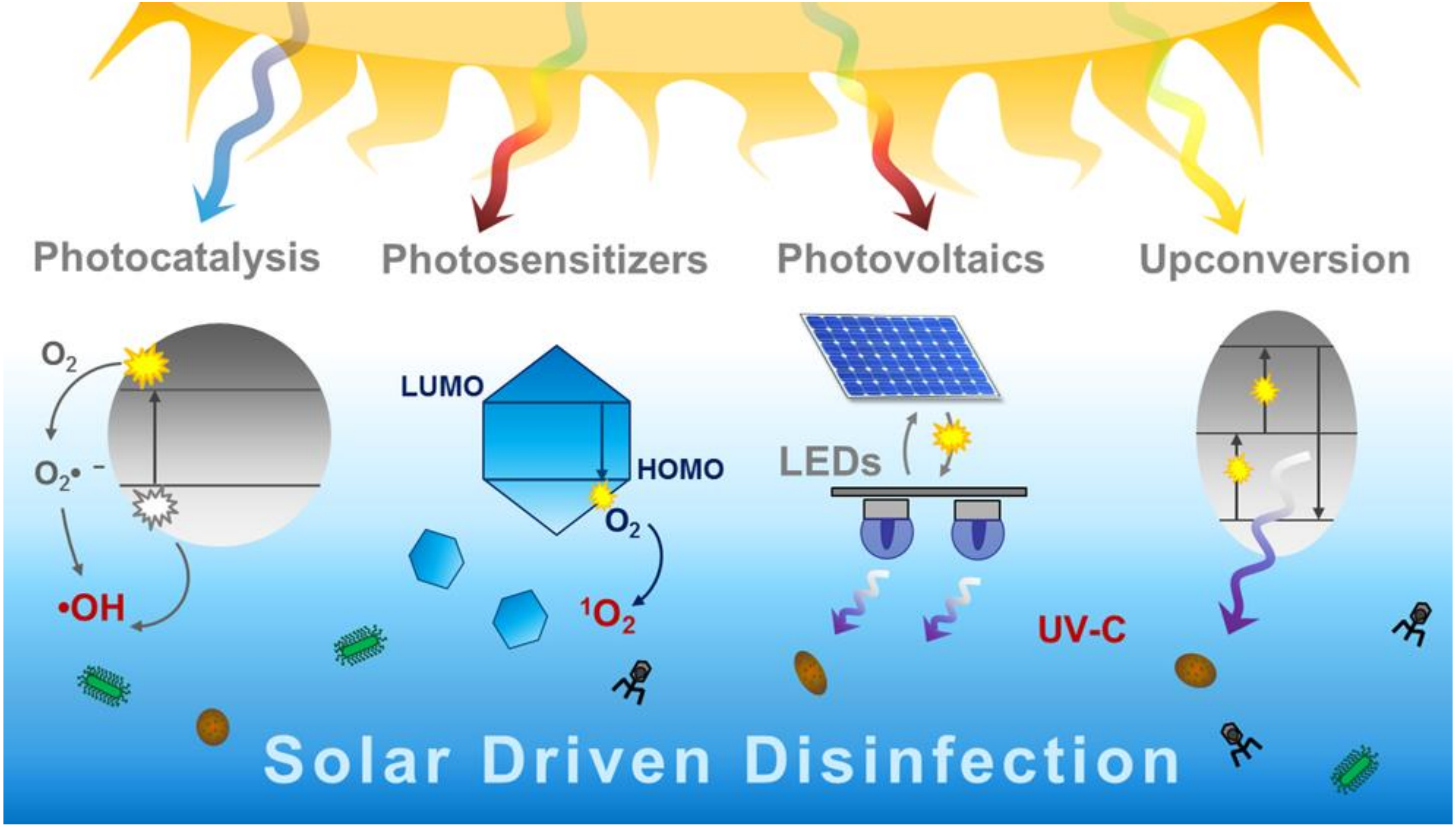


Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	1,25141E-4		
Pearson's r	0,99998		
Adj. R-Square	0,99995		
		Value	Standard Error
Normalized1	Intercept	0,04797	6,08849E-4
	Slope	4,75714E-4	6,14814E-7

