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INSTYTUT METALURGII I INŻYNIERII MATERIAŁOWEJ
im. Aleksandra Krupkowskiego
Polskiej Akademii Nauk

Photovoltaic systems – theory and practice

Part 2

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Projekt nr WND-POWR.03.02.00-00-I043/16
Międzynarodowe interdyscyplinarne studia doktoranckie z zakresu nauk o materiałach z wykładowym językiem angielskim
Program Operacyjny Wiedza Edukacja Rozwój 2014-2020, Działanie 3.2 Studia doktoranckie

1. Introduction to photovoltaics

Basic information about the solar energy and photovoltaic Energy conversion

2. Technology of solar cells

The industrial technology of silicon solar cells and thin films solar cells

3. Emerging photovoltaics

Emerging materials and devices including dye-sensitized solar cell, organic solar cell, perovskite solar cell and quantum dot solar cell

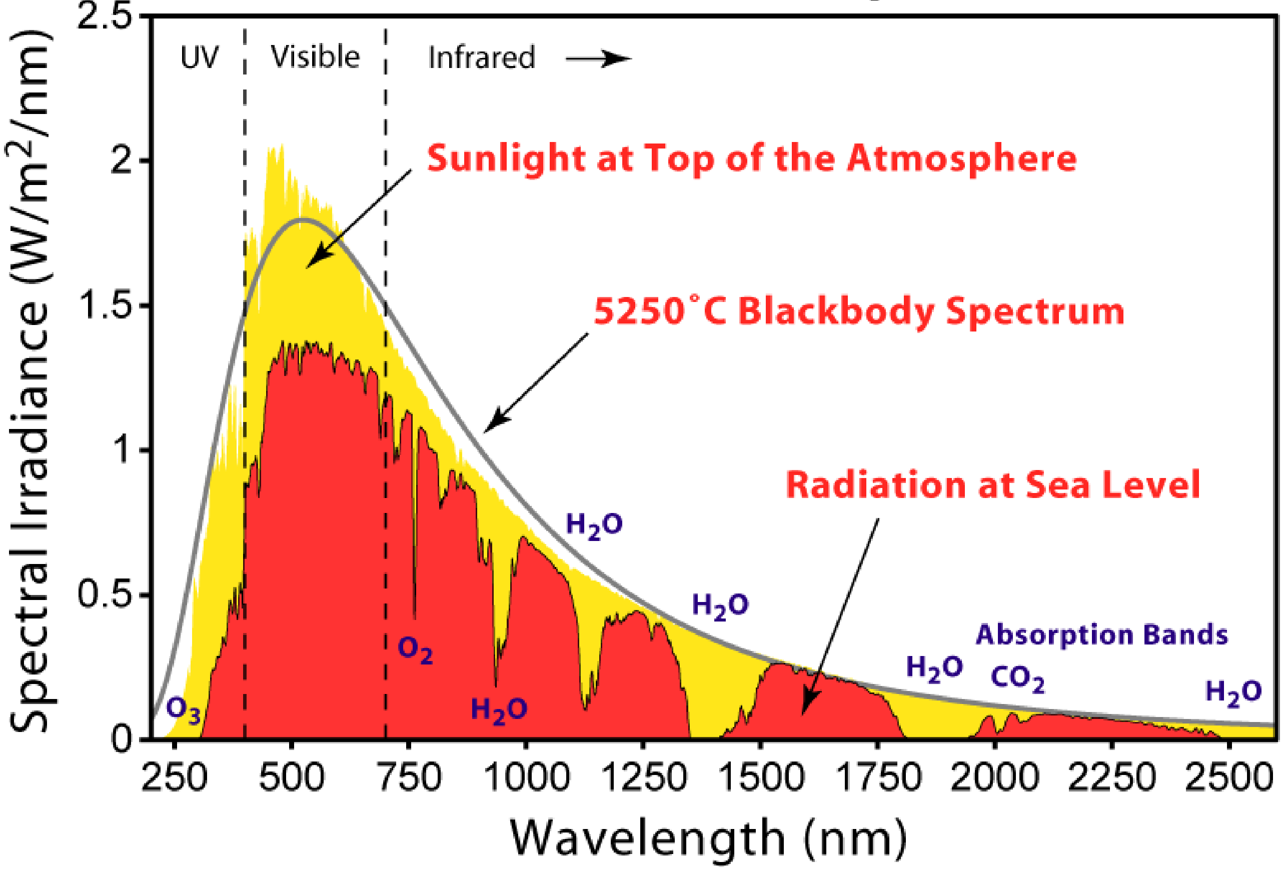
4. Photovoltaic systems

Technology, applications, economics of photovoltaic systems

Will solar power replace fossil fuels as the main energy source? ***Solar is the Energy of Tomorrow***
michio kaku solar energy

Solar radiation spectrum

Solar Radiation Spectrum



ttps://en.wikipedia.org/wiki/Air_mass_(solar_energy)#/media/File:Solar_Spectrum.png

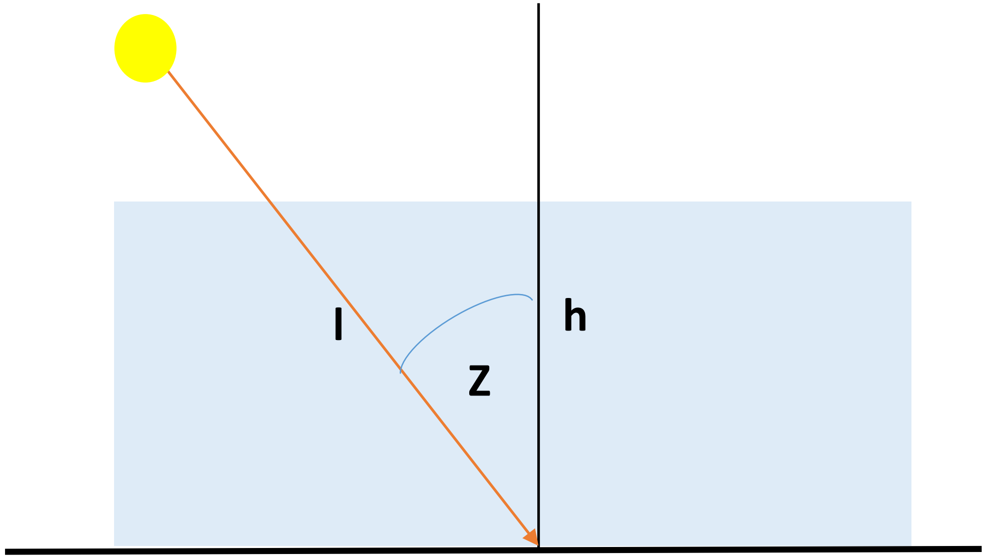
Dla Krakowa szerokość geograficzna ϕ = 50°03′41″N

Air Mass AM = l/h

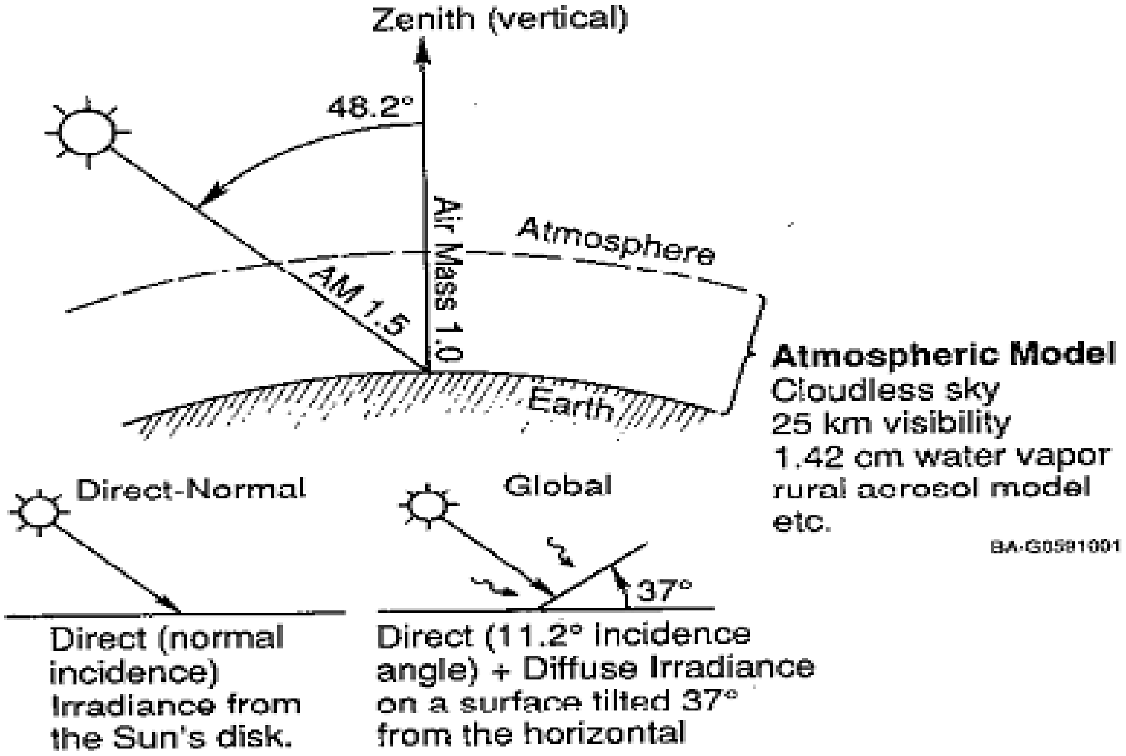
AM ≈ 1/cos(Z)
for Z ≤ 70°

Z: ϕ - 23°27′ ≤ Z ≥ ϕ - 23°27′
Z : 26°36′41′ ≤ Z ≥ 73°30′41′
AM: 1.1 ≤ Z ≥ 3.5

AM 1.5 = 1/cos(48.19)



Solar spectra

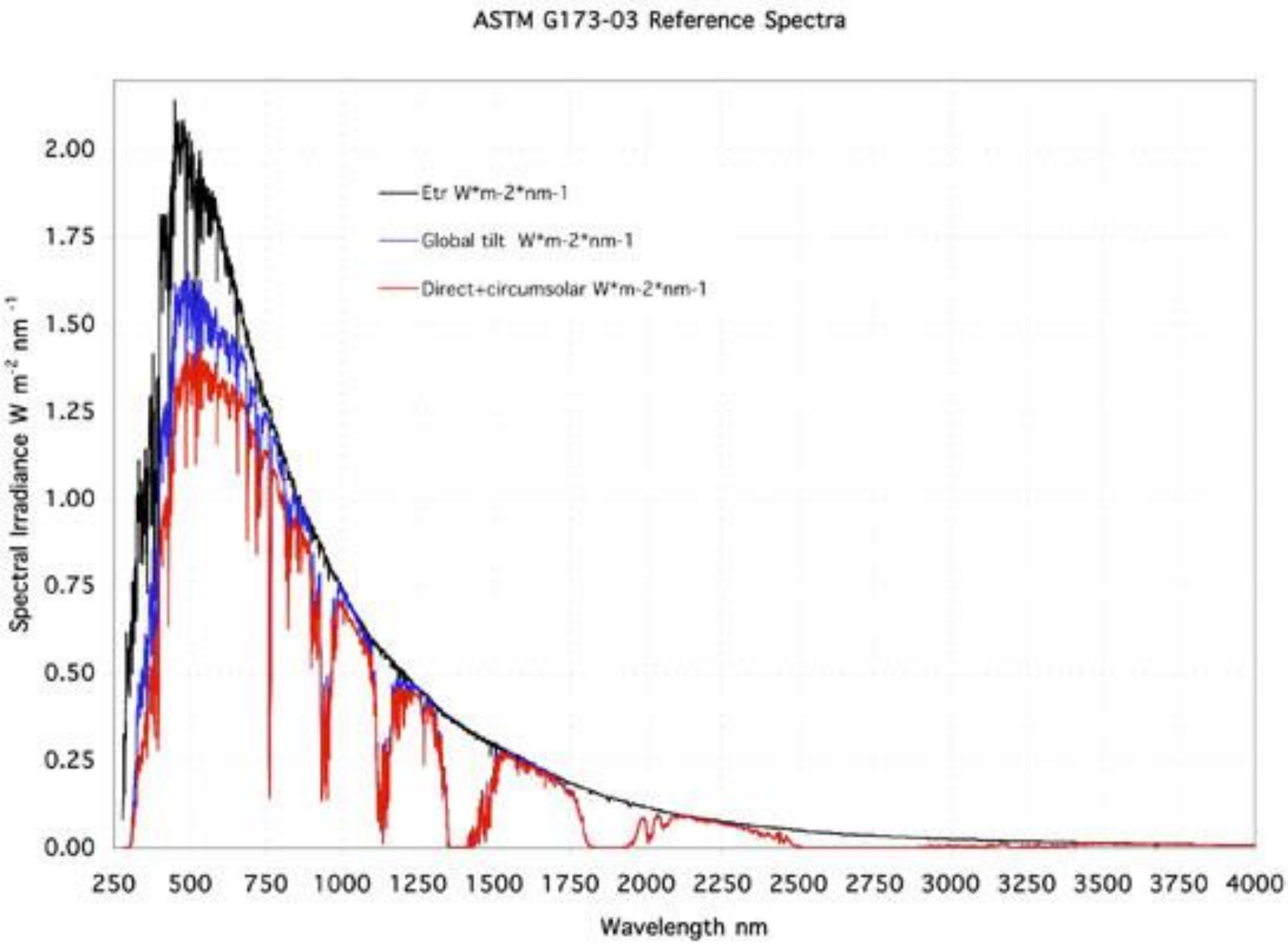


The geometry of the relative positions of the sun and the inclined plane of the PV module, used to simulate a standard distribution of solar radiation AM1.5.

