

# 5. Low Pressure Discharge Lamps

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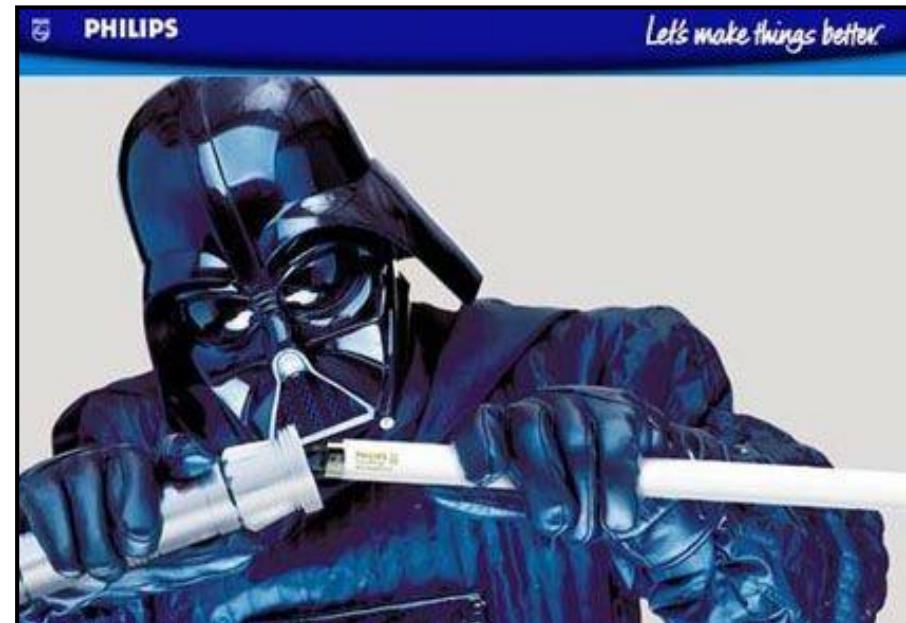
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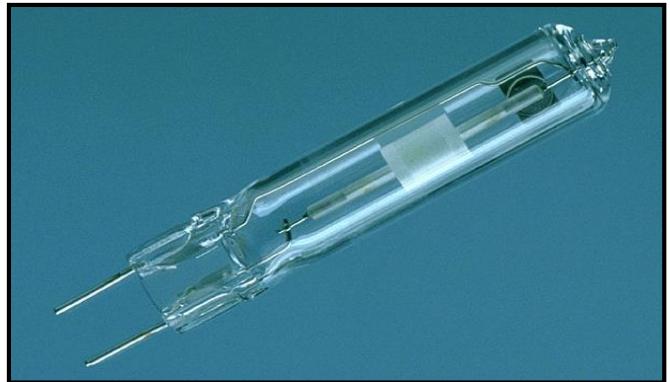


# 5.1 Classification of Gas Discharge Lamps

## Low-pressure gas discharge lamps



## High-pressure gas discharge lamps

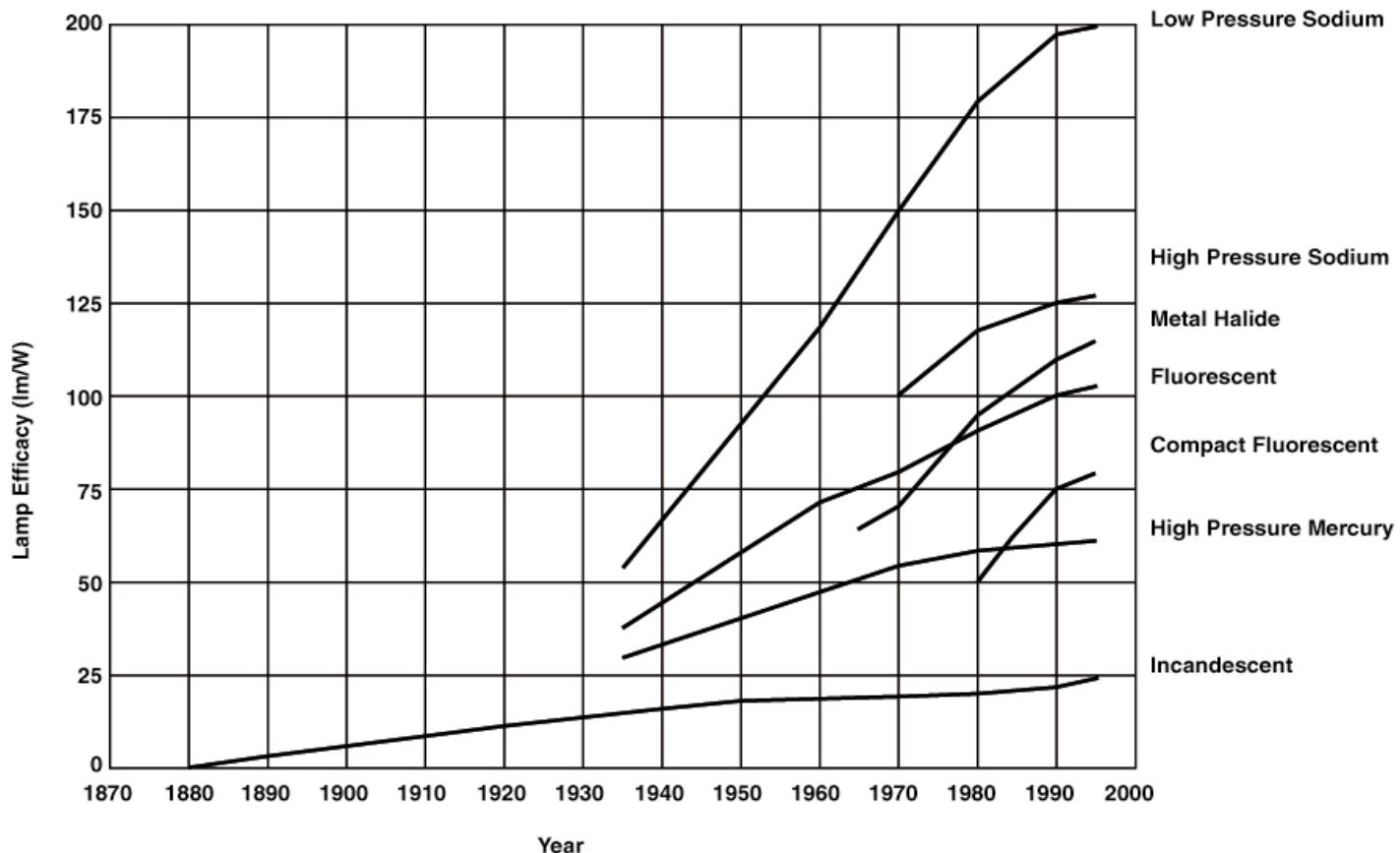


|          |                           |                     |
|----------|---------------------------|---------------------|
| Pressure | <b>10 µbar to 10 mbar</b> | <b>&gt; 1 bar</b>   |
| Length   | <b>approx. 1 m</b>        | <b>approx. 1 cm</b> |
| Power    | <b>4 – 58 W (200 W)</b>   | <b>100 – 2000 W</b> |

# 5.1 Classification of Gas Discharge Lamps

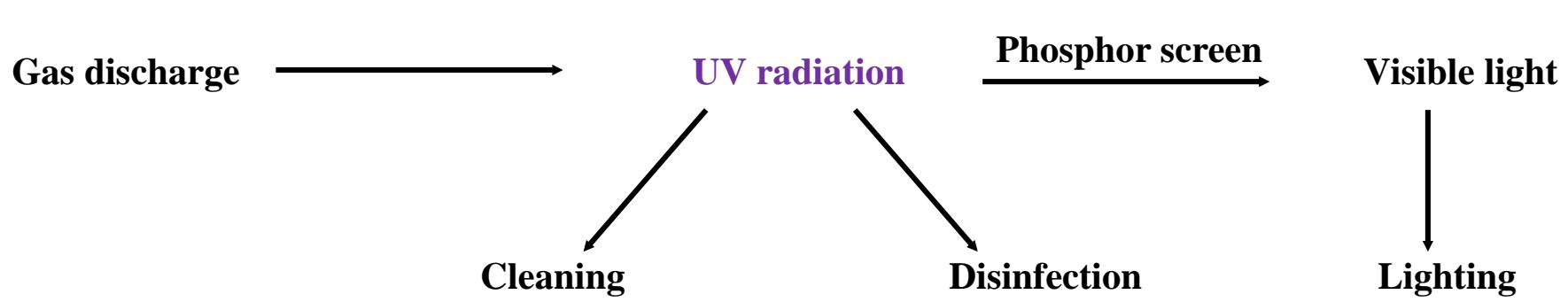
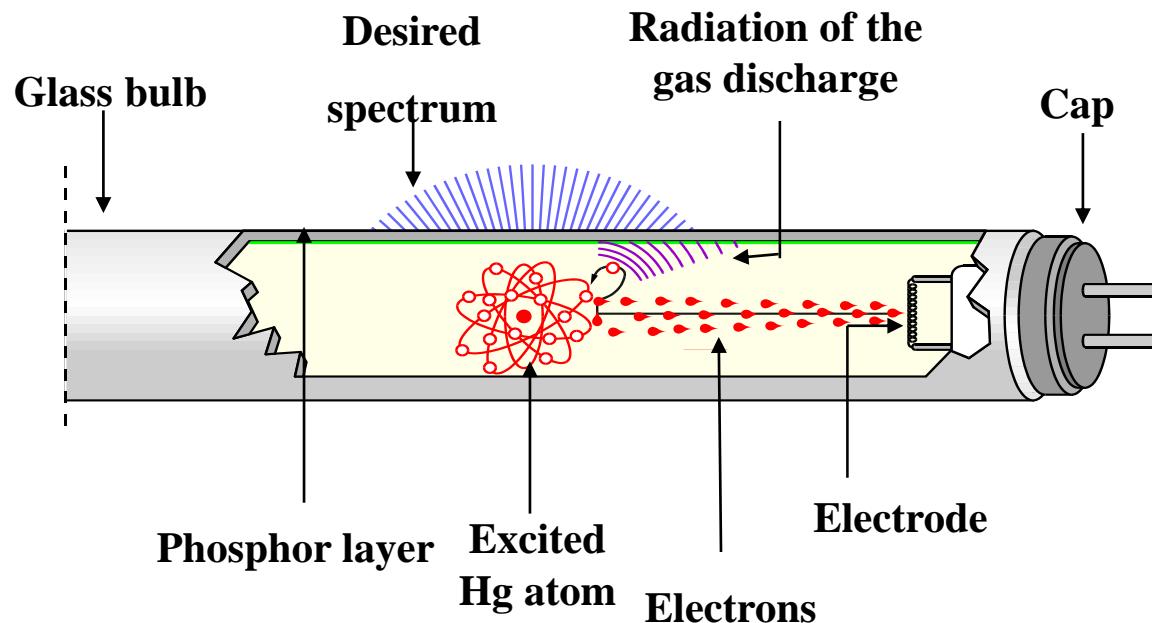
| Mercury   | Sodium   | Noble gases   | Sulphur   |
|---|--|---|---|
| <p>Low pressure<br/><math>p &lt; 10 \text{ mbar}</math></p> <p>Hg/Ar   Hg/Ne</p> <p>185.0 nm<br/>253.7 nm</p> <p>Compact fluorescent lamps or Fluorescent lamps</p> | <p>High pressure <math>p &gt; 1 \text{ bar}</math></p> <p>Hg/Ar</p> <p>Broadband spectrum</p> <p>Line emitters<br/><math>\text{NaX} / \text{TlX} / \text{InX}</math>, <math>X = \text{I}, \text{Br}</math></p> <p>Multi line emitters<br/><math>\text{NaX} / \text{TlX} / \text{LnX}_3</math><br/>(<math>\text{Ln} = \text{Dy}, \text{Ho}, \text{Tm}, \text{Sc}</math>)</p> <p><math>\text{SnX}_2</math></p> <p>Metal halide lamps</p> | <p>Low pressure</p> <p>Na/Ar/Ne</p> <p>589 nm</p> <p>High pressure</p> <p>Na/Hg/Xe</p> <p>Sodium vapour lamps</p> | <p>Low pressure</p> <p>Ne</p> <p>74 nm</p> <p>Medium pressure</p> <p>Xe/Ne</p> <p>147 + 172 nm</p> <p>Plasma displays</p> |