Ref.: T. Jansen, D. Böhnisch, T. Jüstel, ECS J. of Solid State Science and Technology 5 (2016) R91

7. Summary and Outlook

Trend: Use solar light & combine with traditional light sources, e.g. for indoor lighting and/or water, air, and surface disinfection

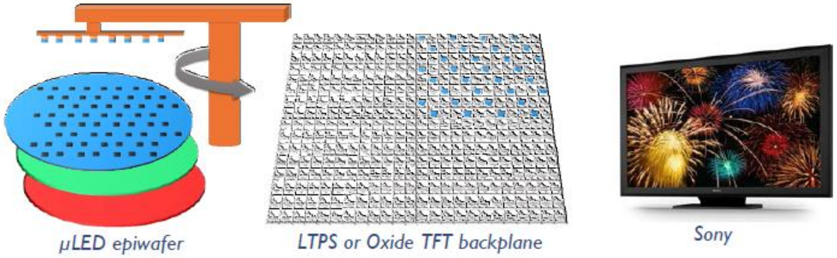


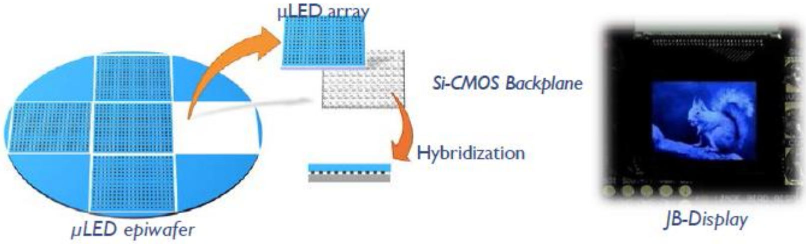
7. Summary and Outlook

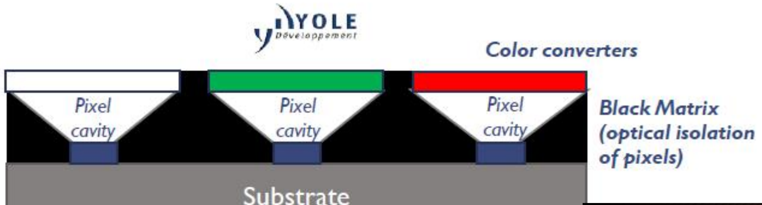
Trend: Micro LEDs for next generation displays (beyond LCD and OLED)

Large displays with low pixel densities (TV, smartphones…): R,G,B LED or Blue + color converter

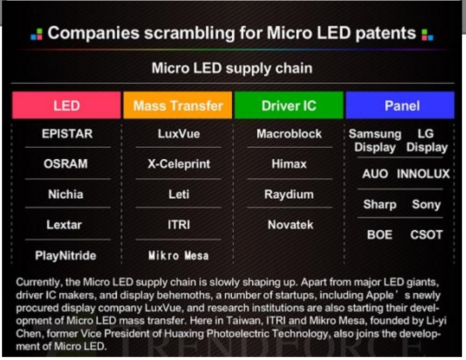
High resolution/pixel density integrated arrays for microdisplays (AR/MR/VR):







Ref.: Eric Virey, YOLE, Phosphor Global Summit, March 2018, San Diego, CA
Energy efficient µ-LEDs cinemas are under construction worldwide



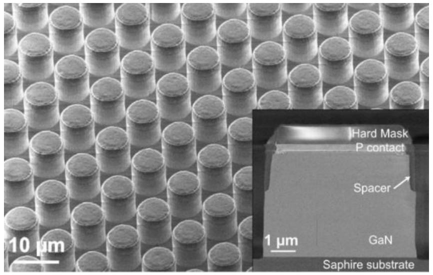
Companies scrambling for Micro LED patents

Micro LED supply chain

LED	Mass Transfer	Driver IC	Panel
EPISTAR	LuxVue	Macroblock	Samsung Display LG Display
OSRAM	X-Celeprint	Himax	AUO INNOLUX
Nichia	Leti	Raydium	Sharp Sony
Lextar	ITRI	Novatek	BOE CSOT
PlayNitride	Mikro Mesa		