The 37° slope of the sun-facing tilted surface was chosen to represent the average latitude of the 48 contiguous United States.

C. Riordan and R. Hulstrom, 1990 IEEE, 1085-1088

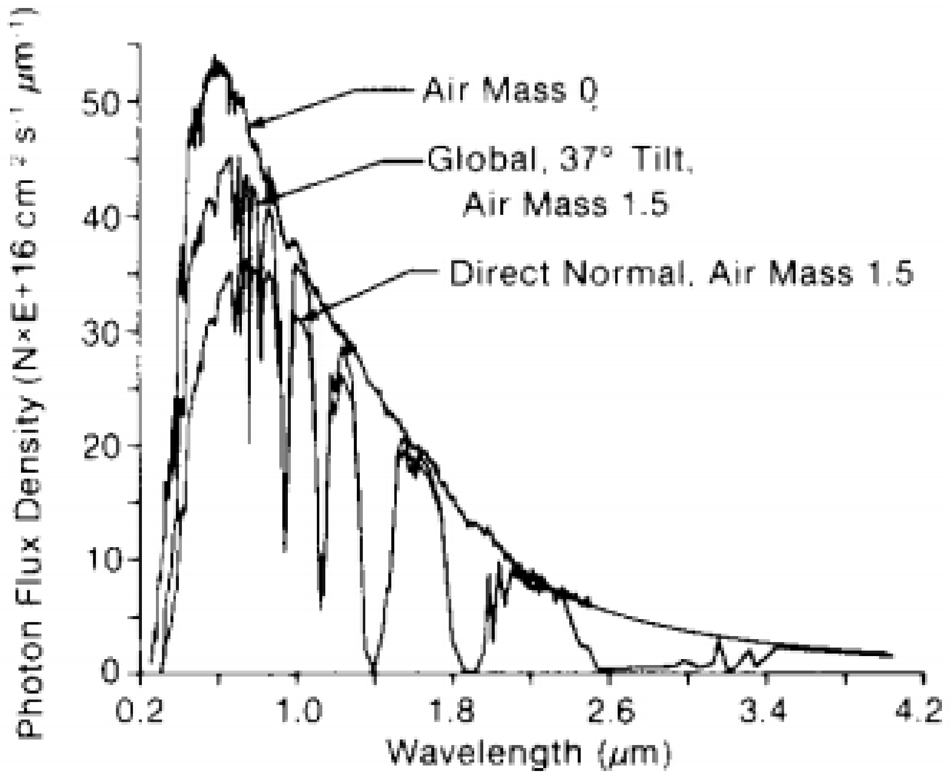
Solar spectra



AM0 extraterrestrial spectrum and AM1.5 direct normal (+ circumsolar) and global AM1.5G (ASTM G173-03 and IEC 60904-3: 2008). The references spectra calculated by SMARTS v 2.9.2 program

source: http://rredc.nrel.gov/solar/spectra/am1.5/

Solar spectra



Photon flux density vs. wavelenght λ

$$N_{ph}(\lambda) = E(\lambda)\frac{\lambda}{hc}$$

where N_{ph} = the number of photons per wavelength λ interval , E(λ) spectral irradiance, h = 6.626176 x 10^{-34} J s , c = 2.99792458 x 10^{14} μm s^{-1}

R. Hulstorm, R. Bird and C. Riordan, Solar Cells, 15(1985) 365-391.

Standard Test Conditions STC

Solar spectrum AM 1.5G (ASTM G173-03)

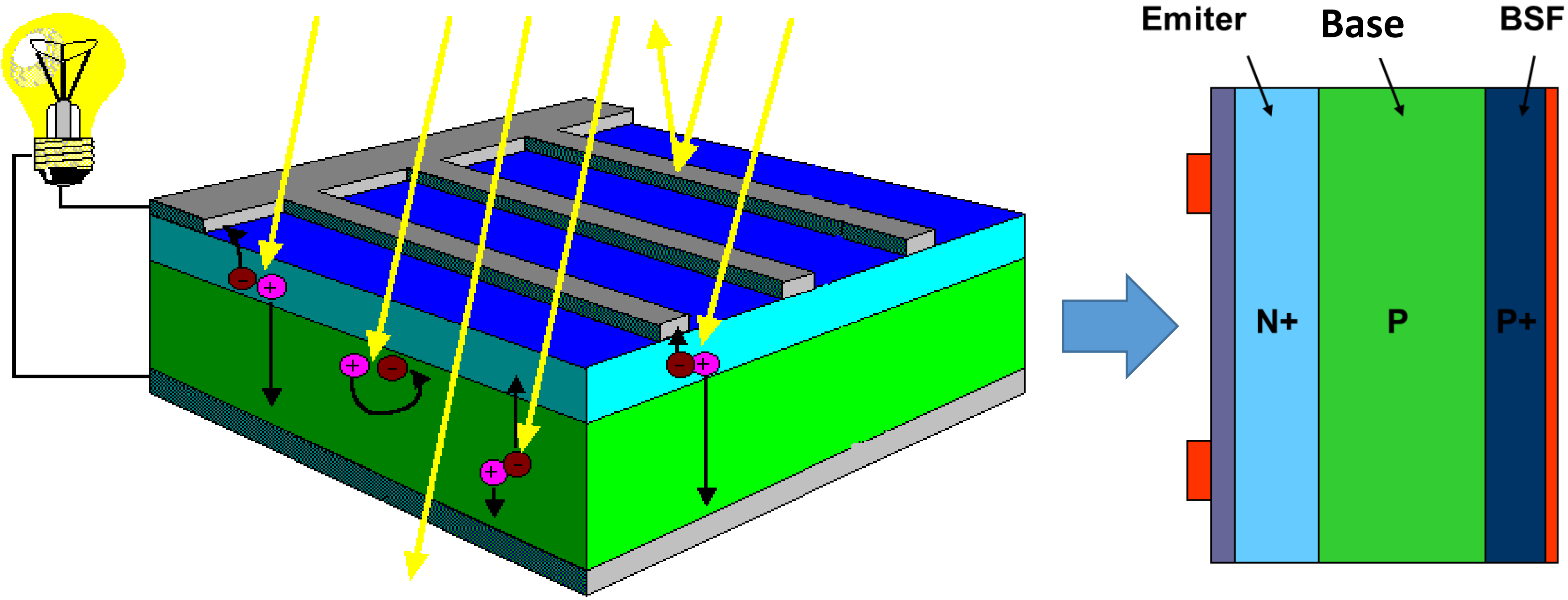
$P_{in} = 1000 \text{ W/cm}^2$

$T = 25^oC$

Solar cells

Photovoltaic effect

Si solar cell

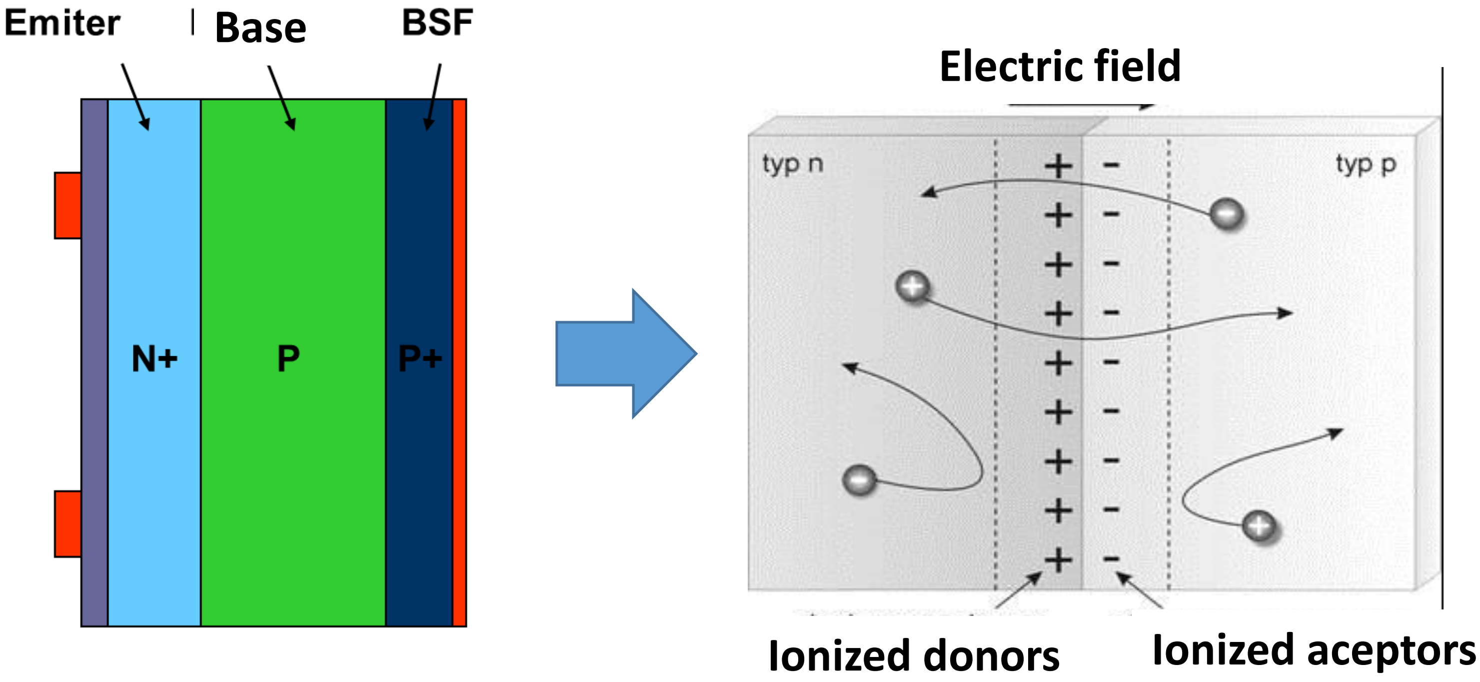


ionized donors

Photovoltaic effect

Junction n-p. The existence in photovoltaic cell of two areas with different types of conductivity creates a spatial charge in which there is a strong electric field. This field acts as a filter to pass electrons from area p to n and holes from area n to p, as shown in the figure.