## 5.2 Historical Development

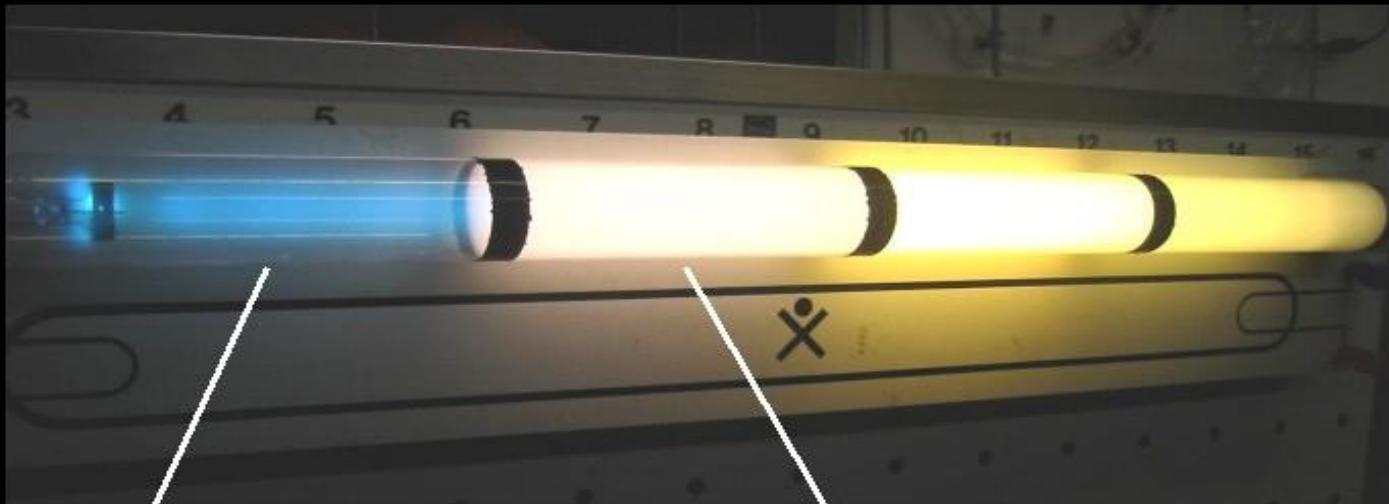


- 1852 Stokes: Monitoring of the phenomena “fluorescence”
- 1938 General electric: First fluorescent lamp, phosphor =  $(\text{Zn},\text{Be})_2\text{SiO}_4:\text{Mn}$  ( $\sim 40 \text{ lm/W}$ )
- 1942 Fluorescent lamps with halophosphate:  $60 \text{ lm/W}$
- 1971 Trichromatic fluorescent lamps:  $100 \text{ lm/W}$

## 5.3 Principle of Fluorescent Lamps



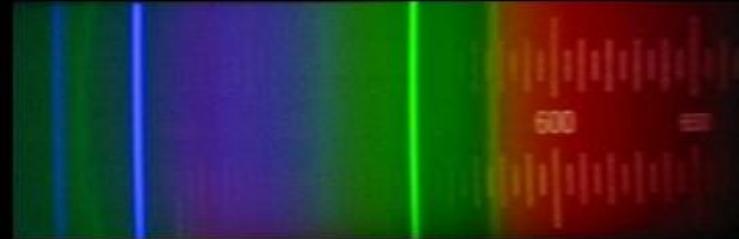
## 5.3 Principle of Fluorescent Lamps



Without phosphor



With phosphor



## 5.4 Low-Pressure Mercury Discharge

In gas discharge lamps, light is generated primarily by an electrically excited plasma

### Definition of a plasma

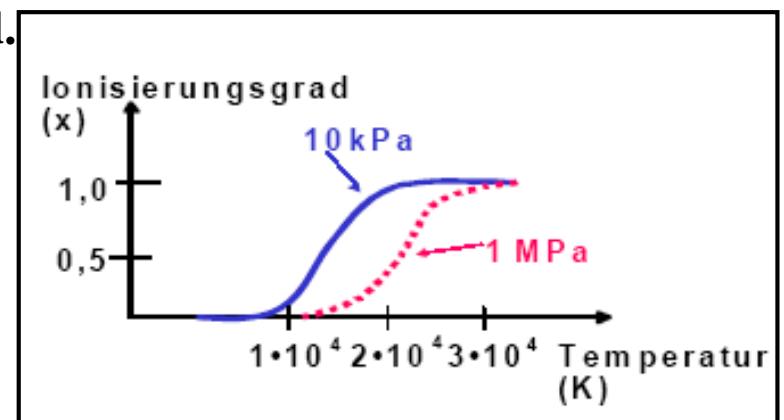
Mixture of electrons, ions and neutral particles in different excited states and with strong interaction with each other

a) Isothermal plasma: All particles are in thermodynamic equilibrium  
(high temperature plasmas: stars)

b) Non-isothermal plasma: Only electrons are in thermodynamic equilibrium  
(electrically generated plasmas: gas discharge lamps)

In gas discharge lamps gas atoms are in fact not ionized.

A significant ionization starts to occur at temperatures above 4000 K



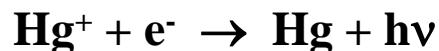
# 5.4 Low-Pressure Mercury Discharge

Spectrum of a gas discharge is caused by several physical processes

1. Line emission (fluorescence)



2. Recombination radiation

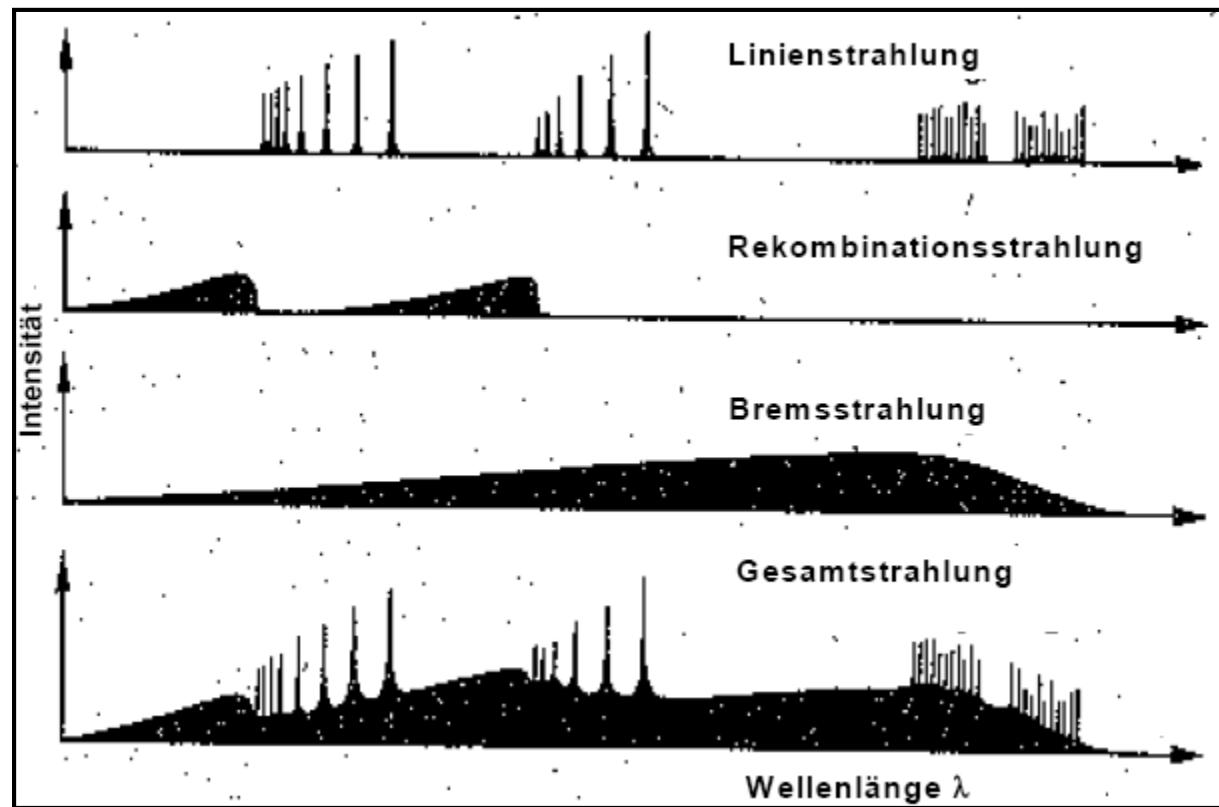


3. Bremsstrahlung

Thermalization of electrons

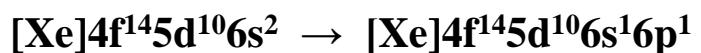
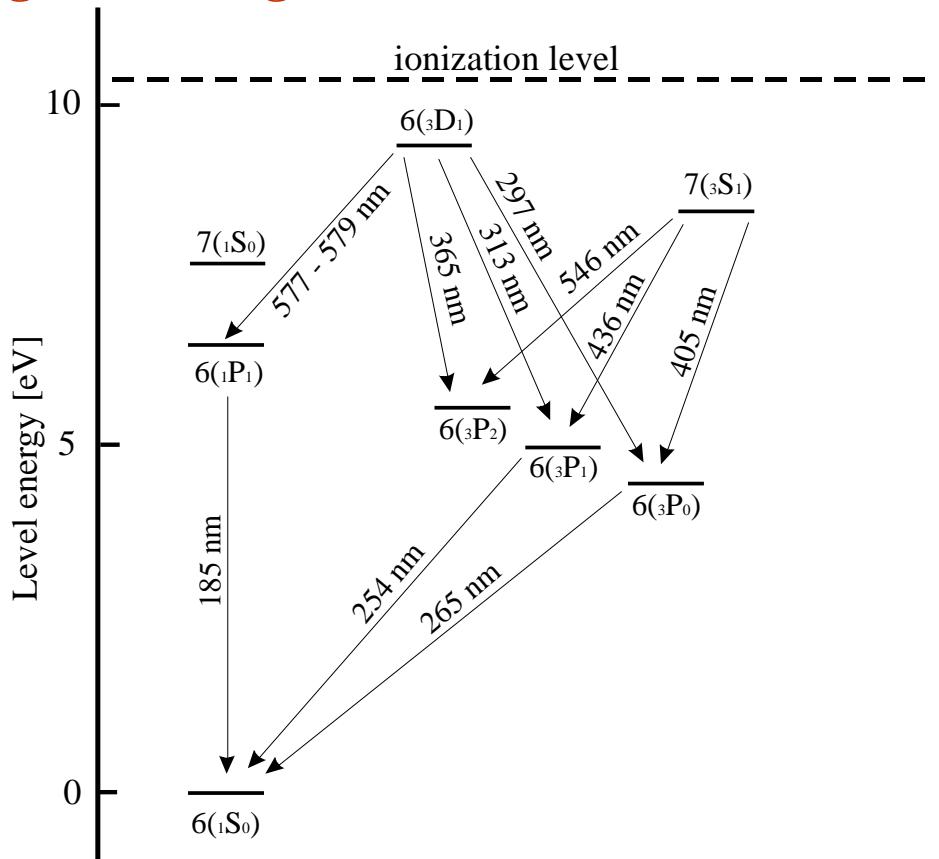
Additional contributions

- Excimer radiation
- Phosphor emission
- Emission of  $\text{LnX}_3$ -filling  
( $X = \text{Br}, \text{I}$ )

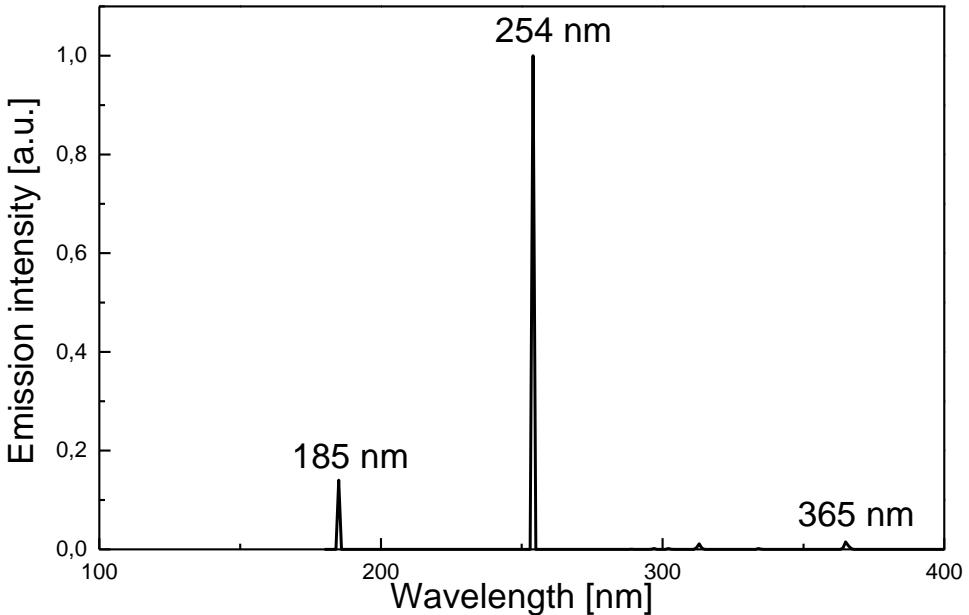


## 5.4 Low-Pressure Mercury Discharge

Energy level diagram of Hg-atom and emission spectrum of a low pressure mercury gas discharge



Ground state term:  $^1S_0$  (all shells filled)



Other lines are in the visible range at  
405, 436, 546, and 579 nm

⇒ Hg discharge appears bluish-white

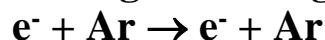
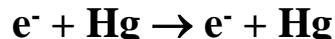
# 5.4 Low-Pressure Mercury Discharge

## Processes in the gas discharge

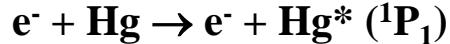
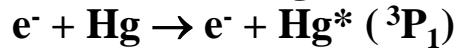
1. Thermal emission of electrons



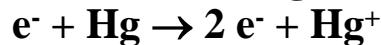
2. Elastic scattering of Hg and Ar (buffer gas)