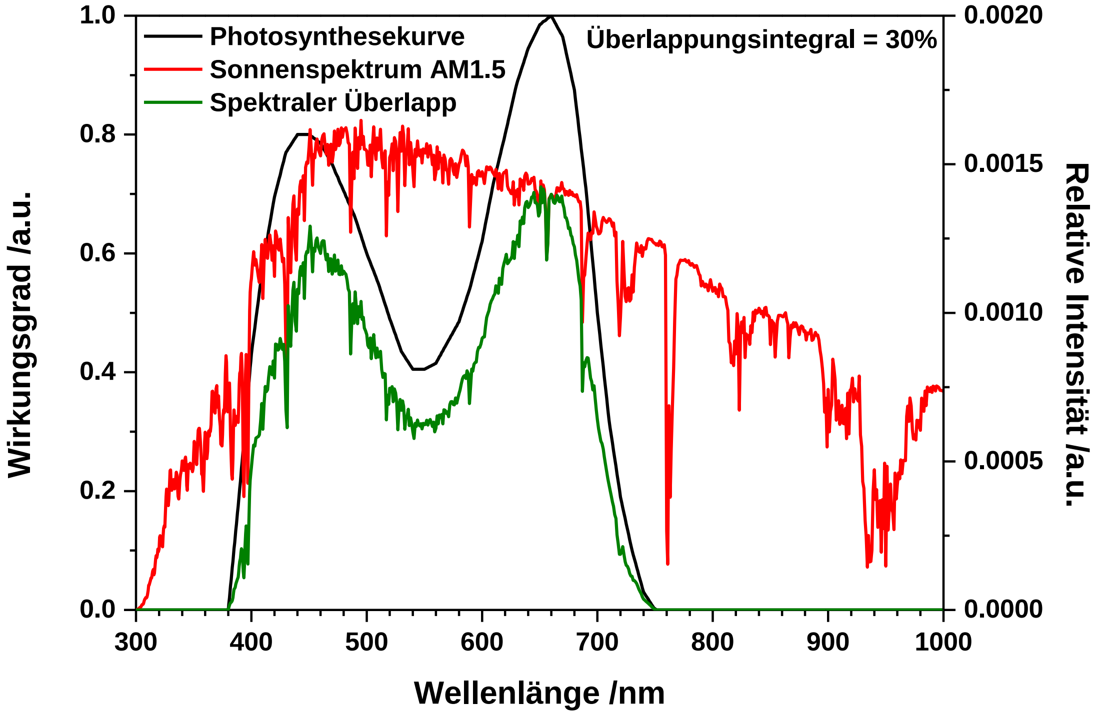
Currently, the Micro LED supply chain is slowly shaping up. Apart from major LED giants, driver IC makers, and display behemoths, a number of startups, including Apple's newly procured display company LuxVue, and research institutions are also starting their development of Micro LED mass transfer. Here in Taiwan, ITRI and Mikro Mesa, founded by Li-yi Chen, former Vice President of Huaxing Photoelectric Technology, also joins the development of Micro LED.