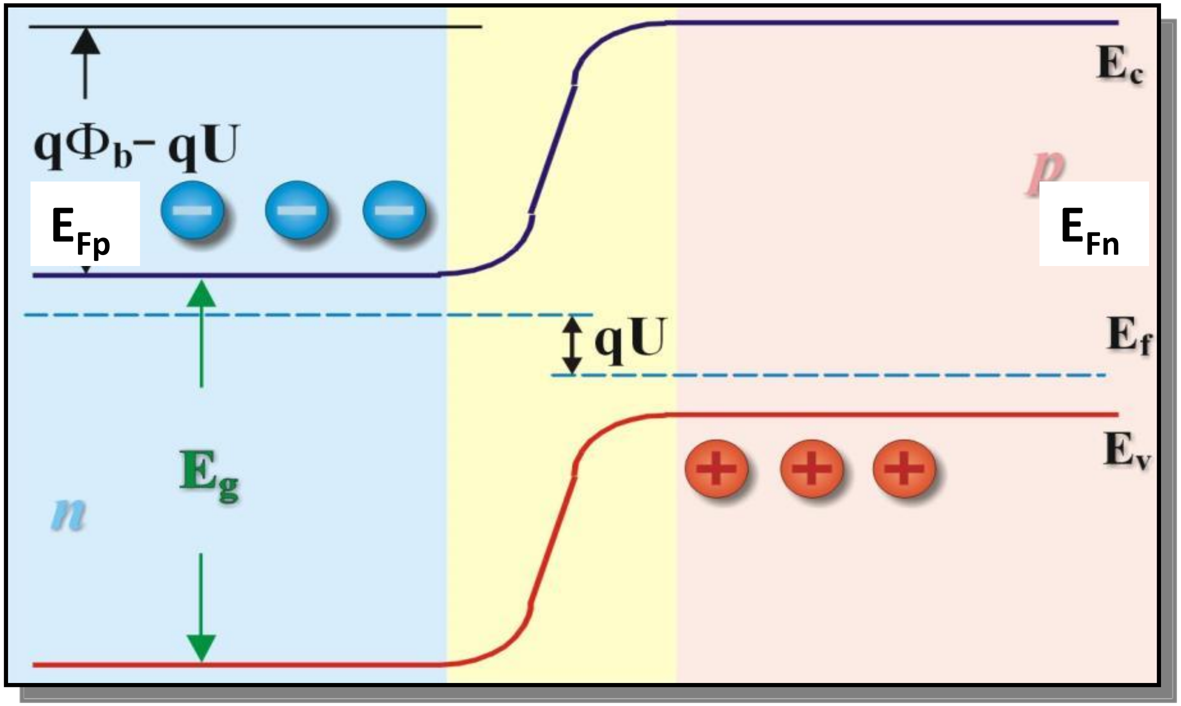
$$I = I_0\left[\exp\left(\frac{V}{V_t}\right) - 1\right]$$



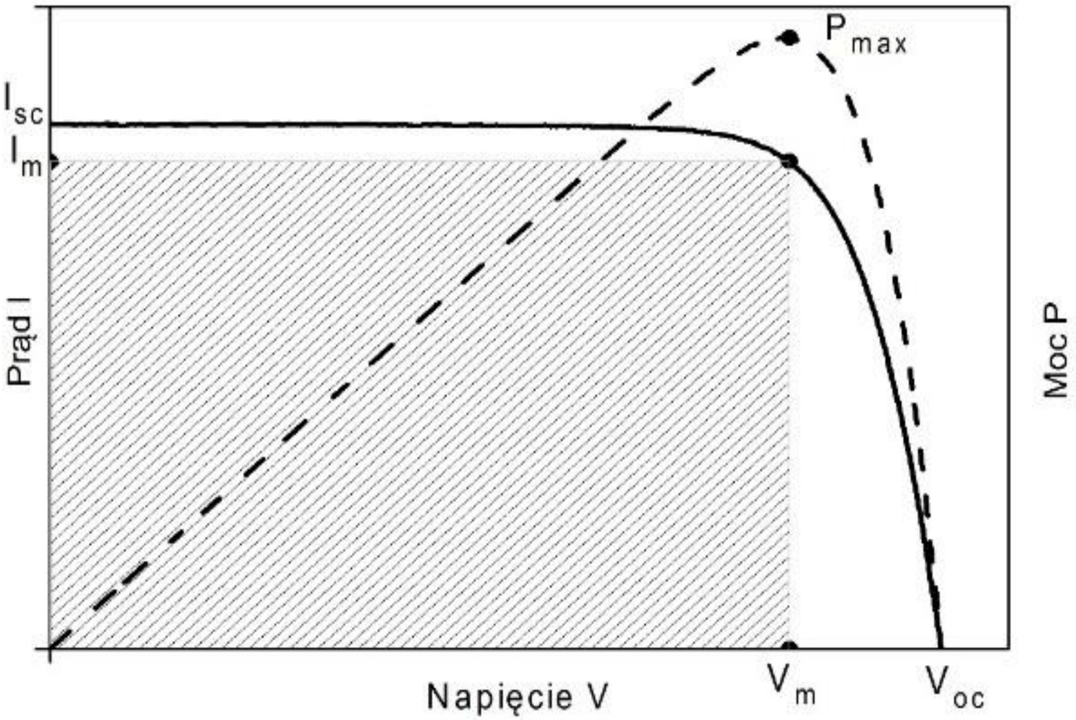
Photovoltaic effect

If radiation with photon energy greater than the forbidden width falls on the semiconductor, it is absorbed and its energy is used to excite the electron from the valence band to the conductivity band.

$$h\nu \geq E_g$$



Current - voltage characteristic and the power of the solar cell



I_{sc}	**Short-circuit current**
V_{oc}	**Open circuit voltage,**
P_{max}	**Maximum power point (mpp)**
I_m	**Current at the mpp**
V_m	**Voltage at maximum mpp**

Fill Factor (FF):

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

Power Conversion Efficiency (PCE or η) :

$$\eta = \frac{I_m V_m}{A P_{in}} \times 100\% = \frac{FF J_{sc} V_{oc}}{P_{in}} \times 100\%$$

Measurement for STC: AM 1.5, P_{in}= 1000 W/m^2, T = 25^o

Ideal solar cell

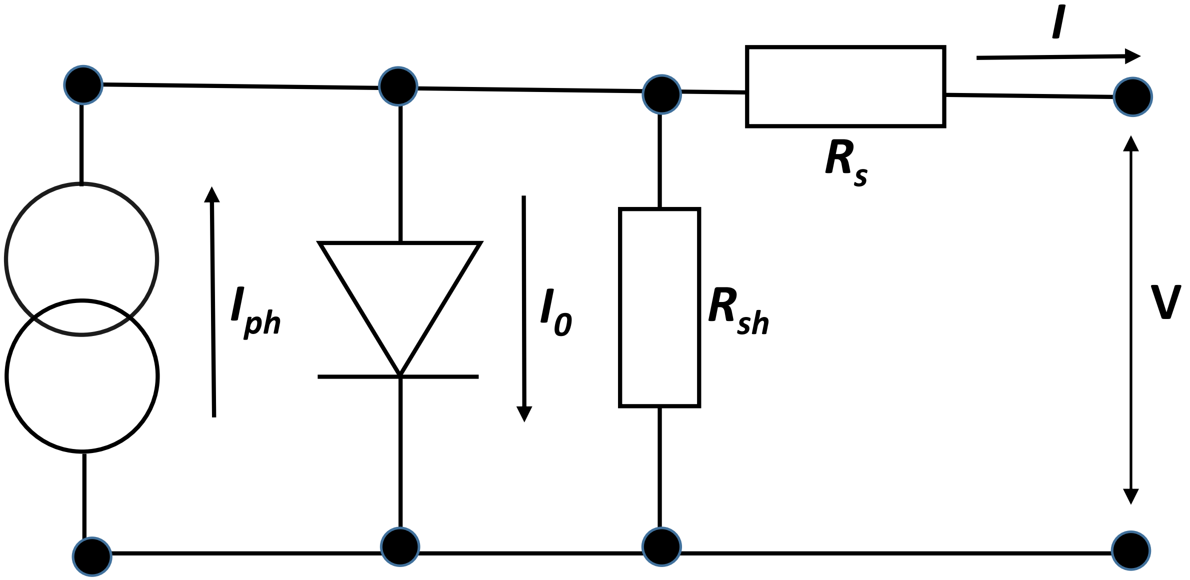
An ideal solar cell with an n - p connector can be presented as a current source connected in parallel with a rectifying diode, whose current-voltage characteristic (I-V) is described by the Shockley equation:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V}{V_t} \right) - 1 \right]$$

where: I_{ph} photocurrent, I_0 – dark saturation current, a V_t = kT/q thermal voltage (V_t =kT/q ~25,69 mV for T = 298,15 K (25^{o} C))

$$V_{oc} = \frac{kT}{q} \ln \frac{I_{sc} + I_0}{I_0} \approx \frac{kT}{q} \ln \frac{I_{sc}}{I_0}$$

Real solar cell



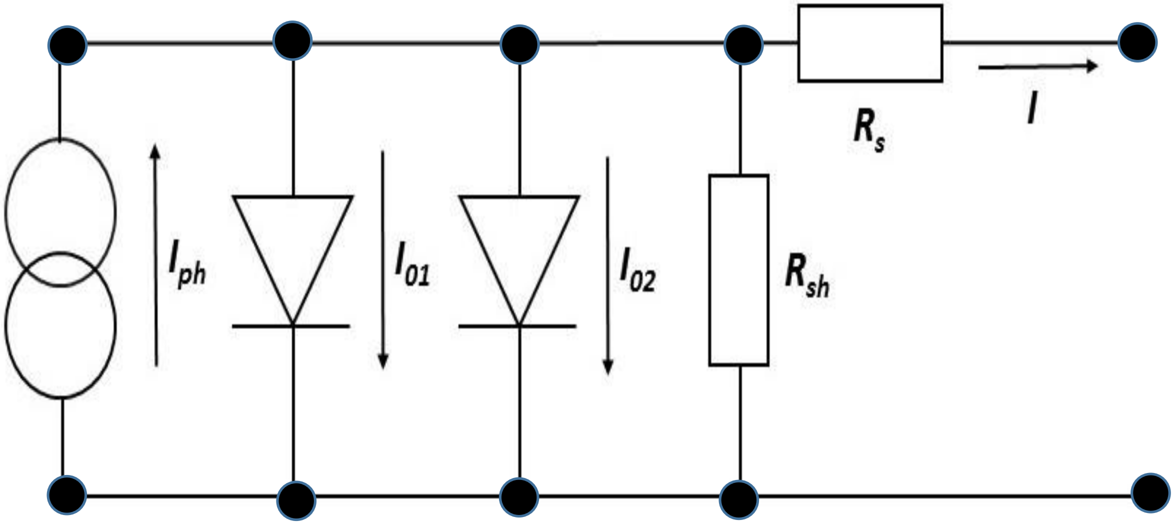
$$I = I_{ph} - I_0\left[\exp\left(\frac{V + I \cdot R_s}{nV_t}\right) - 1\right] - \frac{V + I \cdot R_s}{R_{sh}}$$

$$J = J_{ph} - J_0\left[\exp\left(\frac{V + J \cdot r_s}{nV_t}\right) - 1\right] - \frac{V + J \cdot r_s}{r_{sh}}$$

I_{ph} - photocurrent
R_s - serial resistance
R_s - parallel resistance
n - diode quality parameters
I_0 - dark saturation currents

$r_s = R_s \times A$ i $r_{sh} = R_{sh} \times A$ specific resistances in $\Omega \times \mathrm{cm}^2$.