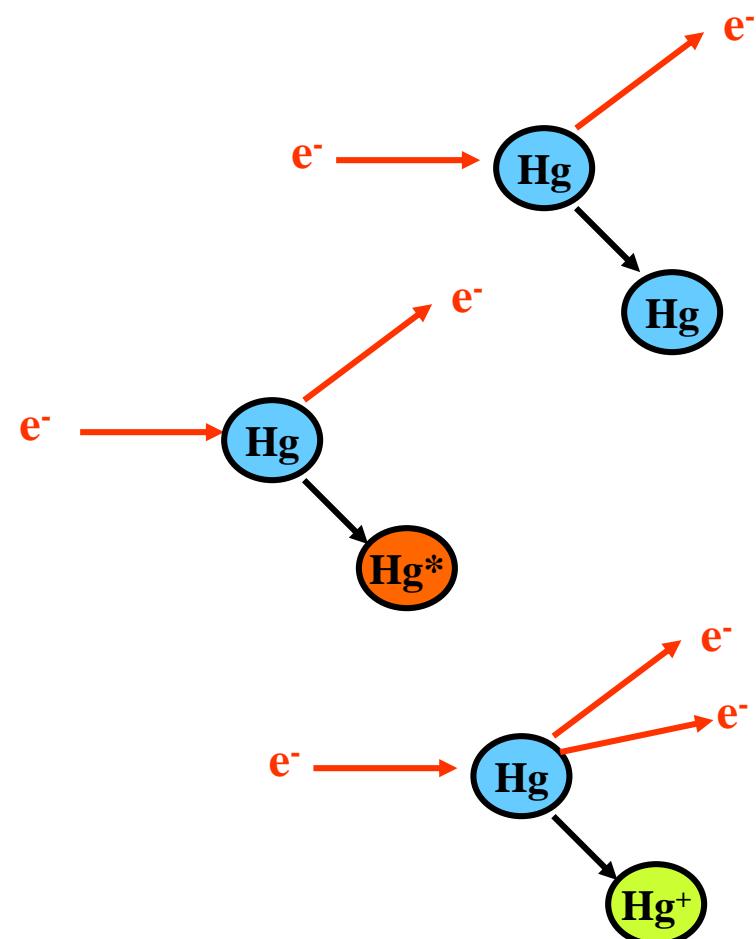
3. Excitation of Hg atoms



4. Ionization of Hg atoms



5. Relaxation of excited Hg atoms



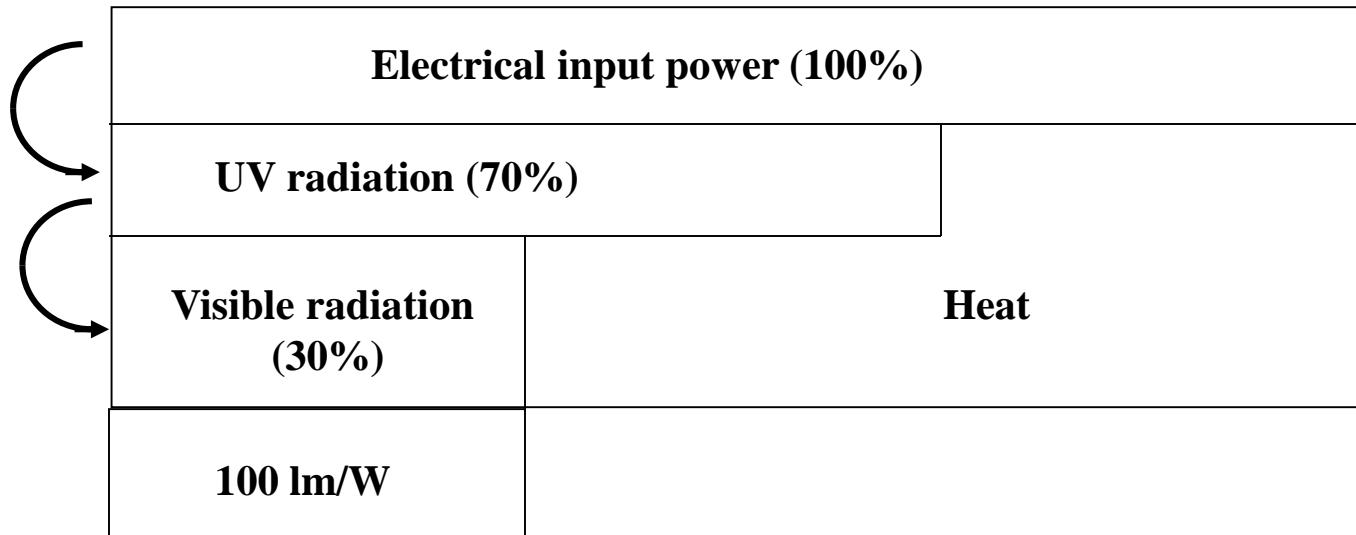
In a low pressure mercury gas discharge about 70% of electrical input power is converted into UV radiation

# 5.5 Energy Balance

## Loss processes in fluorescent lamps

Work function +  
plasma efficiency

Stokes shift +  
quantum yield



$\varepsilon_{\text{dis}}$  = Plasma efficiency

$$\varepsilon = \varepsilon_{\text{dis}} * QD * QY$$

Quantum deficit (Stokes-Shift) =  $[\lambda_{\text{Plasma}}/\lambda_{\text{Phosphor}}] = 0.46$

Quantum yield =  $N_{\text{emitted photons}}/N_{\text{absorbed photons}} \sim 0.9$

Linear Fluorescent Lamps (TL)

$$\varepsilon_{\text{dis}} = 70\% \Rightarrow \varepsilon = 30\% \text{ (100 lm/W)}$$

Compact Fluorescent Lamps (CFL)

$$\varepsilon_{\text{dis}} = 40\% \Rightarrow \varepsilon = 18\% \text{ (60 lm/W)}$$

# 5.6 Typical Dimensions

## Fluorescent tubes



| Output | Length | Diameter | Type                                      |
|--------|--------|----------|---|
| 18 W   | 0.6 m  | T8       | $T8 = 8/8 \text{ inch} = 2.54 \text{ cm}$ |
| 36 W   | 1.2 m  | T8       |   |
| 58 W   | 1.5 m  | T8       |   |
| 4 W    | 0.14 m | T5       | $T5 = 5/8 \text{ inch} = 1.59 \text{ cm}$ |
| 6 W    | 0.21 m | T5       |   |
| 8 W    | 0.30 m | T5       |   |
| 13 W   | 0.50 m | T5       |   |

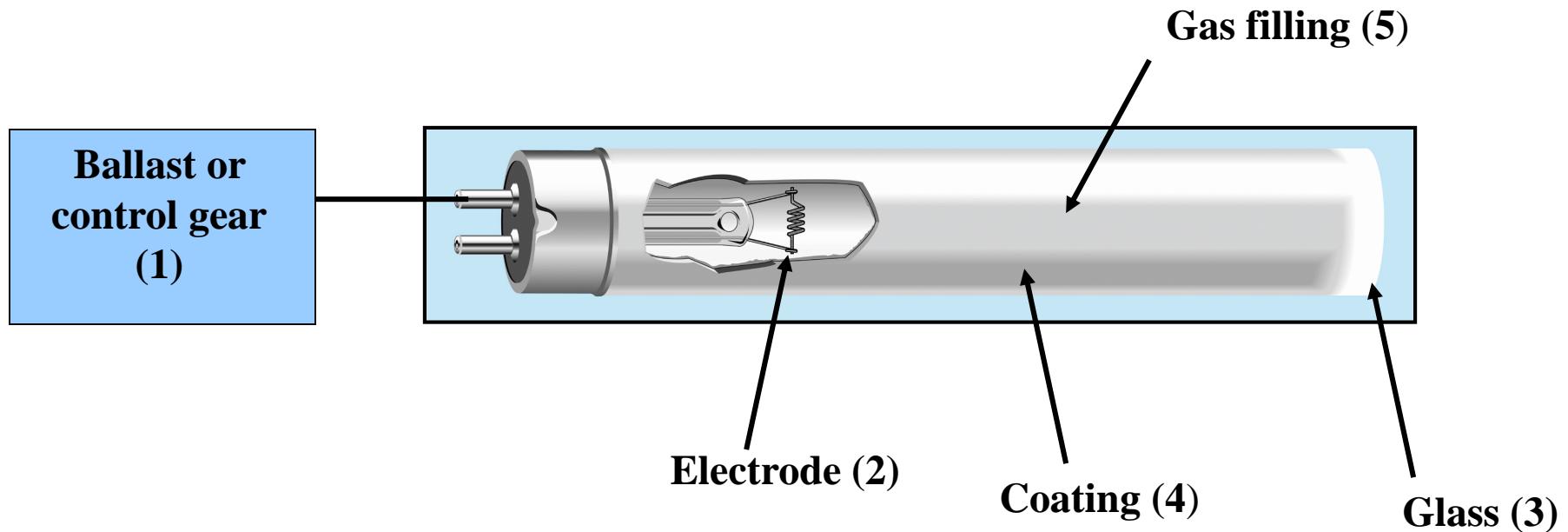
T12 → T8 → T5 → T4 → T3 → T1 (0.32 cm): Increasing wall load

Today: LED Retrofit lamps

# 5.7 Components of Fluorescent Lamps

## Functional parts

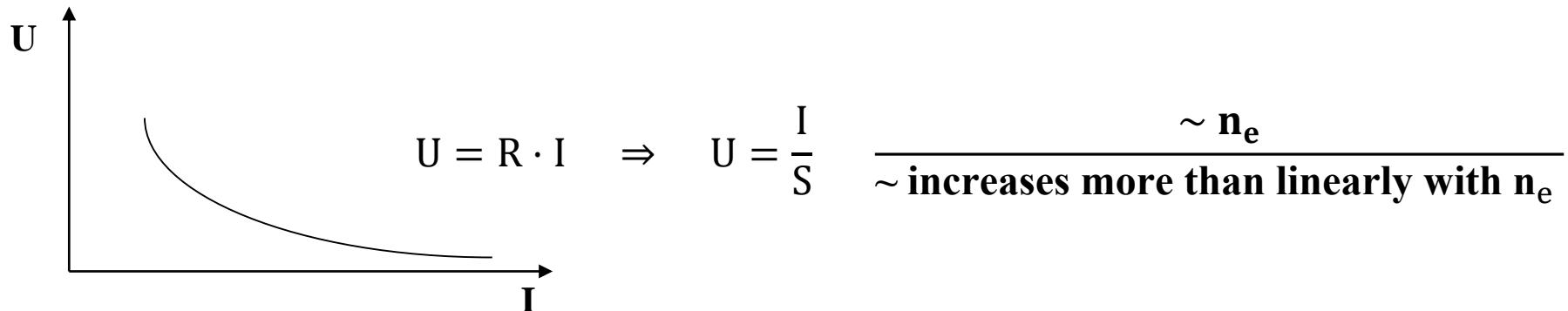
1. Ballast or control gear and starter
2. Electrodes and emitter
3. Glass
4. Coating = pre-coating + phosphor
5. Gas filling



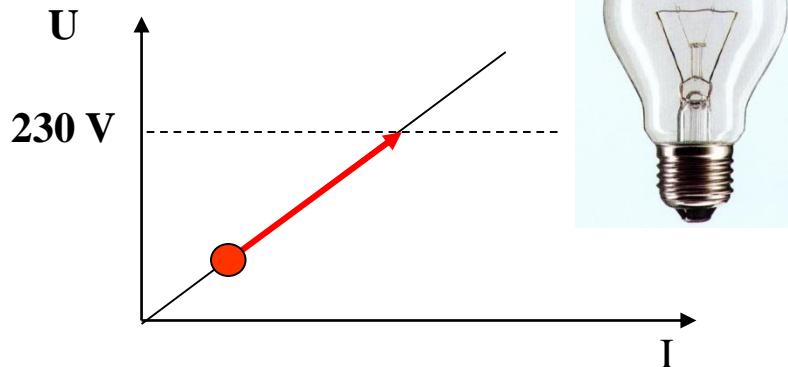
# 5.8 Ballast

## Why is a ballast required?

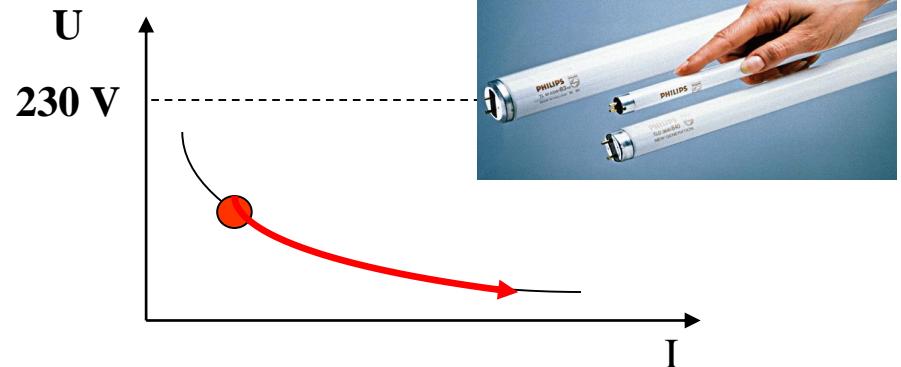
Discharge lamps have a negative current-voltage characteristic ( $S = 1/R = \text{conductivity}$ )



Incandescent lamps



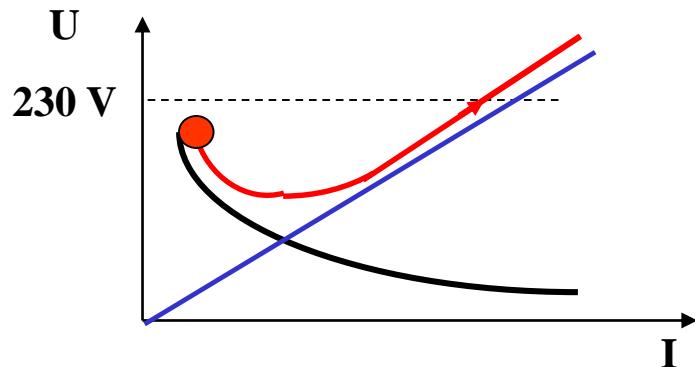
Discharge lamps



## 5.8 Ballast



36 W FL:  $U = 100 \text{ V}$ ,  $I = 0.36 \text{ A}$



$$R: U_R = 130 \text{ V}, \quad I_R = 0.36 \text{ A} \Rightarrow R = 360 \Omega$$