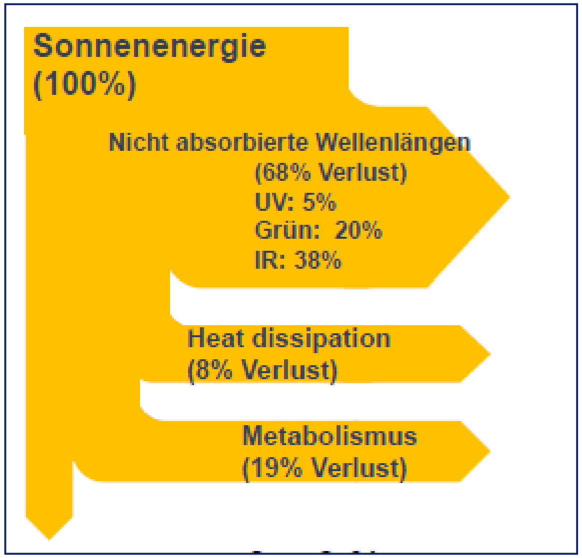
TRENDFORCE



7. Summary and Outlook

Trend: Horticulture Lighting





Solar spectrum AM1.5

Overlap integral: 30% → ~ 70% loss

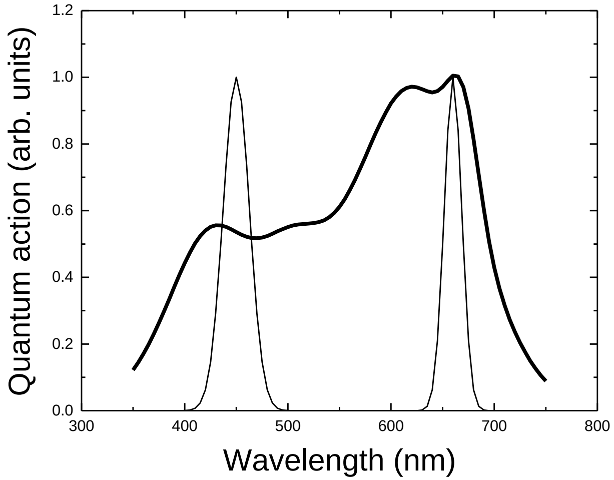
Heat dissipation loss: ~ 8%

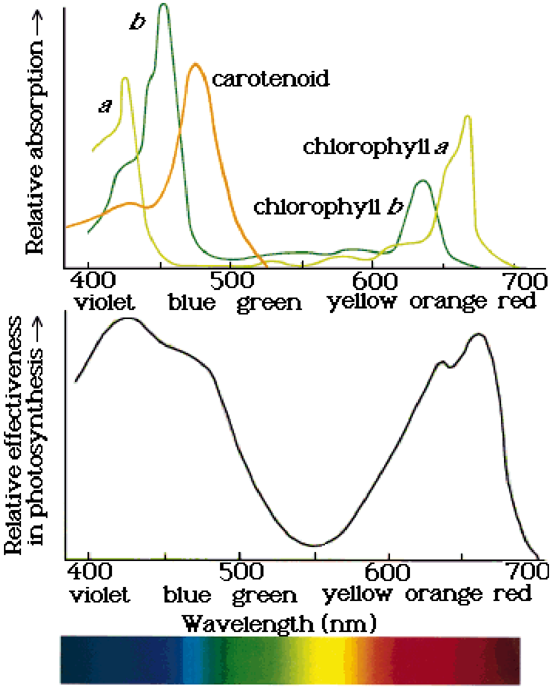
Metabolism losses: ~19% → Efficiency ~ 5%

7. Summary and Outlook

Trend: Horticulture Lighting by using LEDs

- Na low-pressure discharge lamps
- Fluorescent lamps with RB phosphor blend
- Blue and red LEDs
- Blue LEDs + red phosphor (~ 680 nm) → Efficacy↑





Grass cultivated upon daylight or upon LED illumination
Daylight (left vessel) and LED illumination (right vessel)

Plants

Roots

7. Summary and Outlook

Trend: „Biomimetic economy“

Solar Energy

Water splitting ↙ ↘ *PV*

ATP “Biological fuel”