Real solar cell

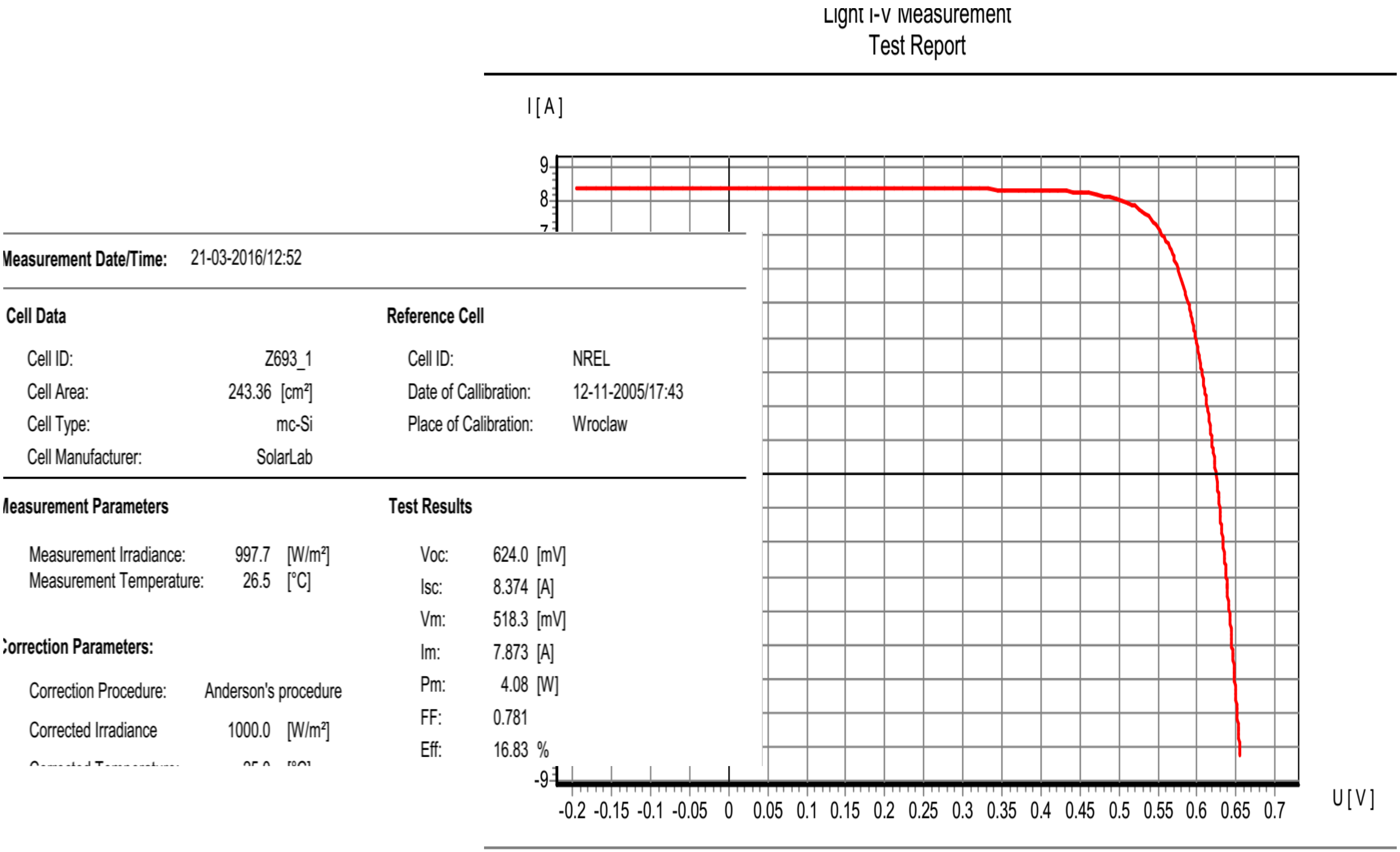


$$I = I_{ph} - I_{01}\left[\exp\left(\frac{V + I \cdot R_s}{n_1 V_t}\right) - 1\right] - I_{02}\left[\exp\left(\frac{V + I \cdot R_s}{n_2 V_t}\right) - 1\right] - \frac{V + I \cdot R_s}{R_{sh}}$$

$$J = J_{ph} - J_{01}\left[\exp\left(\frac{V + J \cdot r_s}{n_1 V_t}\right) - 1\right] - J_{02}\left[\exp\left(\frac{V + J \cdot r_s}{n_2 V_t}\right) - 1\right] - \frac{V + J \cdot r_s}{r_{sh}}$$

n1, n2 diode quality parameters, I_{01}, I_{02} – **dark saturation currents .**

Parameters of solar cells



Light I-V Measurement
Test Report

Measurement Date/Time: 21-03-2016/12:52

Cell Data

Cell ID:	Z693_1
Cell Area:	243.36 [cm²]
Cell Type:	mc-Si
Cell Manufacturer:	SolarLab

Reference Cell

Cell ID:	NREL
Date of Callibration:	12-11-2005/17:43
Place of Calibration:	Wroclaw

Measurement Parameters

Measurement Irradiance:	997.7	[W/m²]
Measurement Temperature:	26.5	[°C]

Correction Parameters:

Correction Procedure:	Anderson's procedure	
Corrected Irradiance	1000.0	[W/m²]
Corrected Temperature:	25.0	[°C]

Test Results

Voc:	624.0	[mV]
Isc:	8.374	[A]
Vm:	518.3	[mV]
Im:	7.873	[A]
Pm:	4.08	[W]
FF:	0.781	
Eff:	16.83	%

Spectral response (SR) is the ratio of the current generated by the solar cell to the power incydent on the solar cell

$$SR(\lambda) = \frac{I_{SC}(\lambda)}{P(\lambda)}$$

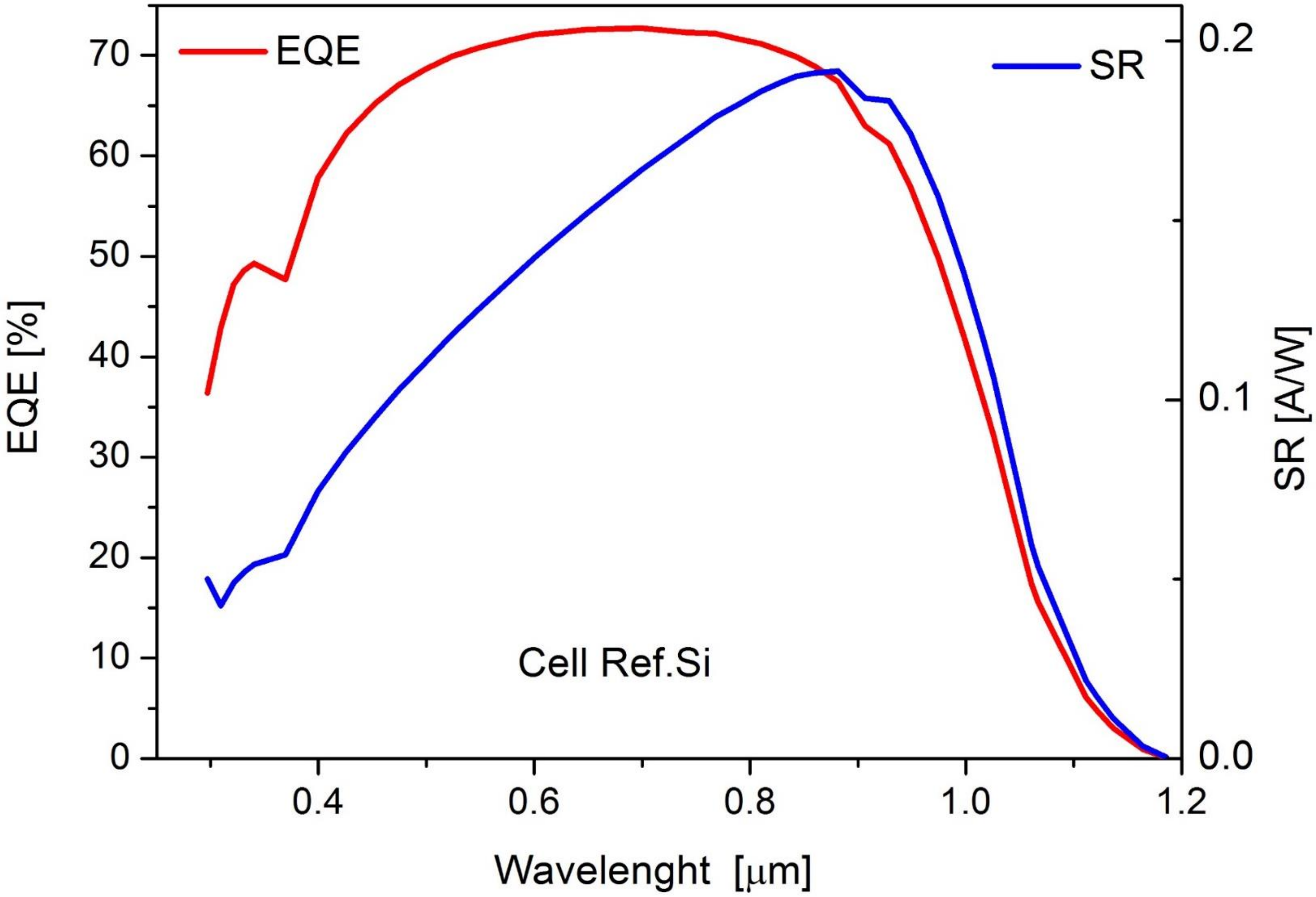
External Quantum Efficiency (EQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy *shining on the solar cell from outside* (incident photons).

$$EQE(\lambda) = SR(\lambda)\frac{hc}{q\lambda}$$

Internal Quantum Efficiency (IQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy that shine on the solar cell from outside *and* are absorbed by the cell.

$$IQE(\lambda) = EQE(\lambda)\frac{1}{1-R(\lambda)}$$

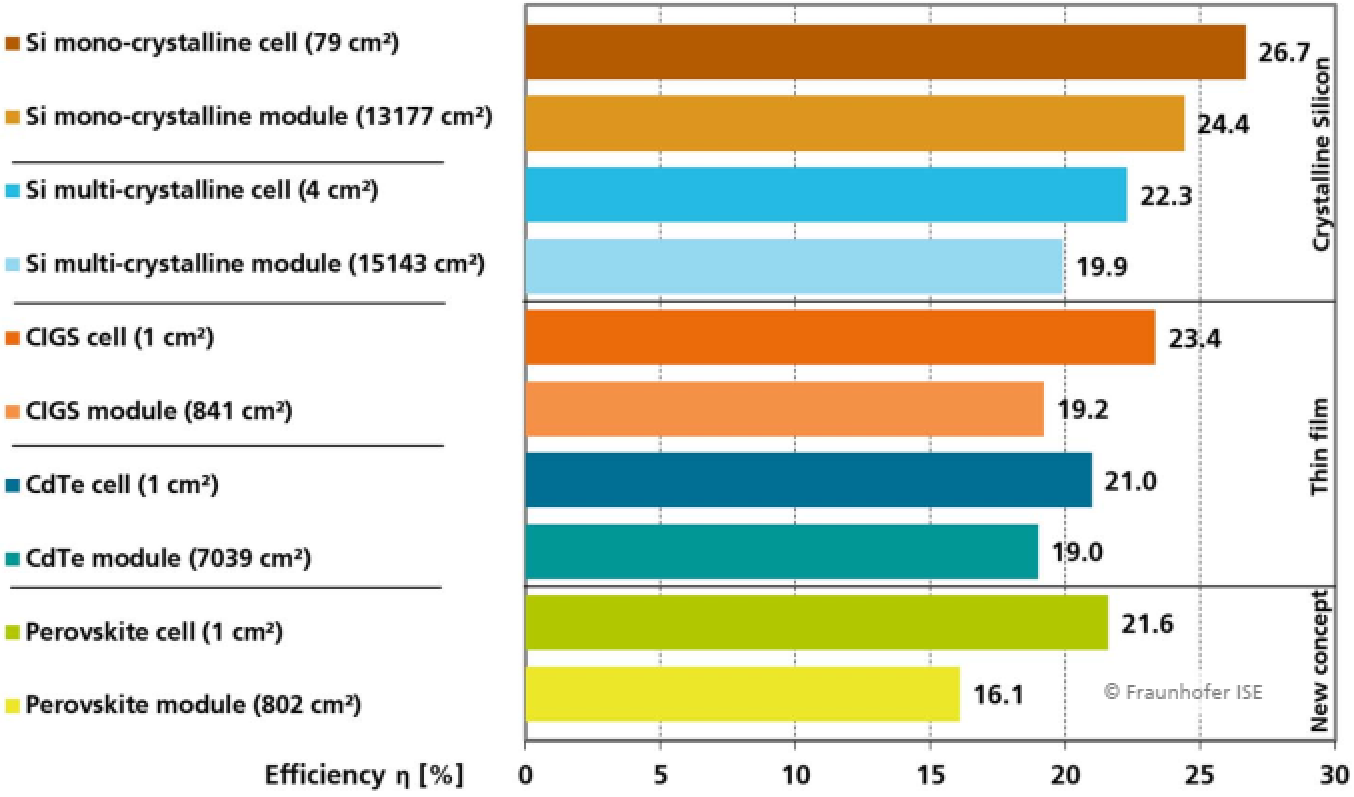
$$J_{sc} = q\int_{0}^{hc/E_g} EQE(\lambda)N_{ph}(\lambda)d\lambda$$



The external quantum efficiency EQE and the spectral response SR of the reference Ref. Si (005-2013) silicon cell measured in ISE Frauhofer