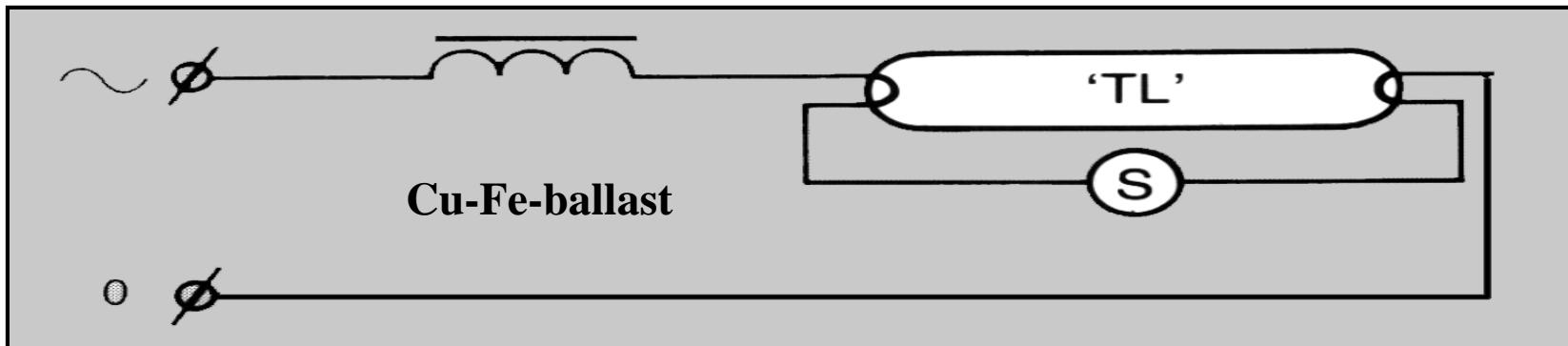
$\Rightarrow 130/230 = 56\%$  of power output is consumed in  $R$

$$\Rightarrow \eta = 100 \text{ lm/W} * 44\% = 44 \text{ lm/W}$$

Solution: "ballasted" with a coil (inductance) or a capacitor (capacitance)

$\Rightarrow$  in L and C are the current and voltage phase shifted by  $90^\circ$

$\Rightarrow$  no power output is consumed

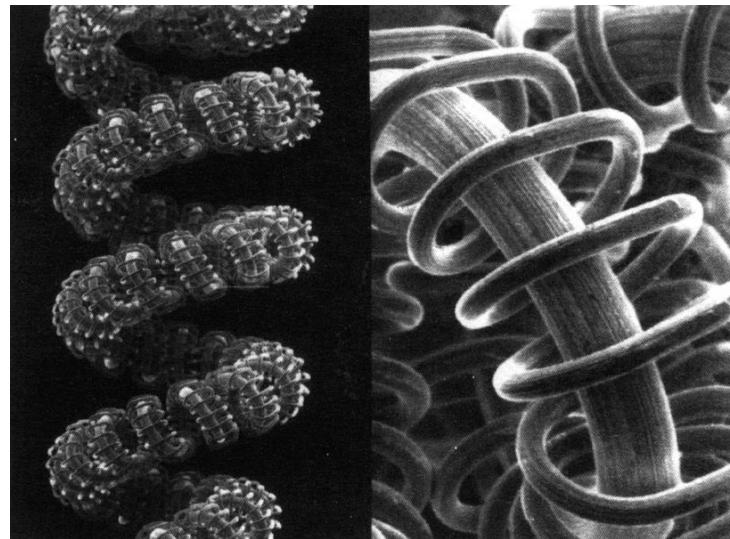
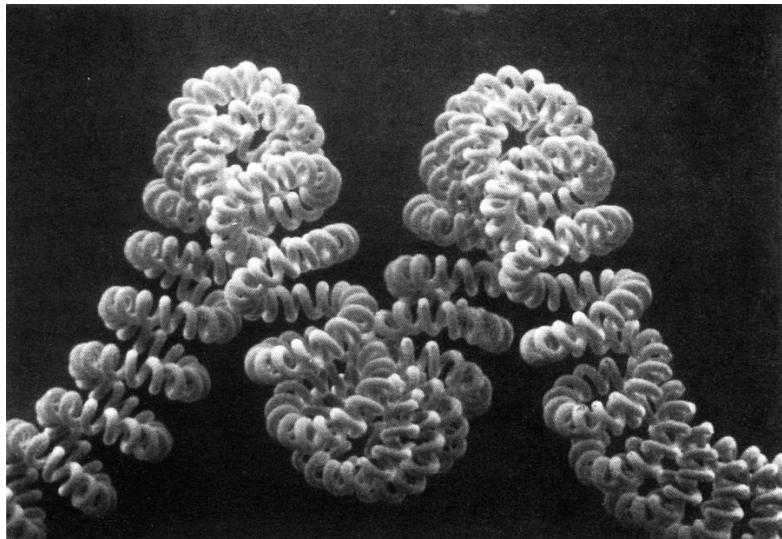


# 5.9 Electrodes and Emitters

**Electrodes release electrons into the gas phase by thermal emission**

**Material: Tungsten (emission of electrons from about 2000 °C)**

**Typical design: Double-coiled wire**



# 5.9 Electrodes and Emitters

Thermal thermionic emission of electrodes is described by the Richardson law

$$I = \text{Area} \cdot A \cdot T^2 \cdot e^{-\frac{W_A}{kT}}$$

A = Richardson constant = 60 A/cm<sup>2</sup>K<sup>2</sup>

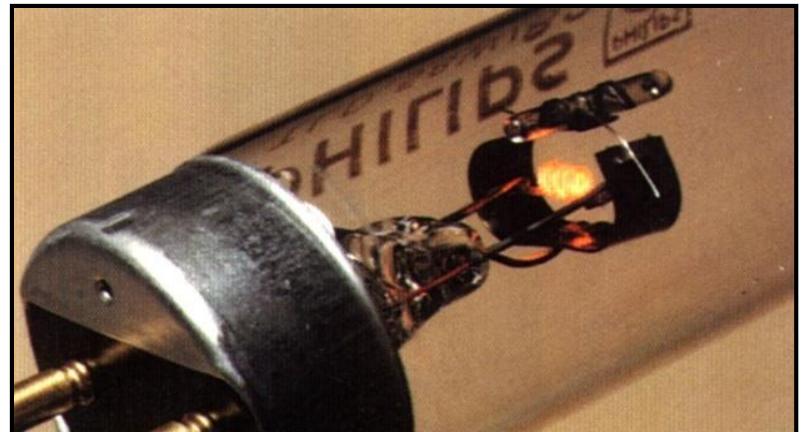
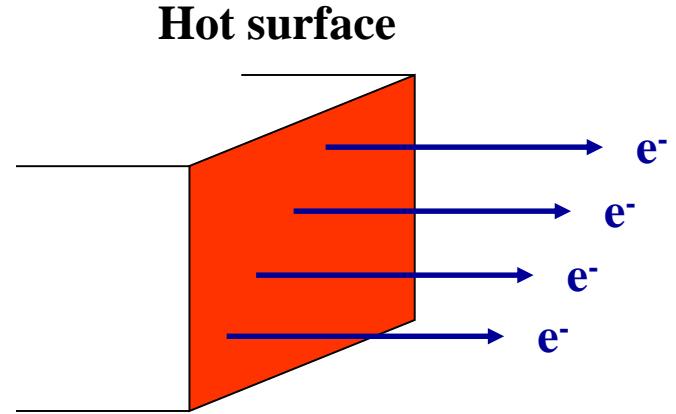
W<sub>A</sub> = Work function (4.54 eV for tungsten)

kT = Thermal energy [J]

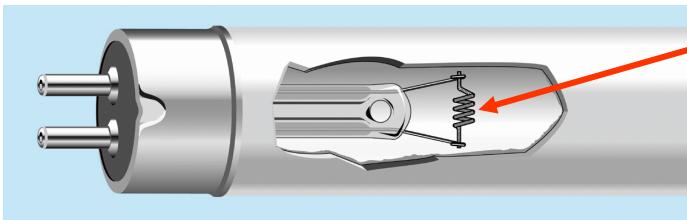
k = Boltzmann's constant = 1.38·10<sup>-23</sup> J/K

Probability that an electron leaves the surface is

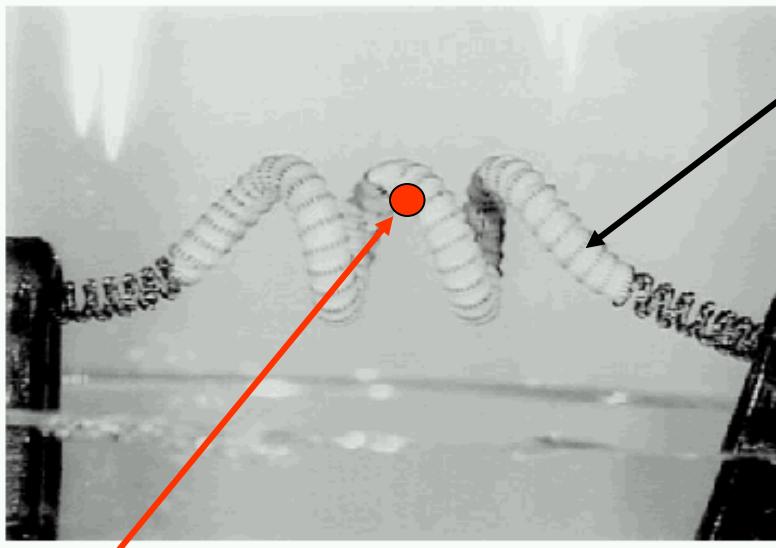
$$\sim e^{-\frac{W_A}{kT}}$$



# 5.9 Electrodes and Emitters



Electrodes made out of tungsten  $\Rightarrow$  Richardson:  $I = 0.5 \text{ A}$   
 $\Rightarrow T_w = 3100 \text{ K}$   
 $\Rightarrow$  Energy costs  
 $\Rightarrow$  Efficiency decreases



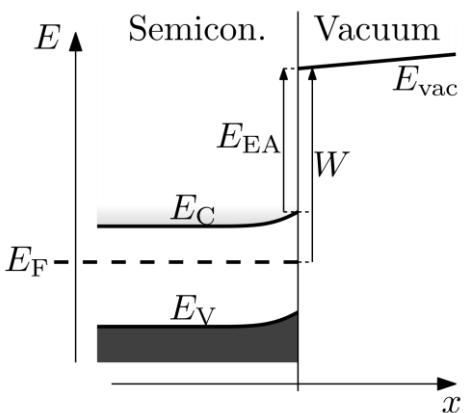
Arc operates at about  $1 \text{ mm}^2$  area

## Solution

Electrode is coated with an emitter

Emitter = Material with low work function

| Material               | Work function $W_A [\text{eV}]$ |   |
|------------------------|---------------------------------|---|
| W                      | 4.3 – 5.2                       |   |
| Ba                     | 2.5                             | $\longrightarrow I = 0.5 \text{ A}$ even at |
| Sr                     | 2.6                             | $T_{\text{Ba}} = 1350 \text{ K}$            |
| Ca                     | 2.9                             |   |
| BaO                    | 1.0 – 1.7                       |   |
| SrO                    | 1.3 – 1.6                       |   |
| CaO                    | 1.6 – 1.9                       |   |
| $\text{Y}_2\text{O}_3$ | 2.0 – 3.9                       |   |



# 5.9 Electrodes and Emitters

## Used emitter materials

$\text{Y}_2\text{O}_3$

High pressure sodium lamps

$\text{BaO/SrO/CaO}$

Na/Hg-low pressure lamps

Application as stable carbonates "triple mix"

1. Dip coating of the electrode with a suspension of the "triple mix"

2. Activation in the lamp:  $\text{MeCO}_3 \rightarrow \text{MeO} + \text{CO}_2 \uparrow$  ( $\text{Me} = \text{Ca, Sr, Ba}$ )

3. Operation of the lamp:  $\text{W} + 6 \text{ BaO} \rightarrow \text{Ba}_3\text{WO}_6 + 3 \text{ Ba}$  (emitter)

# 5.10 Lamp Glass

## General requirements

- Low cost (< 1 ct/lamp)
- High transparency
- Radiation stability (lower solarisation)
- Thermal stability