CO_2 ↙ ↘ *N_2*

trioses + NH_3

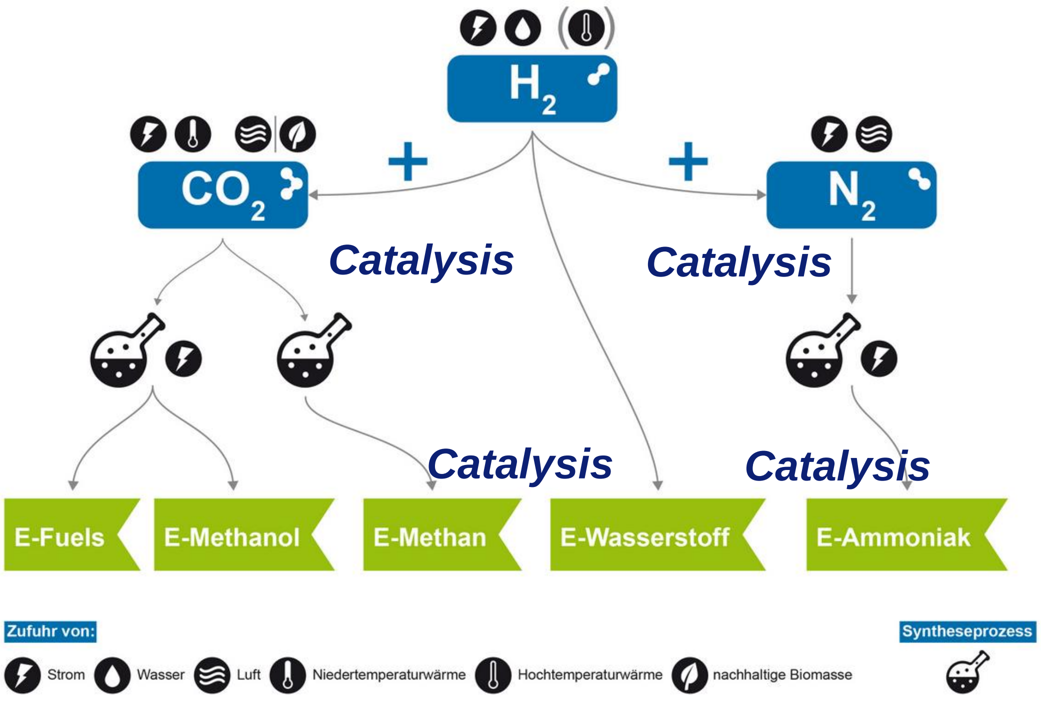
Catalysis ↓ ↓ *Catalysis*

sugars amino acids

starch RNA polypeptides
cellulose DNA ↓
lignin proteins
fatty ↓
acids catalysts

Electricity

↓ *Electrolysis*



Catalysis

Catalysis

Catalysis

Catalysis

Source: Öko-Institute 2019

Literature

Internet-Links

- Homepage T. Jüstel (Download-Portal, PISA & LISA) www.fh-muenster.de/juestel

Further Reading

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- CO_2-storage by silicate chemistry (Energy Procedia 1 (2009) 3149)
- Global Hg Emissions to the atmosphere (Atmos. Chem. Phys. 10 (2010) 5951)
- Extreme melt on Canadas Arctic ice caps in the 21st century (Geophys. Res. Lett. 38 (2011) L11501)
- September Arctic sea ice predicted to disappear near 2°C global warming above present (J Geophys Res 117 (2012) D06104)
- Global warming releases microplastic legacy frozen in Arctic Sea ice (Earths Future 2 (2014) 315)
- Global oxygen budget and its future projection (Science Bull. 63 (2018) 1180)
- The Information Factories (Nature 561 (2018) 163)
- Kunststoffe in der Umwelt (Fraunhofer Umsicht Juni 2018)
- Arctic sea ice is an important temporal sink for microplastic (Nature Comm. (2018) 1)
- Plastic degradation in cold marine habitats (Appl. Microbiol. Biotech. 102 (2018) 7669)

Literature

Further Reading

- Ecotoxicity of the two veterianarian antibiotics ceftiofur and cefapirin before and after phototransformation (Science Total Environment 619-620 (2018) 866)
- Existential climate-related security risk (Policy Paper May 2019)
- CO_2-Das Klimagas vergraben (Spektrum der Wissenschaft 7 (2019) 62)
- Rapid increase in Asian bottles in the South Atlantic Ocean (PNAS (2019) 1)
- Assessing Plastic Ingestion from Nature to People (Dalberg WWF analysis (2019) 1)
- UN Report: Nature's Dangerous Decline Unprecedented; Species Extinction Rates Accelerating (2019)
- New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding (Nature Commun. 10 (2019) 4844)
- Four Decades of Antarctic Ice Sheet Mass Balance from 1979-2017 (PNAS 116 (2019) 1097)
- How hot will earth get until 2100? (Nature 580 (2020) 444)
- Permian–Triassic mass extinction pulses (Nature Geosciences (2020))
- Global food system emissions could preclude achieving the 1.5 and 2 °C climate change targets (Science (2020))
- Global human-made mass exceeds all living biomass (Nature (2020))