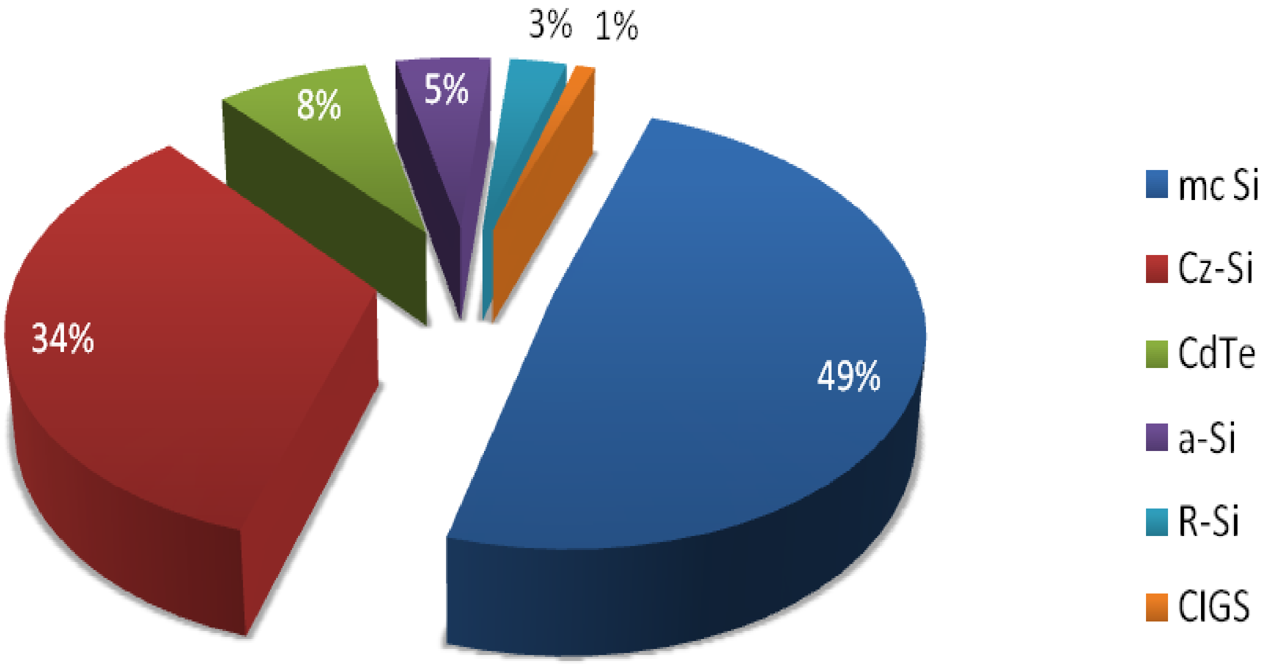
Solar cells

Efficiency Comparison of Technologies:
Best Lab Cells vs. Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables (Version 55), Progress in PV: Research and Applications 2019. Graph: PSE GmbH 2020

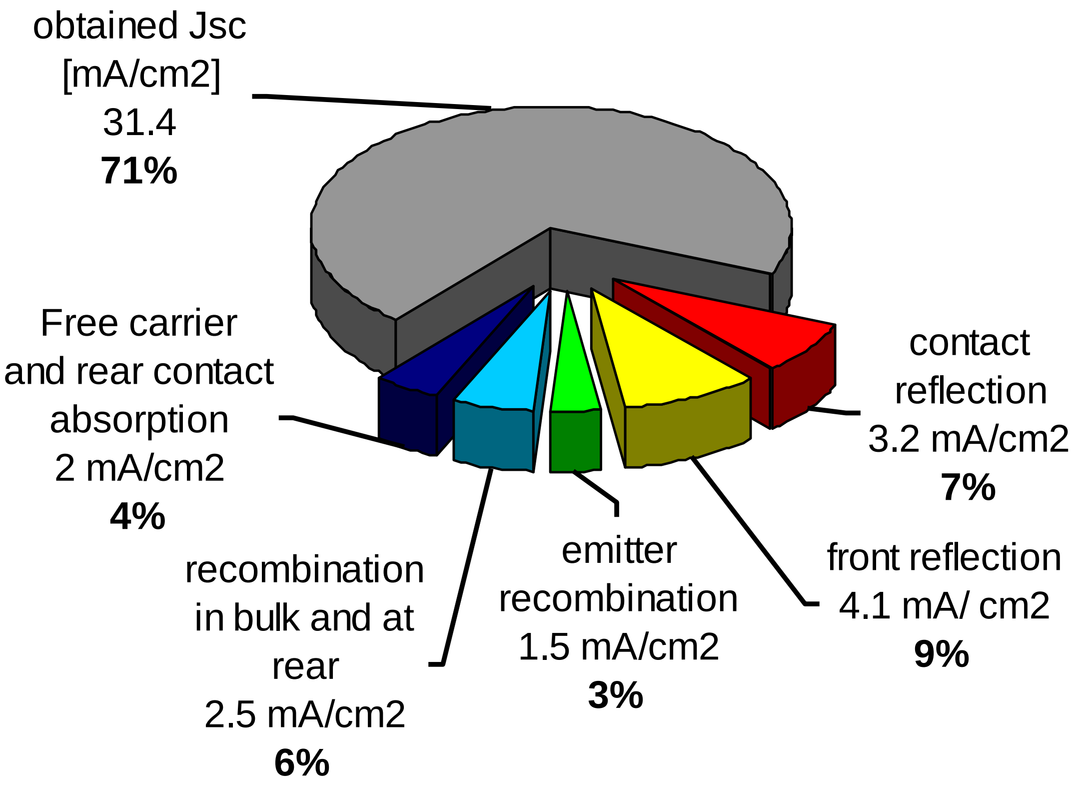
Proportional share of a given solar cell type in the total solar cell production of global photovoltaics in 2008



Silicon solar cells

Silicon solar cells

Industrial mc-Si solar cell losses



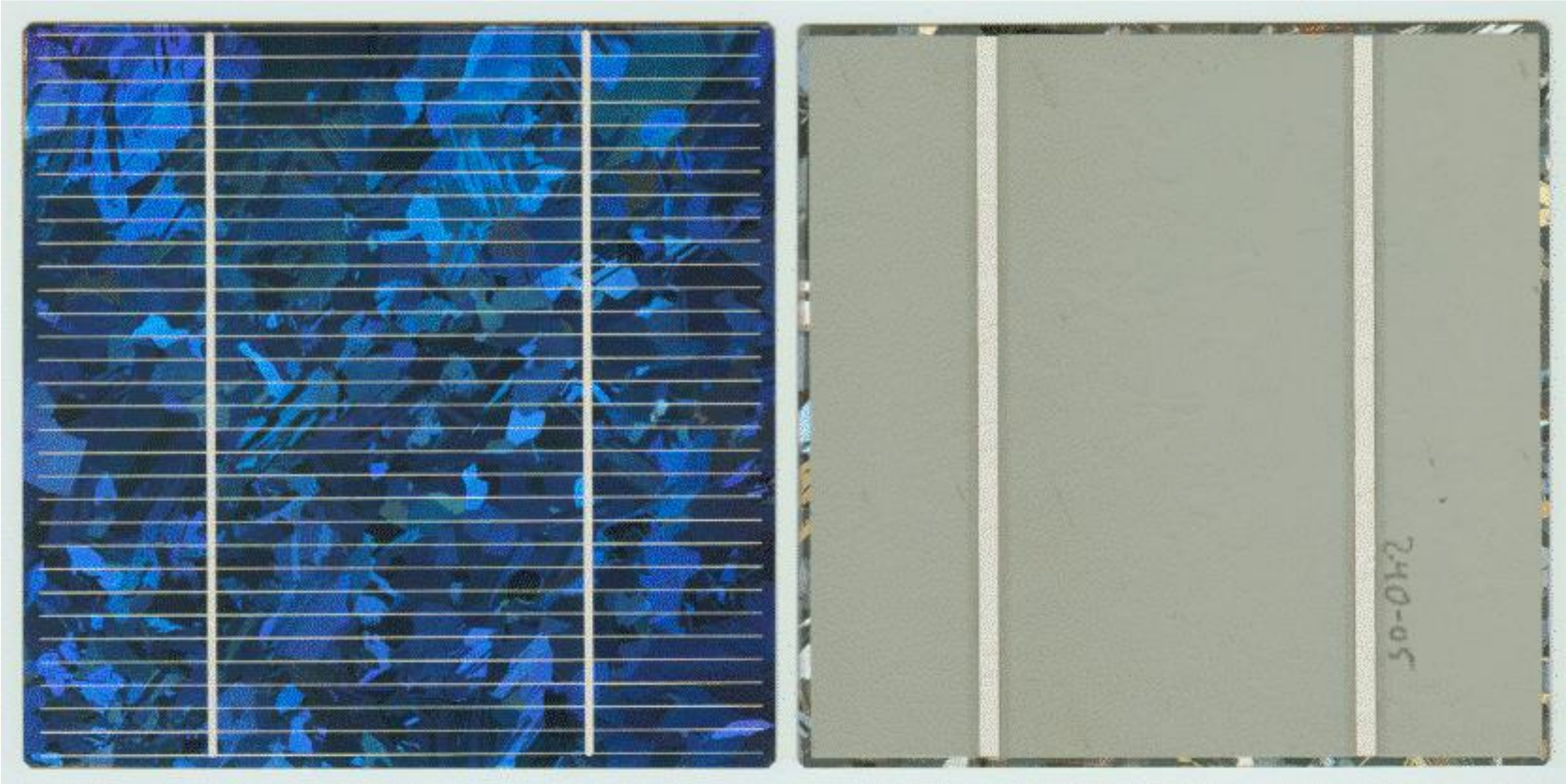
- Losses by front reflection dominant !