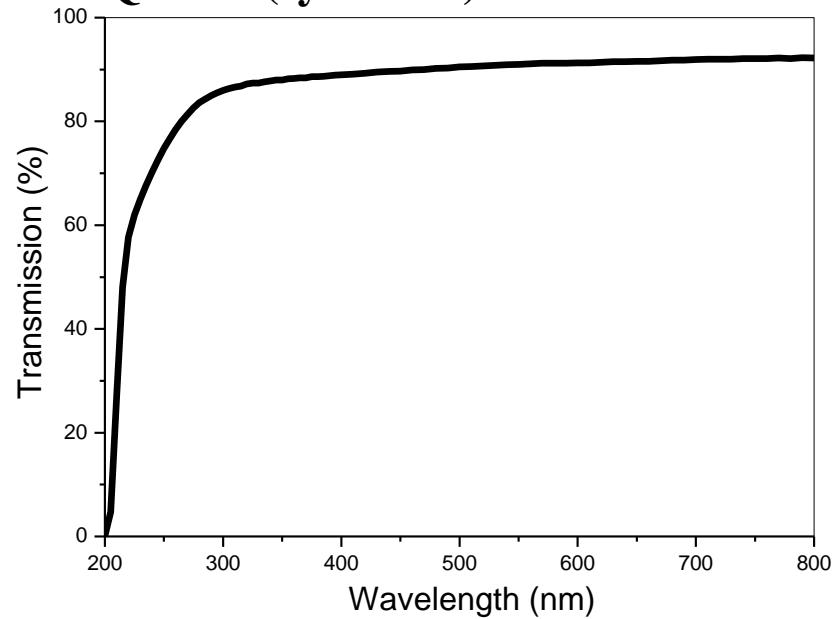
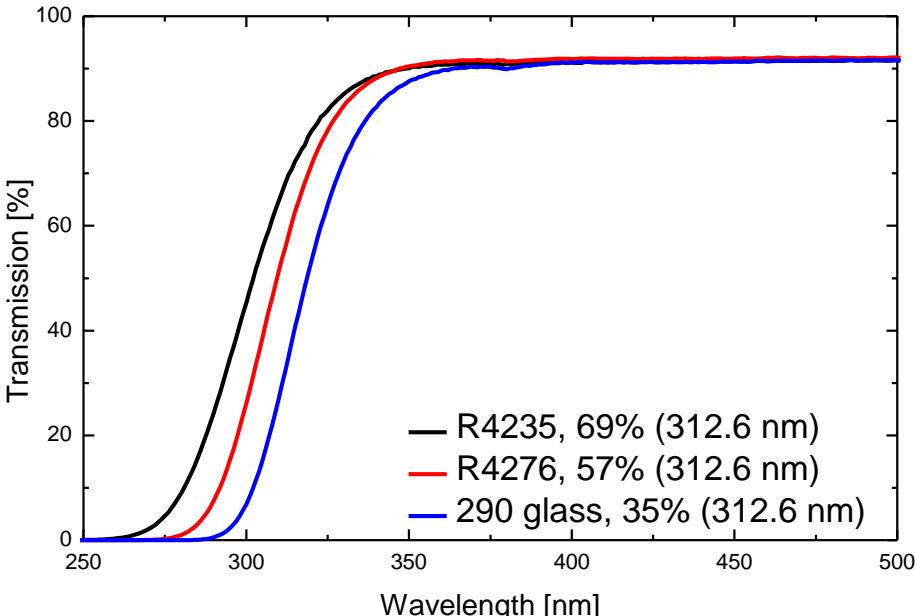
## Composition of typical glasses for lamps

| Komposition [%]                | Natriumsilikat                  | Bleisilikat                     | Borsilikat         | Aluminosilikat | Aluminoborat         | Quarz       |
|--------------------------------|---------------------------------|---------------------------------|--------------------|----------------|----------------------|-------------|
| SiO <sub>2</sub>               | 73                              | 64                              | 75                 | 63             | 8                    | 100         |
| Na <sub>2</sub> O              | 16                              | 8                               | 4                  |                | 14                   |             |
| K <sub>2</sub> O               | 1                               | 6                               | 2                  |                |                      |             |
| CaO                            | 5                               |                                 |                    | 9              | 6                    |             |
| MgO                            | 4                               |                                 |                    |                |                      |             |
| Al <sub>2</sub> O <sub>3</sub> | 1                               | 2                               | 1                  | 16             | 24                   |             |
| PbO                            |                                 | 20                              |                    |                |                      |             |
| B <sub>2</sub> O <sub>3</sub>  |                                 |                                 | 18                 |                | 48                   |             |
| Anwendung in                   | Glühlampen<br>Fluoreszenzlampen | Glühlampen<br>Fluoreszenzlampen | Hg-Hochdrucklampen | Halogenlampen  | Na-Niederdrucklampen | UV-C Lampen |

# 5.10 Lamp Glass

## Transmission of lamp glasses

| Lamp application | Absorption edge [nm] | Type of glass                  |
|------------------|----------------------|--------------------------------|
| Lighting         | 320                  | Sodium silicate glass          |
| Tanning beds     | 300                  | Modified sodium silicate glass |
| Disinfection     | 220                  | Modified sodium silicate glass |
| Purification     | 170                  | Quartz (synthetic)             |

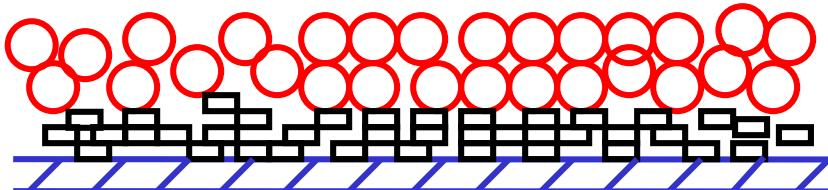


# 5.11 Coating

## Basic structure

- Phosphor coating (phosphor + filling)
- Pre-coating ( $\text{Al}_2\text{O}_3$ ,  $\text{Y}_2\text{O}_3$ ,  $\text{MgO}$ , .....

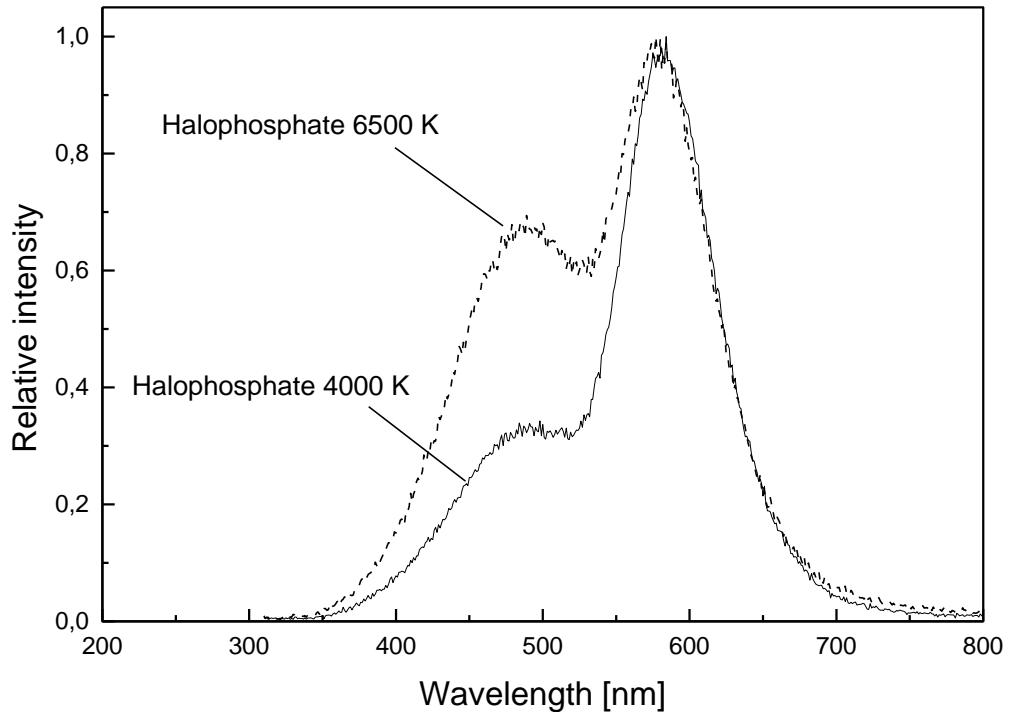
Schematic layer build-up



| <u>Dispersion medium</u> | <u>Butylacetat</u>  | <u>Demineralised water</u>   |
|--------------------------|---|--|
| Binder                   | Nitrocellulose  | Polyethylene oxide   |
| Phosphor (blend)         | Halophosphate<br>Color 80 phosphors<br>Color 90 phosphors<br>UV-phosphors | Halophosphates<br>Color 80 phosphors<br>Color 90 phosphors             |
| Adhesive agent           | Alon-c ( $\text{Al}_2\text{O}_3$ )  | $\text{Ca}_2\text{P}_2\text{O}_7$ or $\text{Sr}_2\text{P}_2\text{O}_7$ |
| Dispersion agent         | 2-Methoxy-1-propanol  | Polyacrylic acid   |

## 5.11 Coating

### With fluorescent halophosphate (apatite)



- **Sb/Mn mass ratio determines color temperature**
- **Light yield = 75 - 80 lm/W<sub>el</sub>**
- **Colour rendering index CRI = 60**

## 5.11 Coating

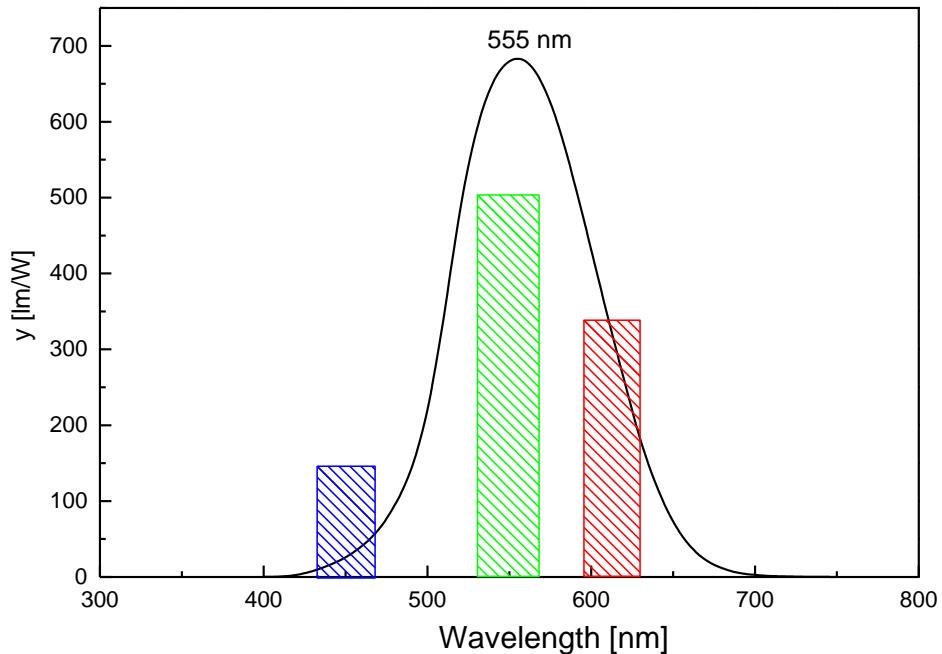
With a trichromatic blend of phosphors (red-green-blue RGB)

Required positions of the emission bands

Blue    440 - 460 nm     $\text{Eu}^{2+}$

Green    540 - 560 nm     $\text{Tb}^{3+}$

Red    590 - 630 nm     $\text{Eu}^{3+}$

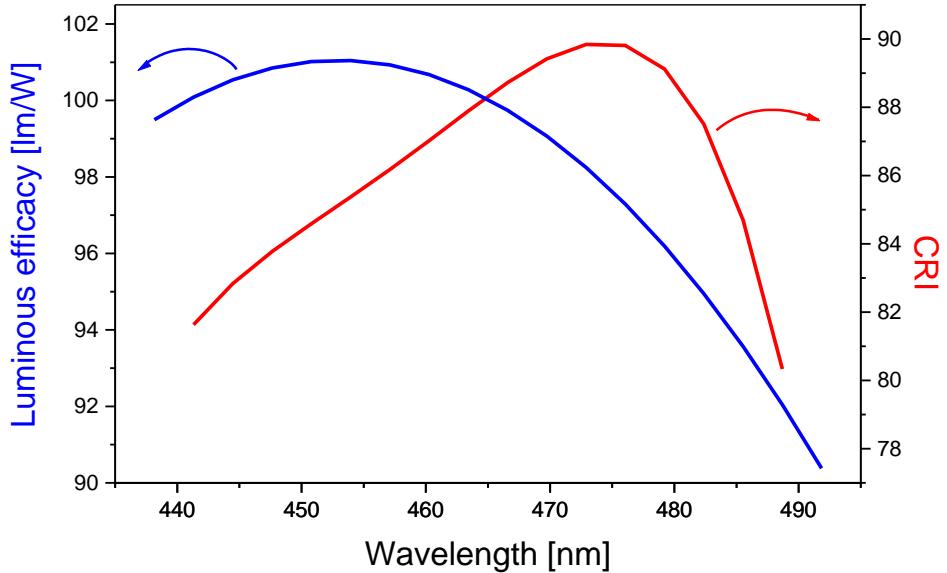


- Light yield = 100 lm/W<sub>el</sub>
- Color rendering index CRI = 80 – 85
- Lifetime L70 > 10,000 h → no fluorides, silicates, titanates, or zirconates