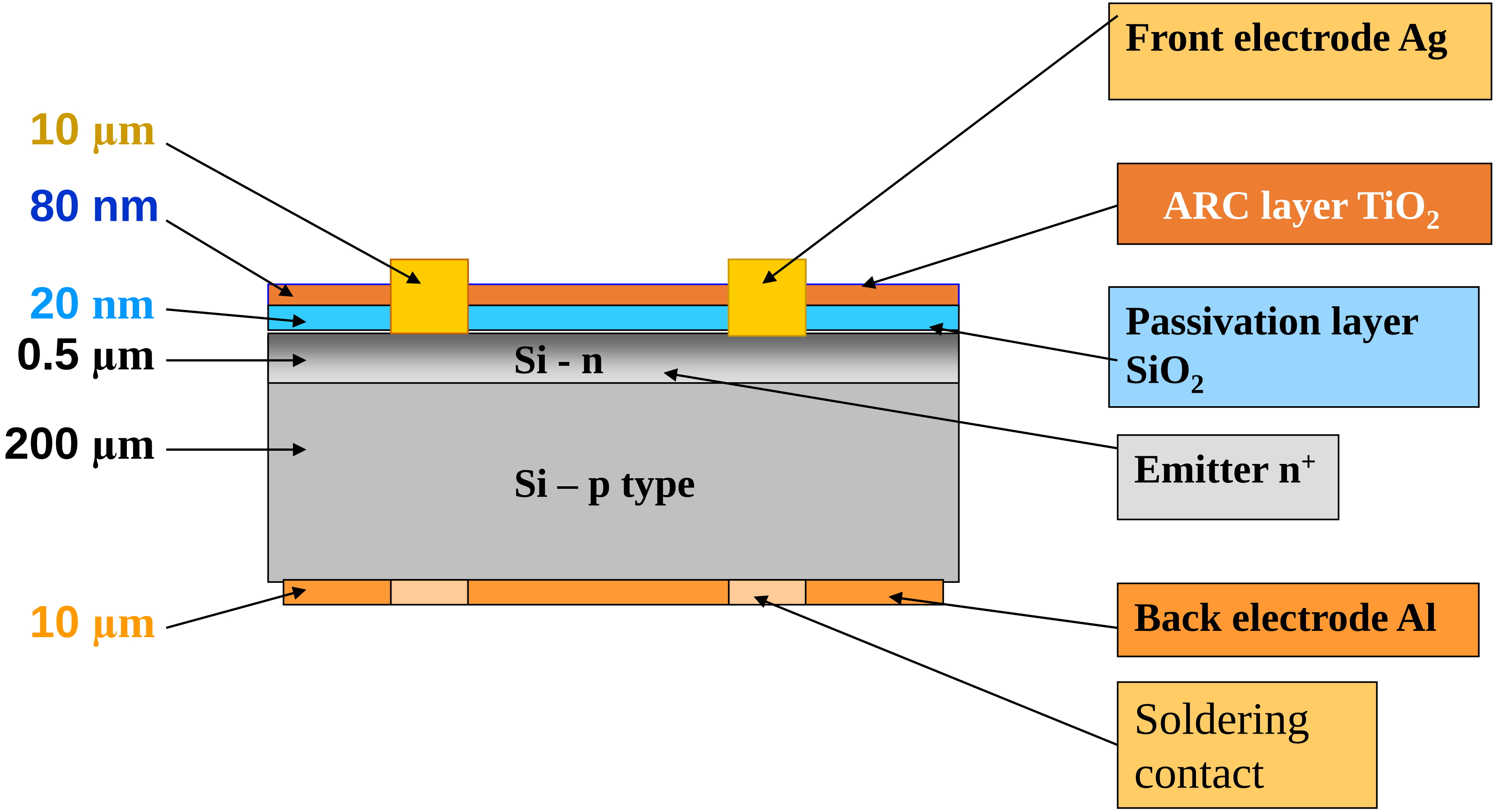
Silicon solar cells

Crystalline Silicon Solar Cell on Multicrystalline Silicon

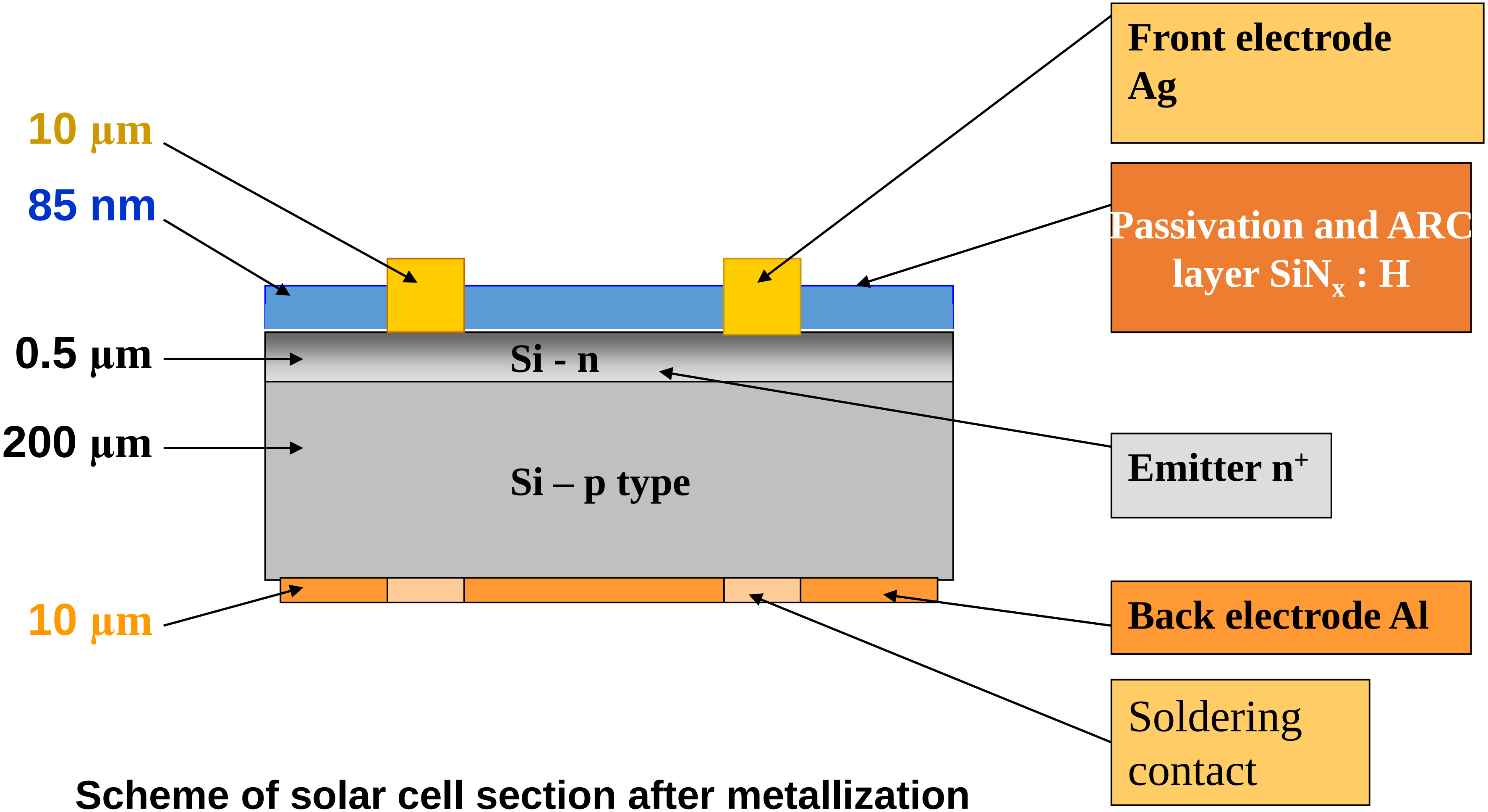
Front

Back





Scheme of solar cell section after metallization with TiO_2 as ARC layer



10 µm

85 nm

0.5 µm

200 µm

10 µm

Si - n

Si – p type

Front electrode Ag

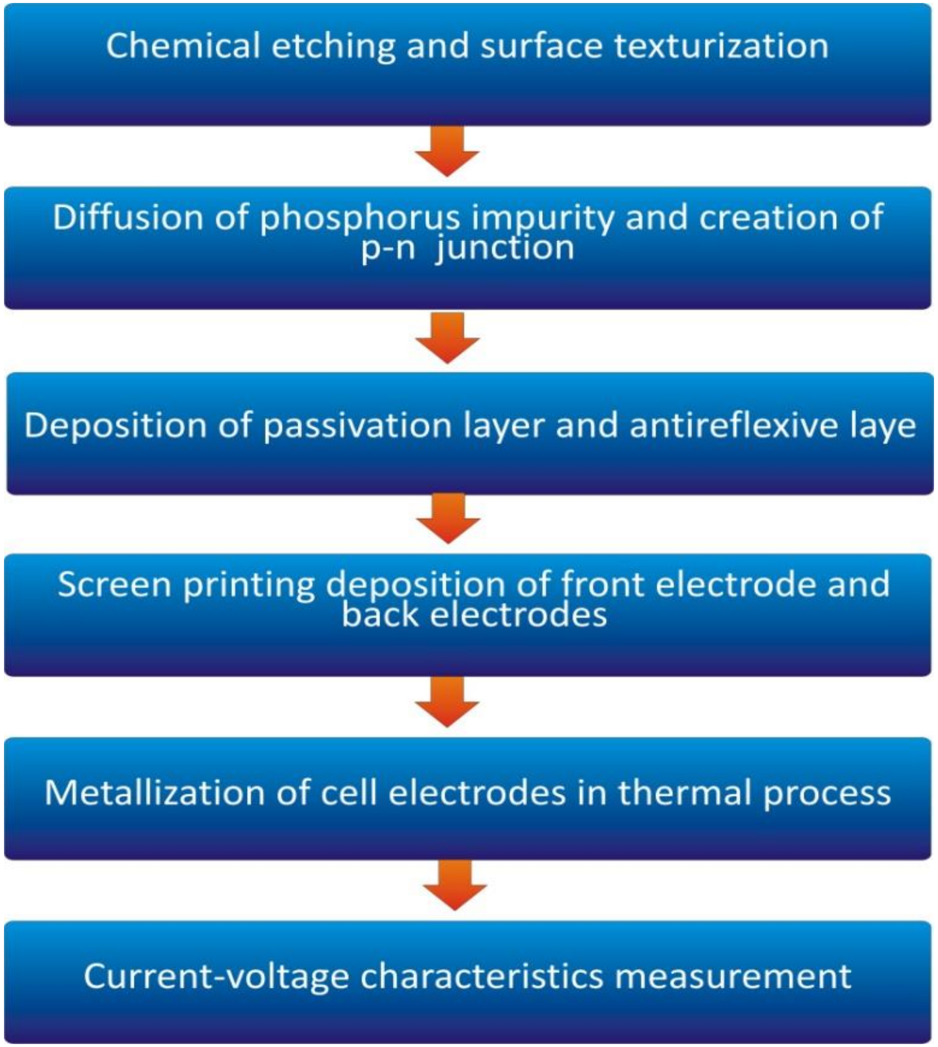
Passivation and ARC layer SiN_x : H

Emitter n^+

Back electrode Al

Soldering contact

Scheme of solar cell section after metallization with SiN_x:H as ARC layer



Chemical etching and surface texturization

Diffusion of phosphorus impurity and creation of p-n junction

Deposition of passivation layer and antireflexive laye

Screen printing deposition of front electrode and back electrodes

Metallization of cell electrodes in thermal process

Current-voltage characteristics measurement

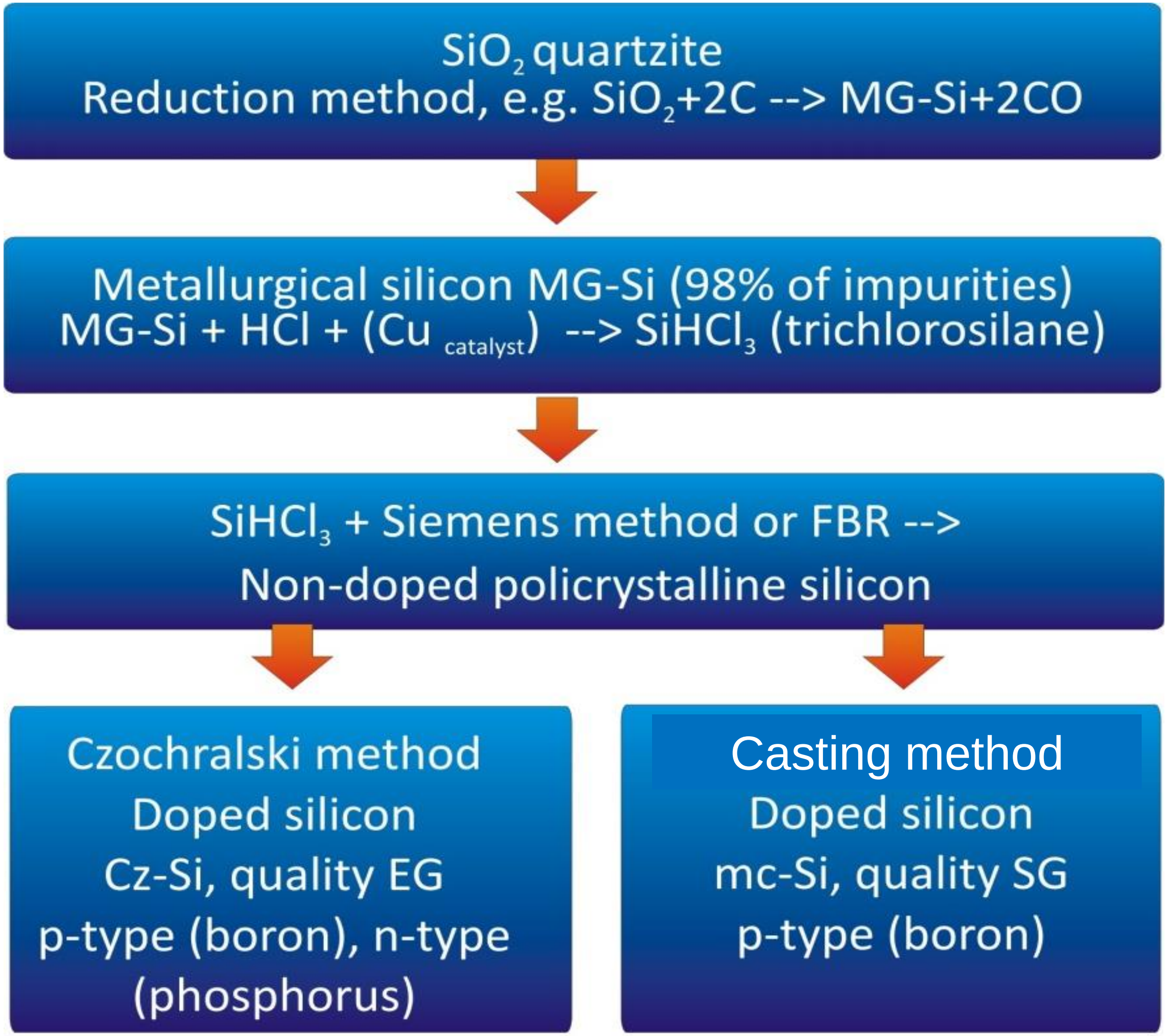
Scheme of the technological process of silicon solar cell production

The way from SiO_2 to PV system

Where from the crystalline silicon came ?