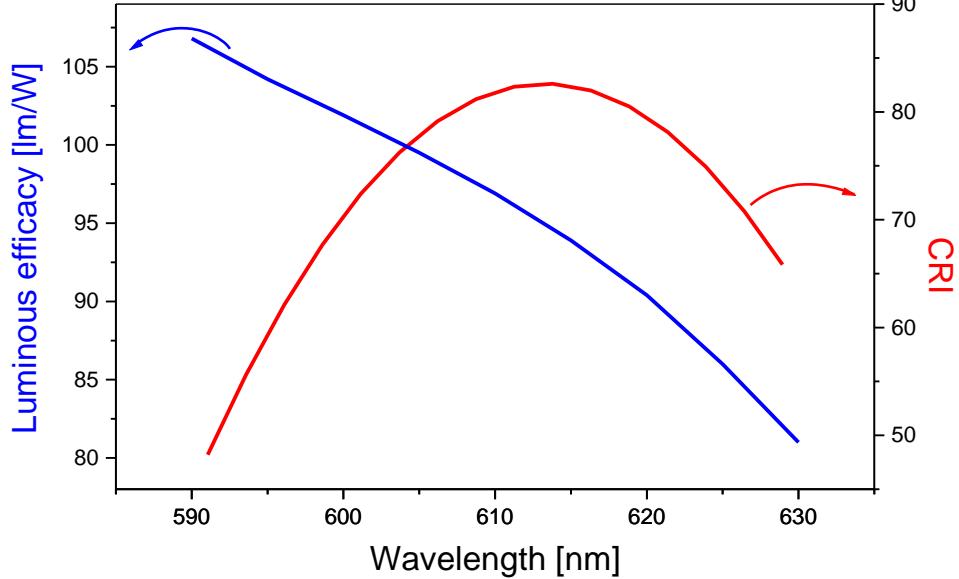
# 5.11 Coating

## Lumen output of a trichromatic lamp

Blue + 545 nm + 610 nm



450 nm + 545 nm + Red

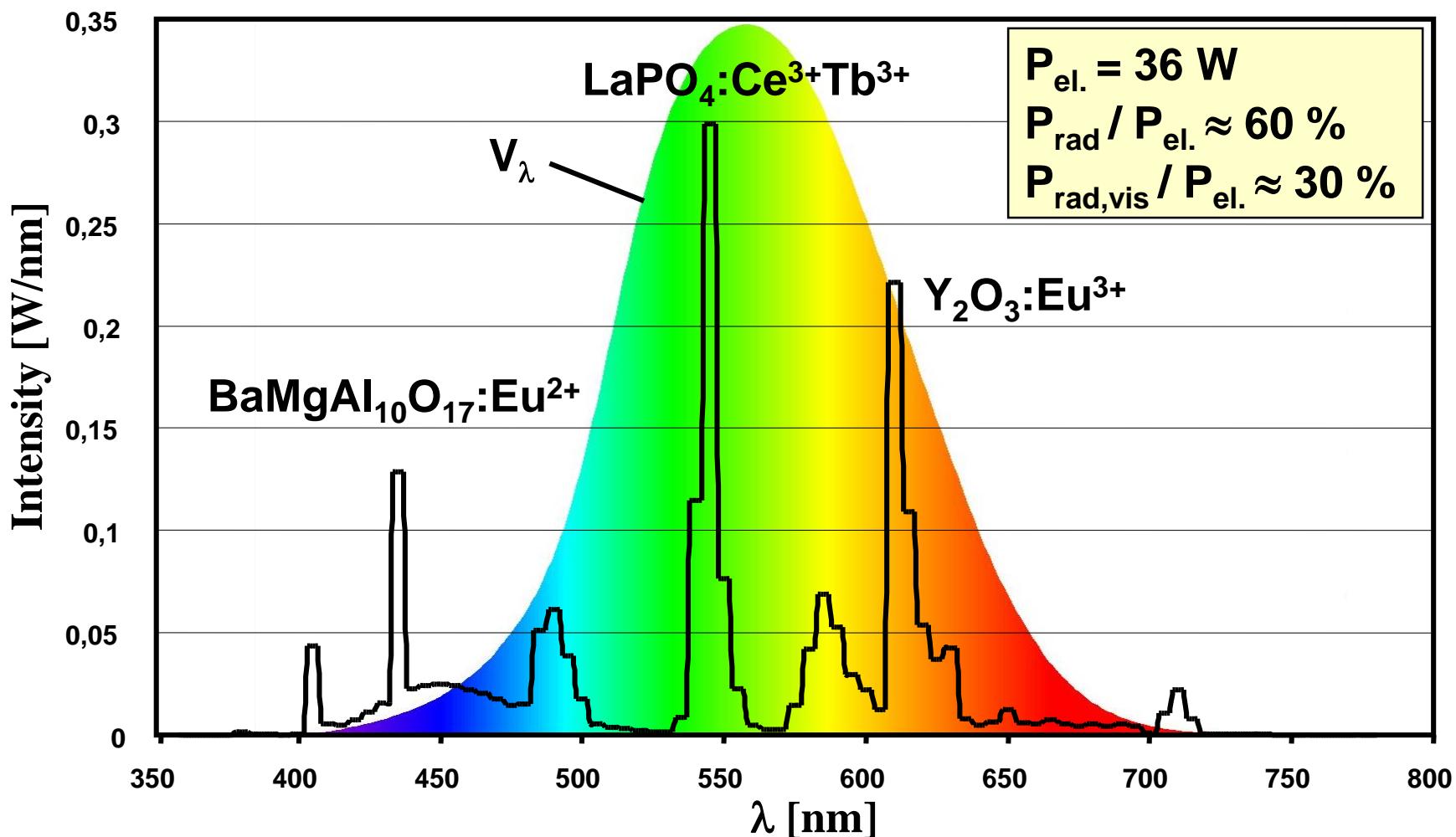


Optimum at about

- Light yield  $100 \text{ lm/W}_{\text{el}}$
- CRI = 80 - 85 ( $\Rightarrow$  color 80 lamps)

## 5.11 Coating

Emission spectrum of a trichromatic lamp



# 5.11 Coating

## Color points of trichromatic lamps

Color temperature

2700 - 6500 K

Only green and red phosphor

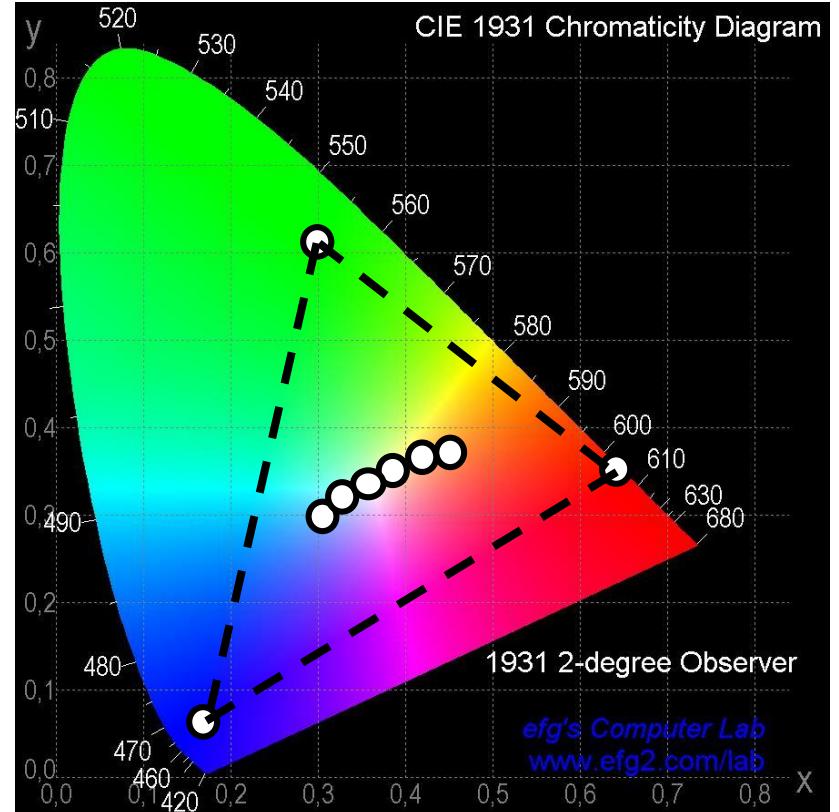
2700 K

RGB phosphor mixture

2700 - 6500 K depending on the mixing ratio

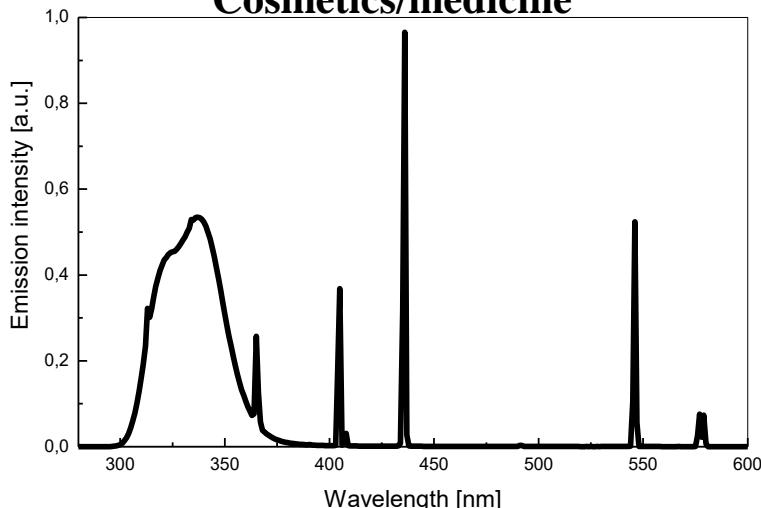
Color point

Is adjusted so that it lies close to the black body-line

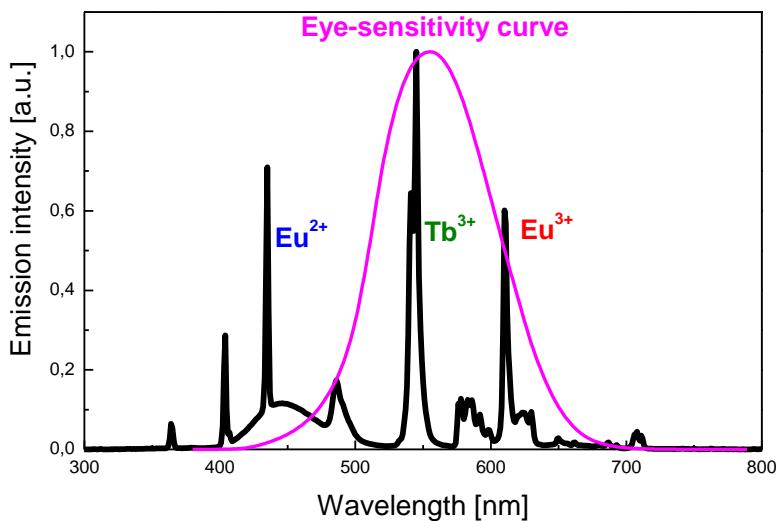


# 5.11 Coating

## Cosmetics/medicine



## Lighting



## Lanthanide ions

$\text{Ce}^{3+}$   
 $\text{LaPO}_4:\text{Ce}$   
 $\text{YPO}_4:\text{Ce}$

$\text{Eu}^{2+}$   
 $\text{Sr}_5(\text{PO}_4)_3(\text{F},\text{Cl}): \text{Eu}$   
 $\text{BaMgAl}_{10}\text{O}_{17}: \text{Eu}$

## Tb³⁺

$\text{LaPO}_4:\text{Ce,Tb}$   
 $\text{CeMgAl}_{11}\text{O}_{19}: \text{Tb}$   
 $\text{LaMgB}_5\text{O}_{10}: \text{Ce,Tb}$

## $\text{Eu}^{3+}$

$\text{Y}_2\text{O}_3: \text{Eu}$   
 $(\text{Y,Gd})(\text{V,P})\text{O}_4: \text{Eu}$

## s<sup>2</sup>- or TM-ions

$\text{Pb}^{2+}$   
 $\text{Sr}_2\text{MgSi}_2\text{O}_7:\text{Pb}$   
 $\text{BaSi}_2\text{O}_5:\text{Pb}$

## $\text{Sb}^{3+}$

$\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl}): \text{Sb}$

## $\text{Mn}^{2+}$

$\text{BaMgAl}_{10}\text{O}_{17}: \text{Eu,Mn}$   
 $\text{Zn}_2\text{SiO}_4: \text{Mn}$   
 $\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl}): \text{Sb,Mn}$   
 $\text{LaMgB}_5\text{O}_{10}: \text{Ce,Tb,Mn}$

## $\text{Mn}^{4+}$

$\text{Mg}_4\text{GeO}_{5.5}\text{F}: \text{Mn}$

# 5.11 Coating

## Color rendering (trichromatic phosphor blends)

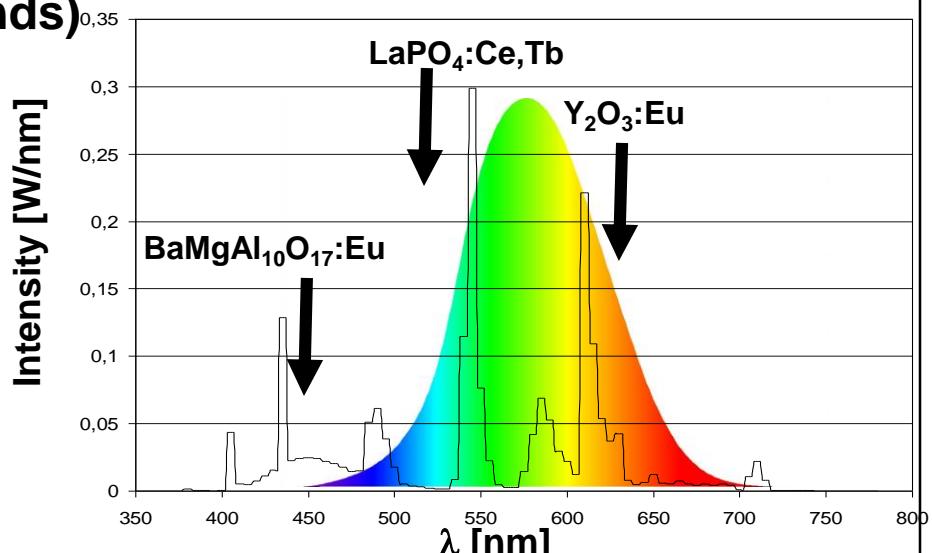
- Fairly good color rendering →  $R_a = 80 - 85$
- Lack of radiation in the
  - cyan      500 – 535 nm
  - yellow    560 – 580 nm
  - deep red   > 610 nm

## Consequences

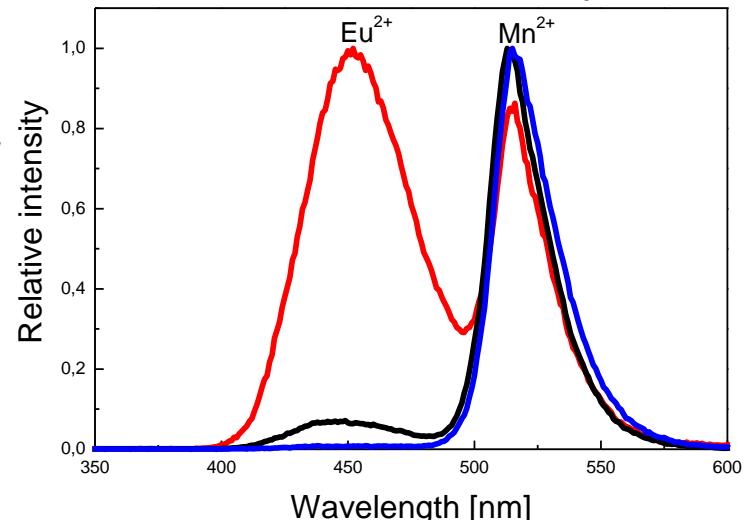
- Additional broad band phosphors
    - $\text{Sr}_4\text{Al}_{14}\text{O}_{25}:\text{Eu}$
    - $\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl}): \text{Sb},\text{Mn}$
  - Modification of applied trichromatic phosphors
    - $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu} \rightarrow \text{BaMgAl}_{10}\text{O}_{17}:\text{Eu,Mn}$
    - $\text{GdMgB}_5\text{O}_{10}:\text{Ce,Tb} \rightarrow \text{GdMgB}_5\text{O}_{10}:\text{Ce,Tb,Mn}$
- $R_a \sim 88 - 90$ , but luminous efficiency  $\sim 60 - 80 \text{ lm/W}$

### Typical blend (Osram Patent EP1306885)

|   |           |
|---|-----------|
| $\text{Sr}_4\text{Al}_{14}\text{O}_{25}:\text{Eu}$                    | 28.5 wt-% |
| $(\text{Ce,Gd})(\text{Zn,Mg})\text{B}_5\text{O}_{10}:\text{Mn}$       | 28.5 wt-% |
| $\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl}): \text{Sb},\text{Mn}$ | 26.9 wt-% |
| $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}$                           | 6.1 wt-%  |
| $\text{CeMgAl}_{11}\text{O}_{19}:\text{Tb}$                           | 10.0 wt-% |



Emission spectra of  $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu,Mn}$

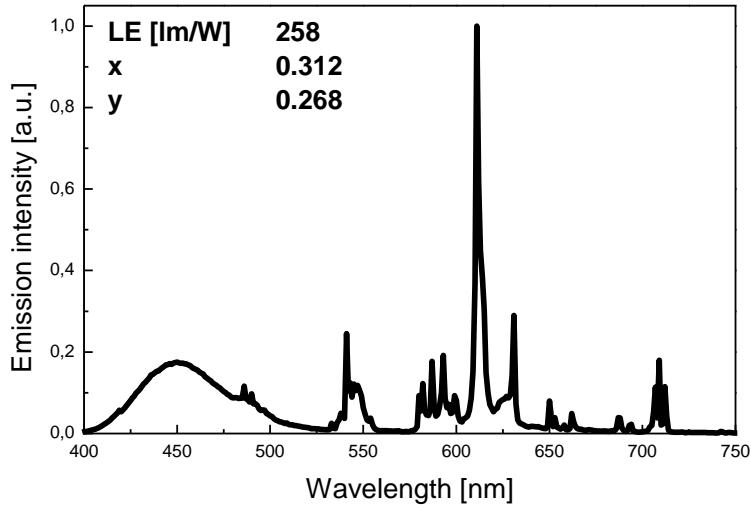


# 5.11 Coating

## Fluorescent lamps with high color rendering

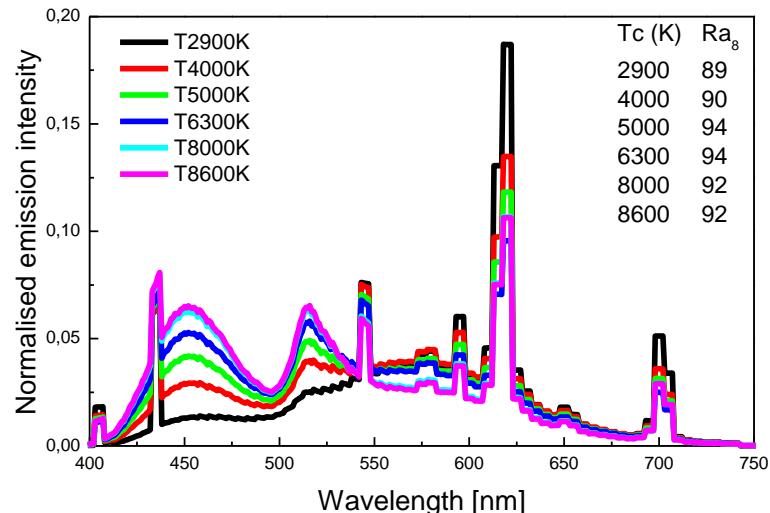
### Application of $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu,Mn}$

Emission spectrum of a mixture of  
 $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu,Mn} + \text{LaPO}_4:\text{Ce,Tb} +$   
 $\text{Y}_2\text{O}_3:\text{Eu}$  at 254 nm excitation



Ra ~ 88

Measured emission spectra of fluorescent lamps  
with a mixture of  $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu,Mn} +$   
 $\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Ce} + \text{YVO}_4:\text{Eu}$  ( $\text{Al}_2\text{O}_3$  coated)



Ra > 90

## 5.12 Hg-Take up

The low-pressure mercury discharge requires for optimum operation 50 µg Hg

Standard filling: 10 - 20 mg / lamp

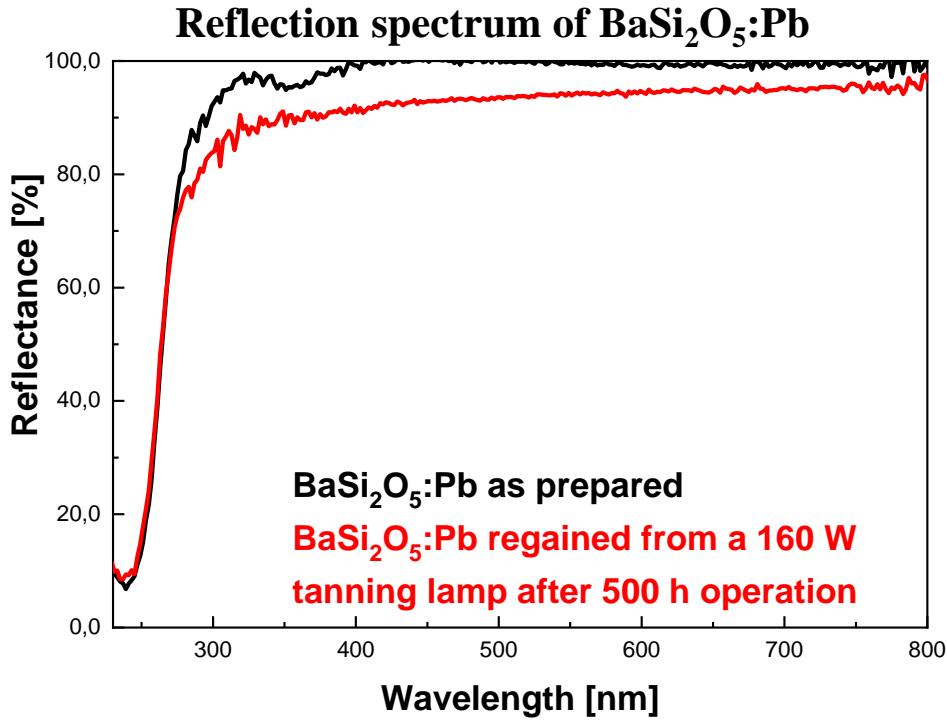
Origin: Hg consumption by lamp components → Hg take-up

| <u>Lamp component</u> | <u>Hg consumption in 10000 h (4 ft TL Lamp)</u> |
|-----------------------|---|
| • Glass               | 5 mg  |
| • Phosphor            | 0.1 - 2.0 mg                                    |
| • Electrodes          | 0.1 - 1.0 mg                                    |

⇒ Hg higher doses to compensate Hg consumption during the specified life time

## 5.12 Hg-Take up

Hg adsorption by glass and phosphor leads to the graying of the phosphor and to reduction of the discharge efficiency



| Material                    | IEP [pH] |
|-----------------------------|----------|
| $\text{WO}_3$               | 2.0      |
| $\text{SiO}_2/\text{Glass}$ | 3.0      |
| $\text{BaSi}_2\text{O}_5$   | 3.0      |
| $\text{TiO}_2$              | 5.6      |
| $\text{ZrO}_2$              | 6.0      |
| $\text{LaPO}_4$             | 7.8      |
| $\text{Al}_2\text{O}_3$     | 9.0      |
| $\text{Y}_2\text{O}_3$      | 9.0      |
| $\text{ZnO}$                | 9.4      |
| $\text{Yb}_2\text{O}_3$     | 9.7      |
| $\text{La}_2\text{O}_3$     | 10.4     |
| $\text{MgO}$                | 11.0     |

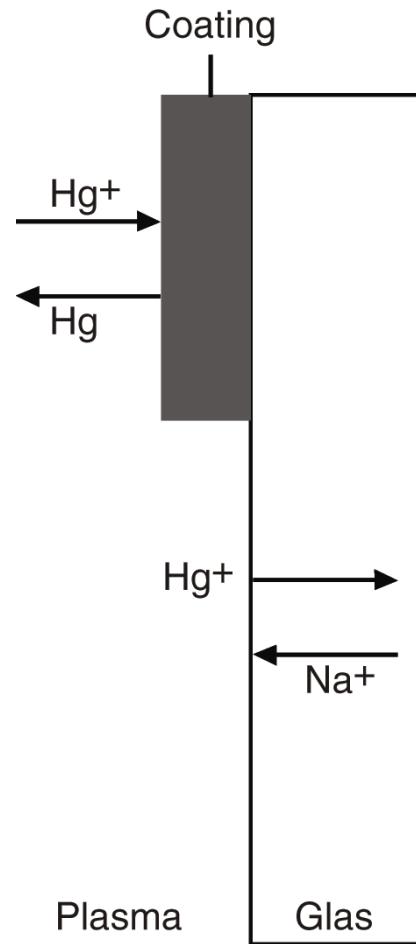
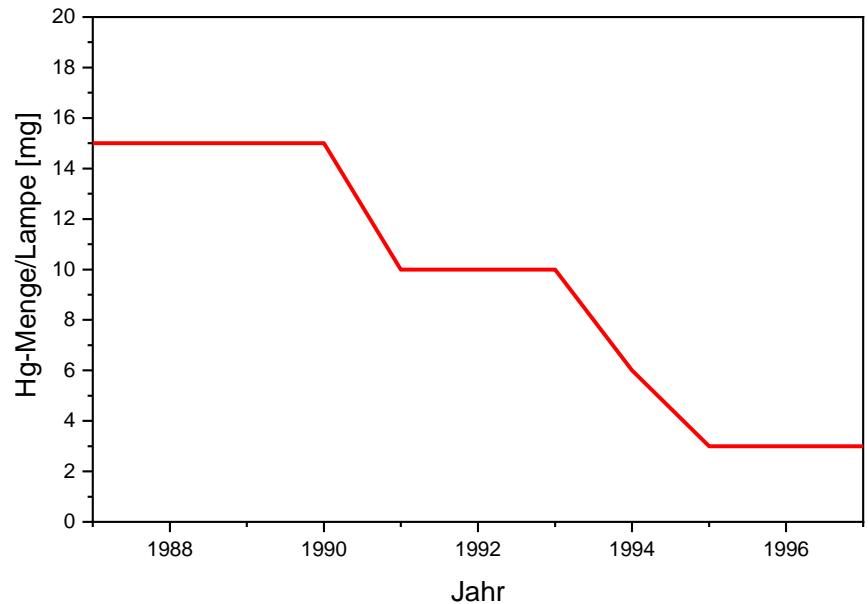
Hg/Hg<sup>+</sup>- take up decreases with increasing electron density of the anions (alkalinity), i.e. with the increase in reactivity toward electrophilic agents, such as CO<sub>2</sub>, H<sup>+</sup>, Hg<sup>+</sup>

# 5.12 Hg-Take up

## Measures to reduce Hg-consumption

- Particle Coating
- Glass Coating

With  $\text{Y}_2\text{O}_3$  or  $\text{Al}_2\text{O}_3$  (low Hg-take up)



3 mg Hg/lamp with  $\text{Y}_2\text{O}_3$ -glass coating

# 5.13 Compact Fluorescent Lamps

Compact fluorescent Lamps, also called energy saving lamps, are fluorescent tubes consisting of several (bent) tubes with an integrated ballast

## Trends

- Miniaturization
- Incandescent lamp form (outer envelope with a scattering layer)