The PV sector involves the production of polycrystalline silicon (mc-Si) type p by means of casting, which is often called the multicrystalline silicon due to the big sections of its grains. Crystalline silicon used in photovoltaics is referred to as the SG (*Solar Grade*) silicon and its quality is lower than that which is used in electronics and which is designated as the EG (*Electronic Grade*) silicon, in which an exemplary value of carbon equals 0,1 ppm ($5\text{x}10^{15}$ atoms/cm^3) and the oxygen content is 0,01 ppm.

Scheme of the production process of crystalline silicon for the IC and PV sectors



SiO_2 quartzite

Reduction method, e.g. SiO_2+2C --> MG-Si+2CO

Metallurgical silicon MG-Si (98% of impurities)

MG-Si + HCl + ($Cu_{catalyst}$) --> $SiHCl_3$ (trichlorosilane)

$SiHCl_3$ + Siemens method or FBR -->

Non-doped policrystalline silicon

Czochralski method

Doped silicon

Cz-Si, quality EG

p-type (boron), n-type (phosphorus)

Casting method

Doped silicon

mc-Si, quality SG

p-type (boron)

Three of the biggest producers of non-doped polycrystalline silicon which are Hemlock (USA), Wacker (Germany) i Tokuyama (Japan) apply the **Siemens method**. The polycrystalline silicon, 20 cm in diameter, is created in a trichlorosilane reactor on a crystalline silicon bar, 10 mm in diameter, heated up to 1100 ^{o}C.

This process takes a few days and requires the provision of 200 kWh electric energy in order to obtain 1 kg of silicon.

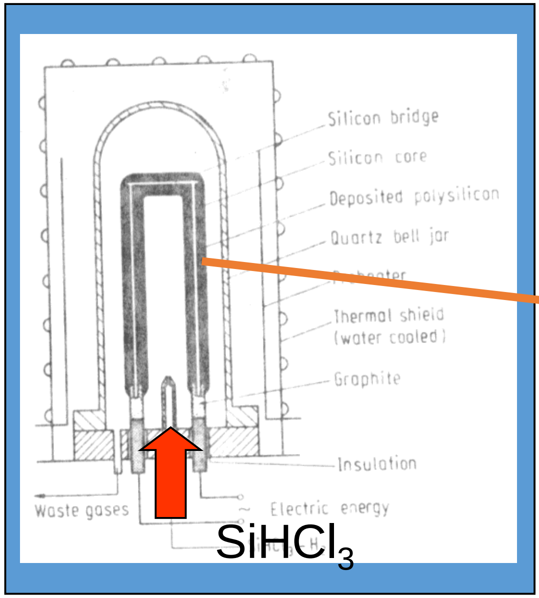
In an alternative method, **FBR** *(Fluidised Bad Reactor), the polycrystals of silicon are created in the form of granulate, in a continuous process* with $SiHCl_3$ at the temperature of 1000 ^{o}C, or SiH_4 at the temperature of 700 ^{o}C.

The method which allows for a further purification of the mc-Si silicon and the obtaining of mono-crystalline silicon is zone melting, in which the FZ (*Float Zone) silicon is* obtained.

The basic method of the Si mono-crystal production for the electronic industry is the Czochralski method.

The SIEMENS method

Scheme of the Siemens method



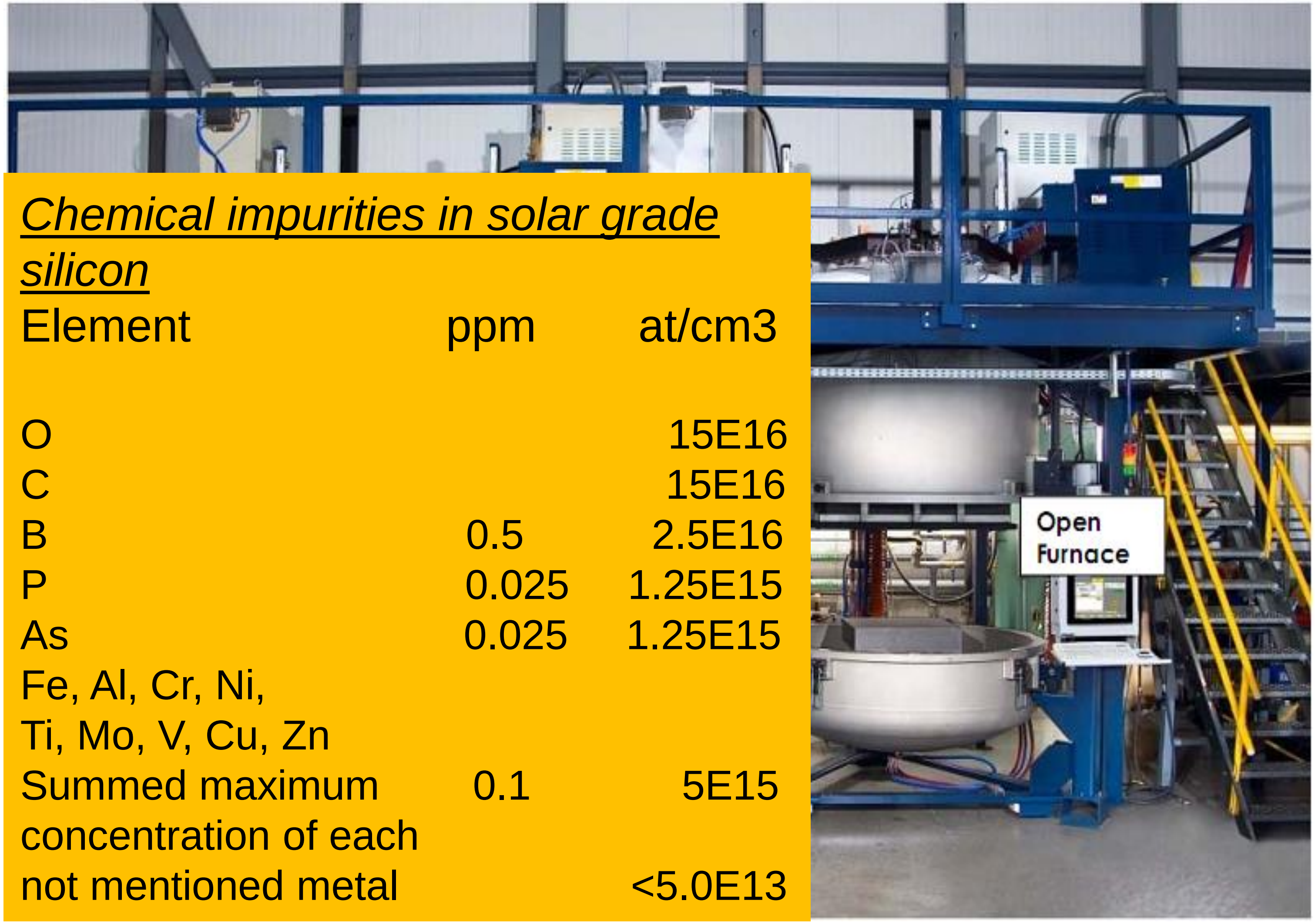
J. L. Vossen, W. Kern,
Thin film process,
Academic Press,
New York, 1978

Kreutzmann,"Robin Hoods of PV",
Photon International, 9, 2006, str.58.

Renewable Energy World, 9, 2006, str.4.

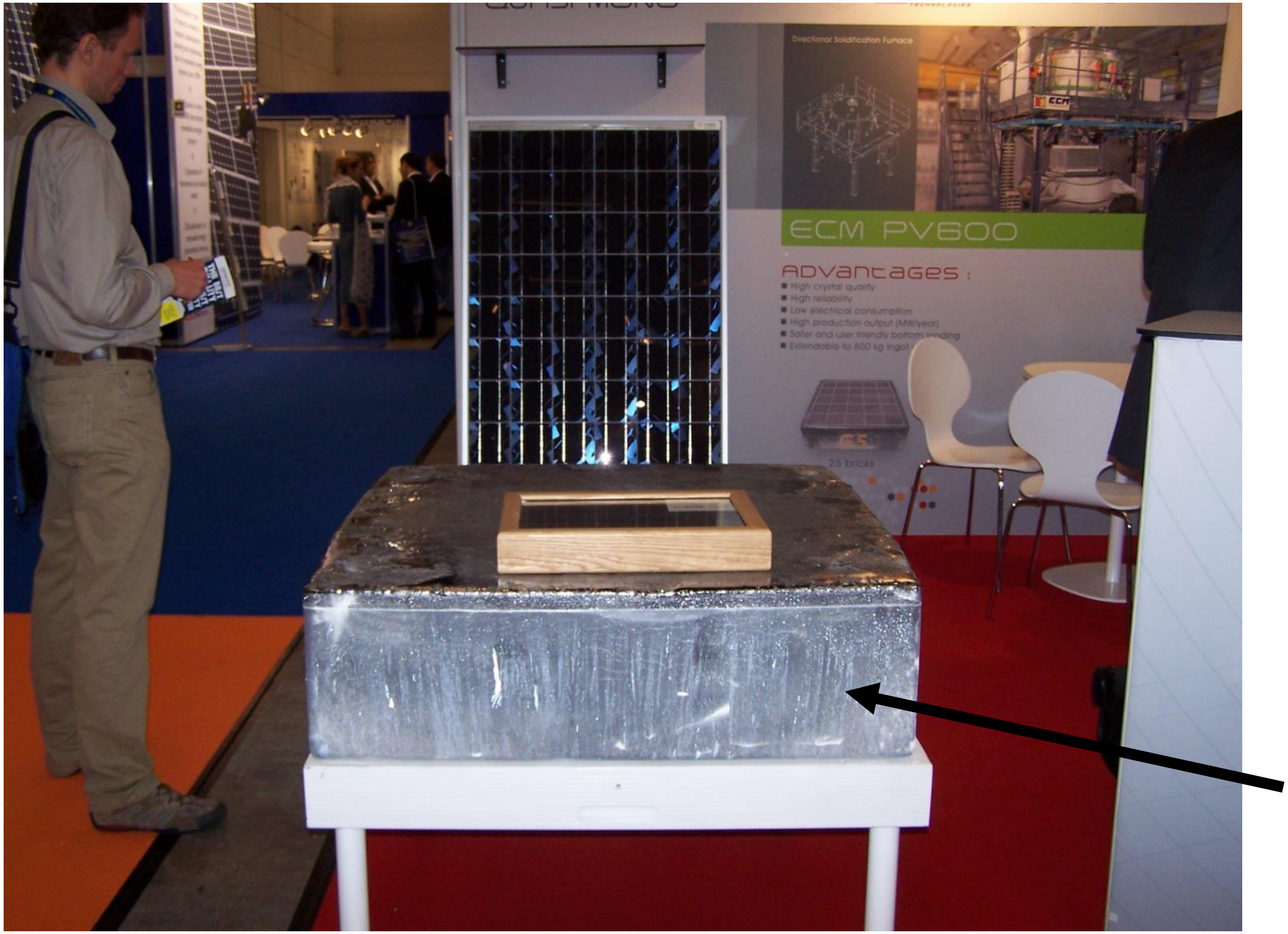
Casting in crucible


Closed Furnace
Open Furnace



Chemical impurities in solar grade silicon

Element	ppm	at/cm3
O		15E16
C		15E16
B	0.5	2.5E16
P	0.025	1.25E15
As	0.025	1.25E15
Fe, Al, Cr, Ni, Ti, Mo, V, Cu, Zn Summed maximum	0.1	5E15
concentration of each not mentioned metal		<5.0E13