„incandescent look-a-like“



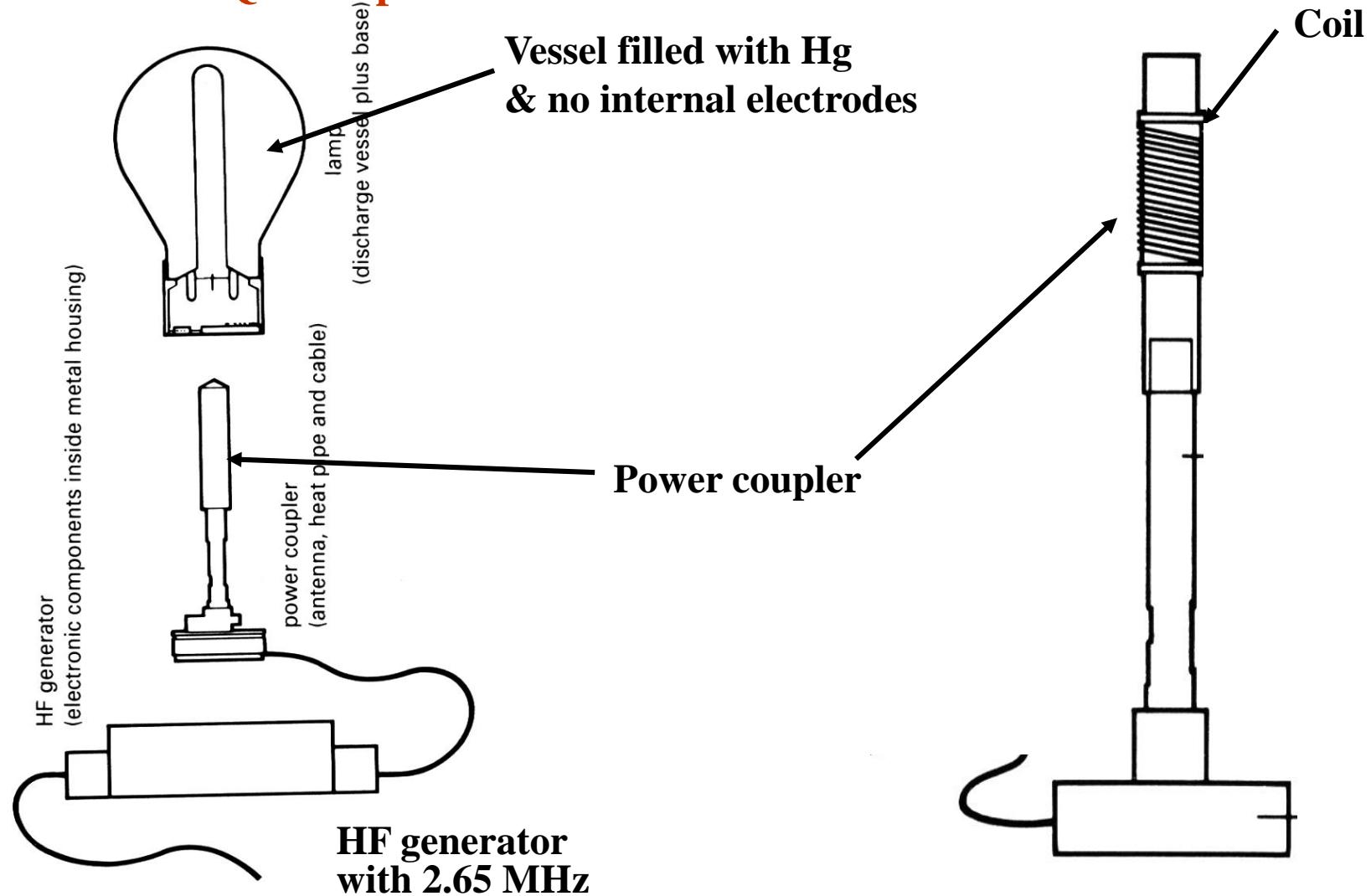
## 5.14 Inductively Driven Lamps

QL (Philips), Endura (Osram) lamps have an extremely long service life due to the lack of internal electrodes (light production as well as in conventional fluorescent lamps)



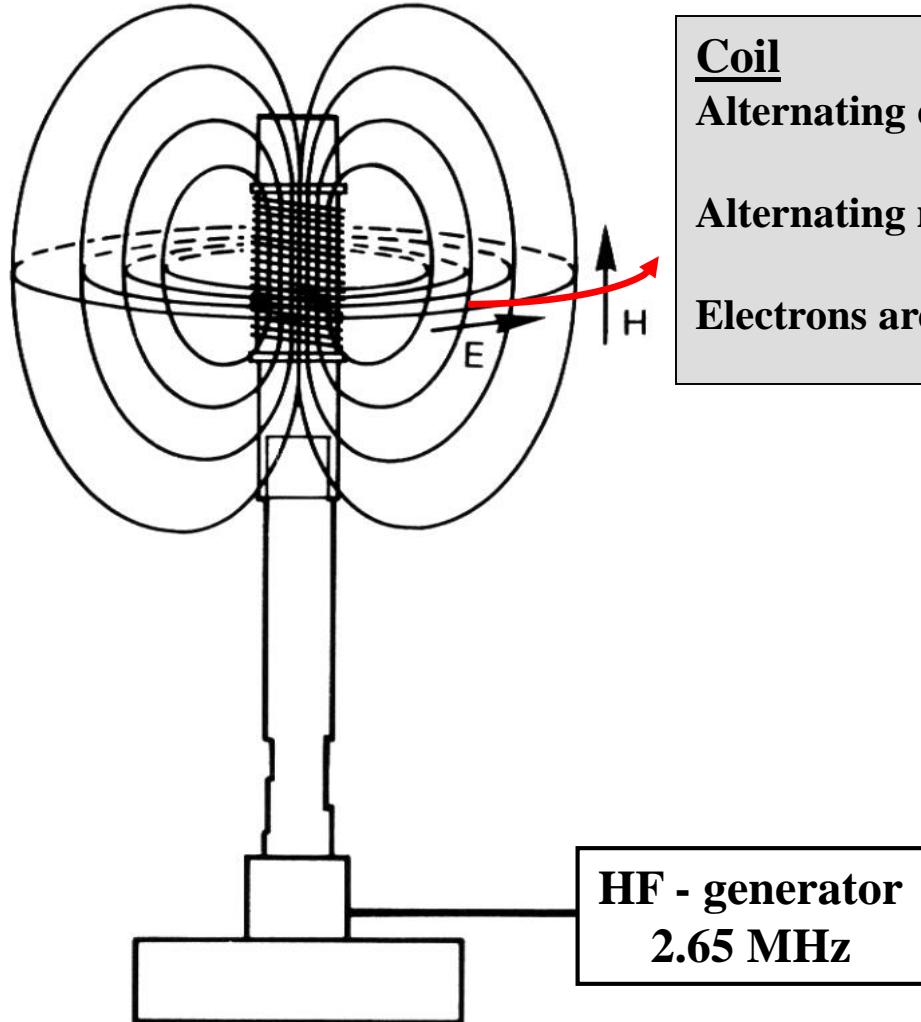
# 5.14 Inductively Driven Lamps

## Construction of a QL-lamp



# 5.14 Inductively Driven Lamps

## Energy in-coupling in a QL-lamp

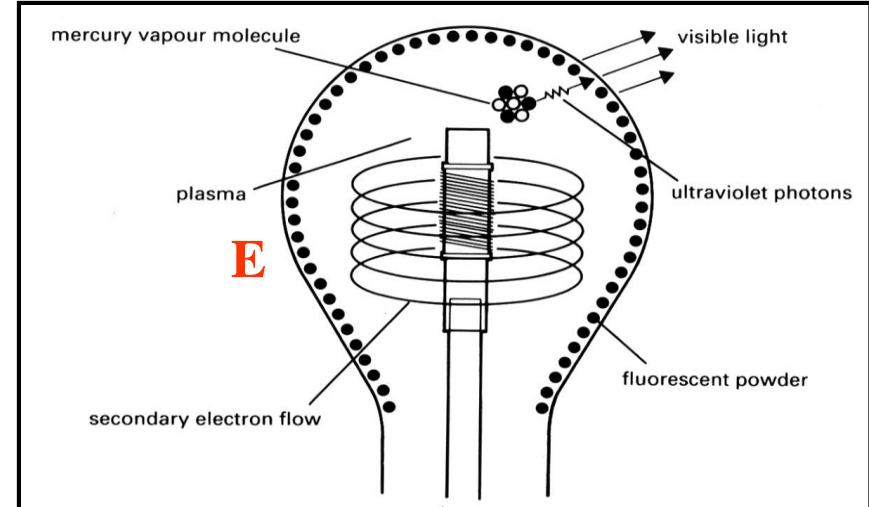


### Coil

Alternating electric field  $\Rightarrow$  alternating magnetic field (**H**)

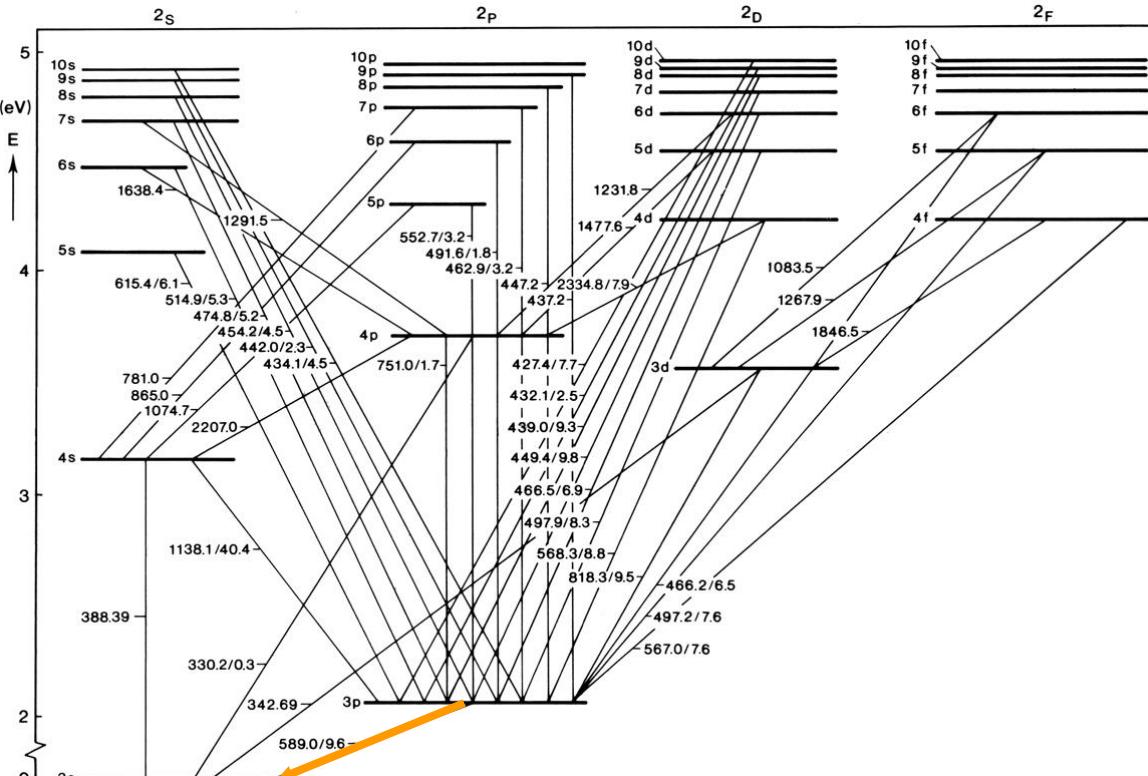
Alternating magnetic field (**H**)  $\Rightarrow$  alternating electric field (**E**)

Electrons are accelerated in this field **E**



# 5.15 Low Pressure Sodium Gas Discharge Lamps

## Energy level diagram of the Na atom

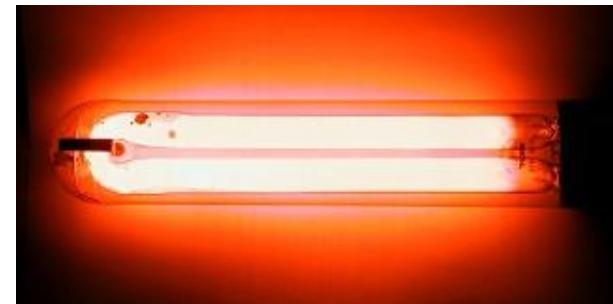
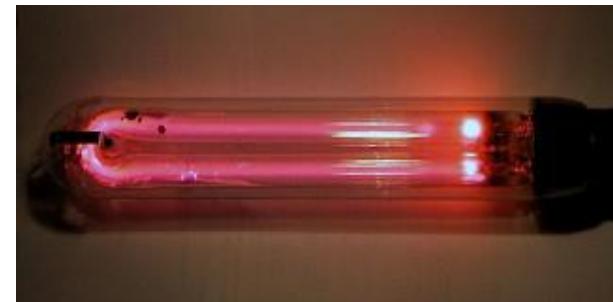


„Yellow Na-D lines“ (Fraunhofer line)

$[\text{Ne}]3\text{p}^1 (2\text{P}_{1/2, 3/2}) - [\text{Ne}]3\text{s}^1 (2\text{S}_{1/2})$

Interconfiguration transitions

Na low pressure discharge: Main emission lines at 589.0 nm, 589.6 nm, 781.0 nm, and 818.3 nm



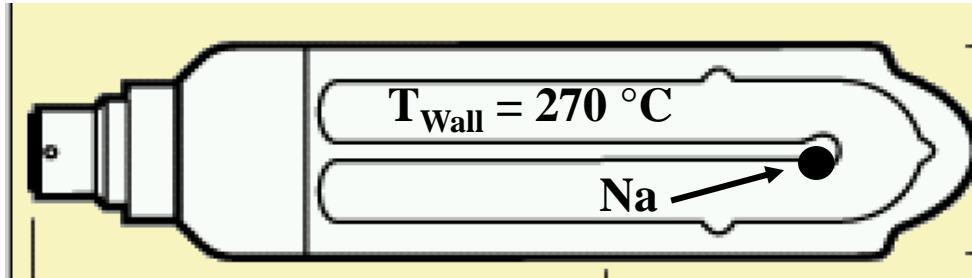
Time after ignition (sublimation of Na)

# 5.15 Low Pressure Sodium Gas Discharge Lamps

## General construction

- Filling element Na with operating pressure of 1 Pa
- Buffer gas: Argon or Krypton
- No phosphor
- Inner and outer glass envelope (bulb)

High luminous efficacy  $\sim 200 \text{ lm/W}$   
but poor color rendering  $R_a = -50$



Outer bulb with heat-reflective coating ( $\rightarrow \text{SnO}_2$ )