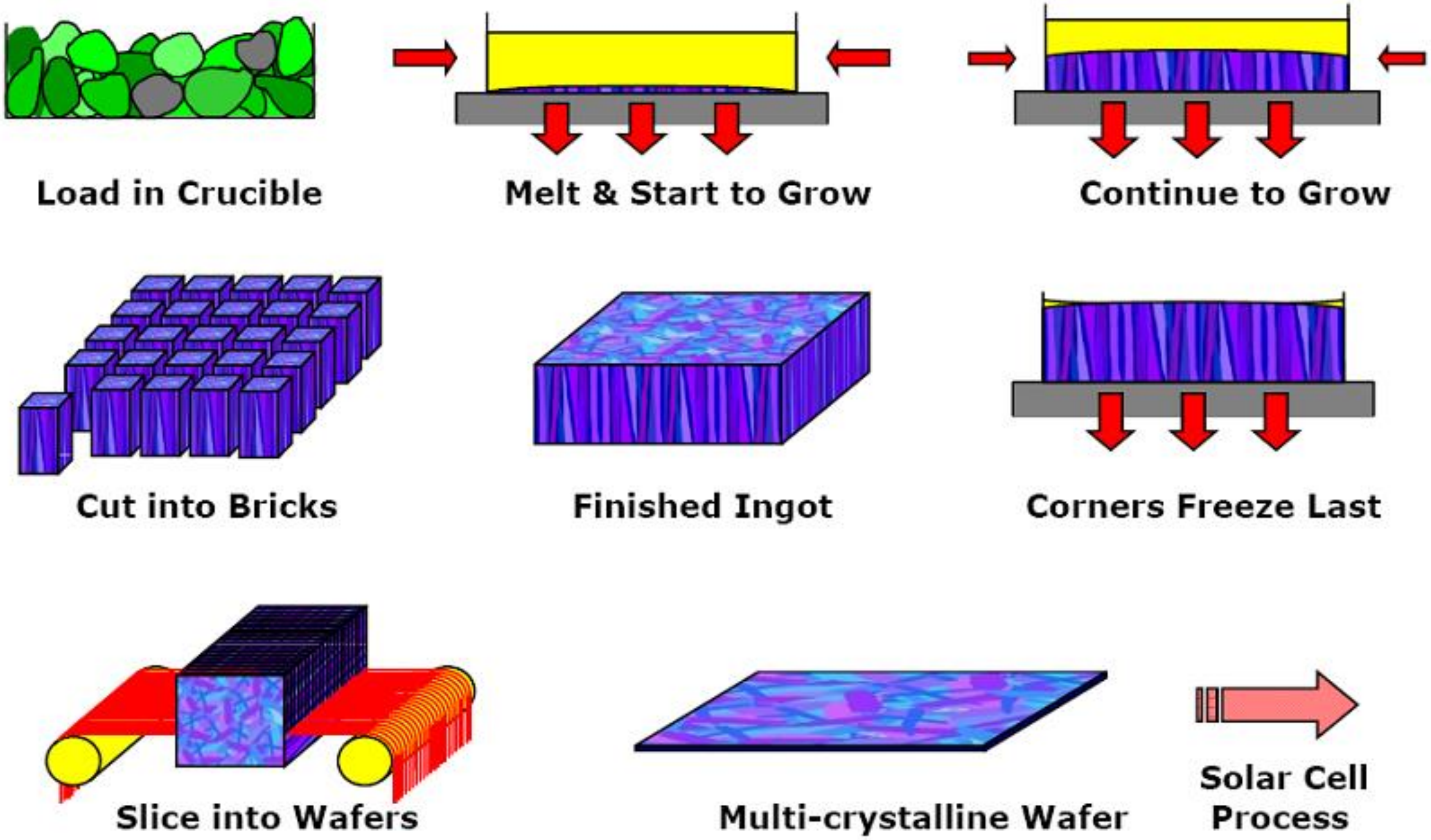


Ingot
Q-Si

Si quasi-mono crystalline


Ingot Crystallization
– monocrystalline silicon: Cz and FZ processing, feedstock, optimization of crucibles
– multicrystalline silicon: crucible coating, nucleation control, n-type and umg-Si
Bricking and Wafering
– brick shaping and surface polishing
– loose and fixed abrasive wafering: thin wafer development, kerf loss reduction, slurry optimization, diamond wire sawing
FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE
SERVICES
Fraunhofer
Fraunhofer
PV Inverter Characterization

Cz-Si



Load in Crucible

Melt & Start to Grow

Continue to Grow

Cut into Bricks

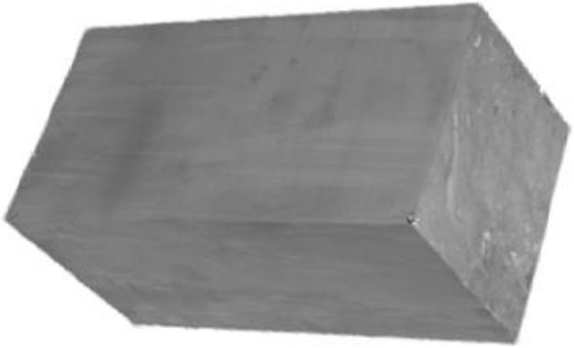
Finished Ingot

Corners Freeze Last

Slice into Wafers

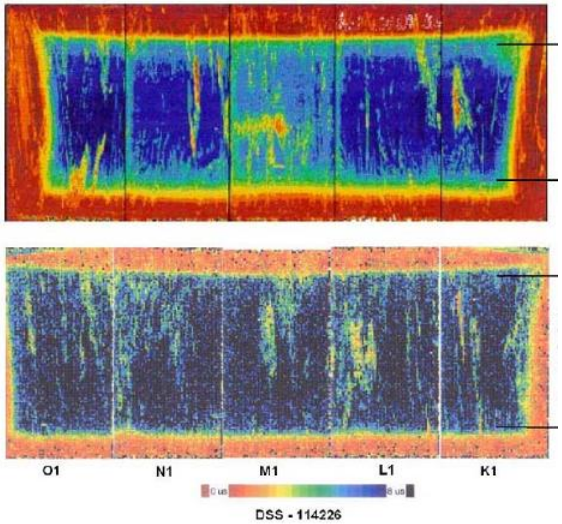
Multi-crystalline Wafer

Solar Cell Process

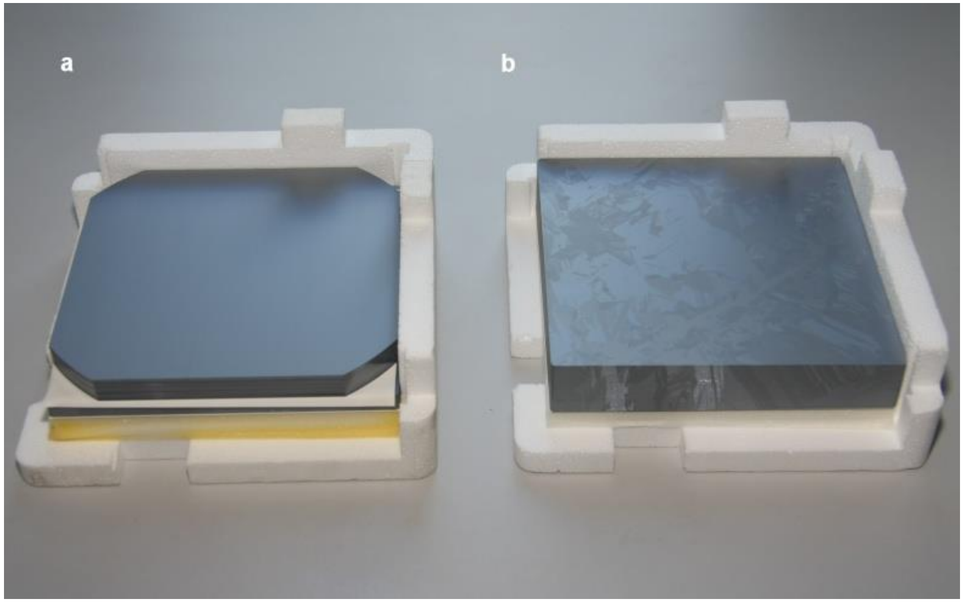


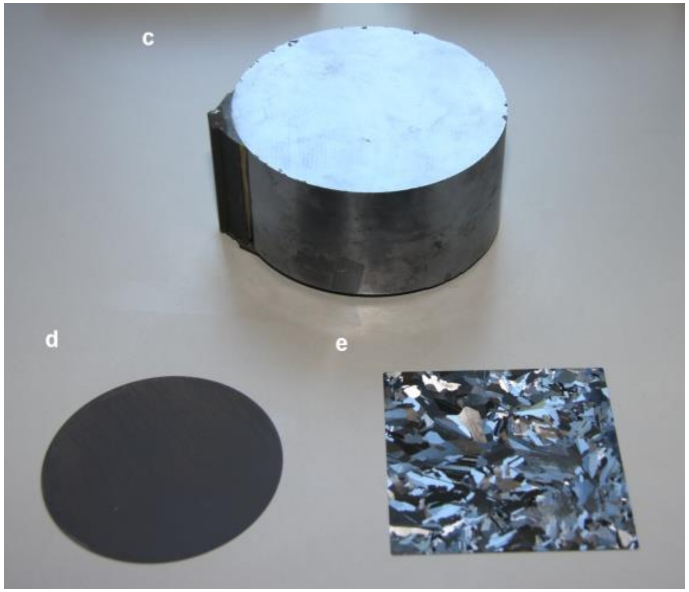
The catting process
by saw wire

The influence
of cutting process
on effective
lifetime



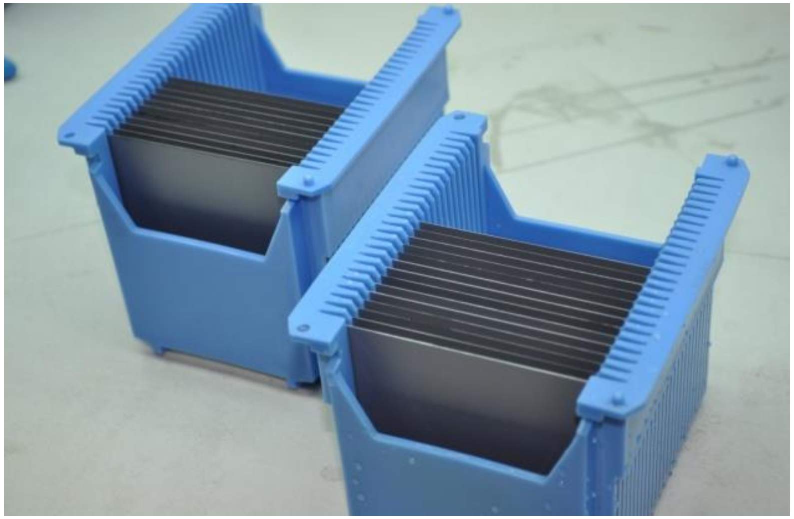
I Chemical etching and surface texturization

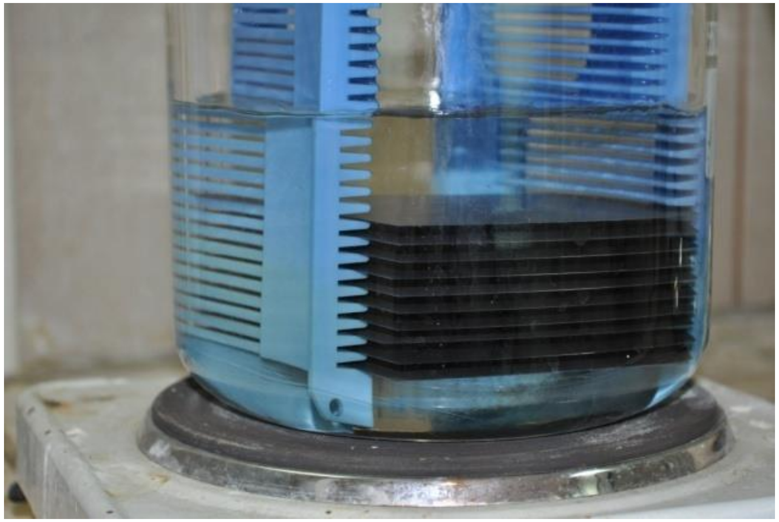




Provided by the producer, original pack of 125 items of six-inch mono-crystalline silicon wafers Cz-Si (a) and poly-crystalline silicon plates mc-Si (b), 200 μm thick, used in the solar cell production. Fragment of a silicon Cz-Si roller made with the Czochralski process (c) and the cut-out plate used in the IC *(Integrated Circuit) sector* (d), next to a four-inch single mc-Si silicon plate, after the elimination of the defected layer, resulting from the block sawing (e).

I Chemical etching and surface texturization





Chemically prepared silicon pates placed in teflon holders (left) and chemical etching process (right)

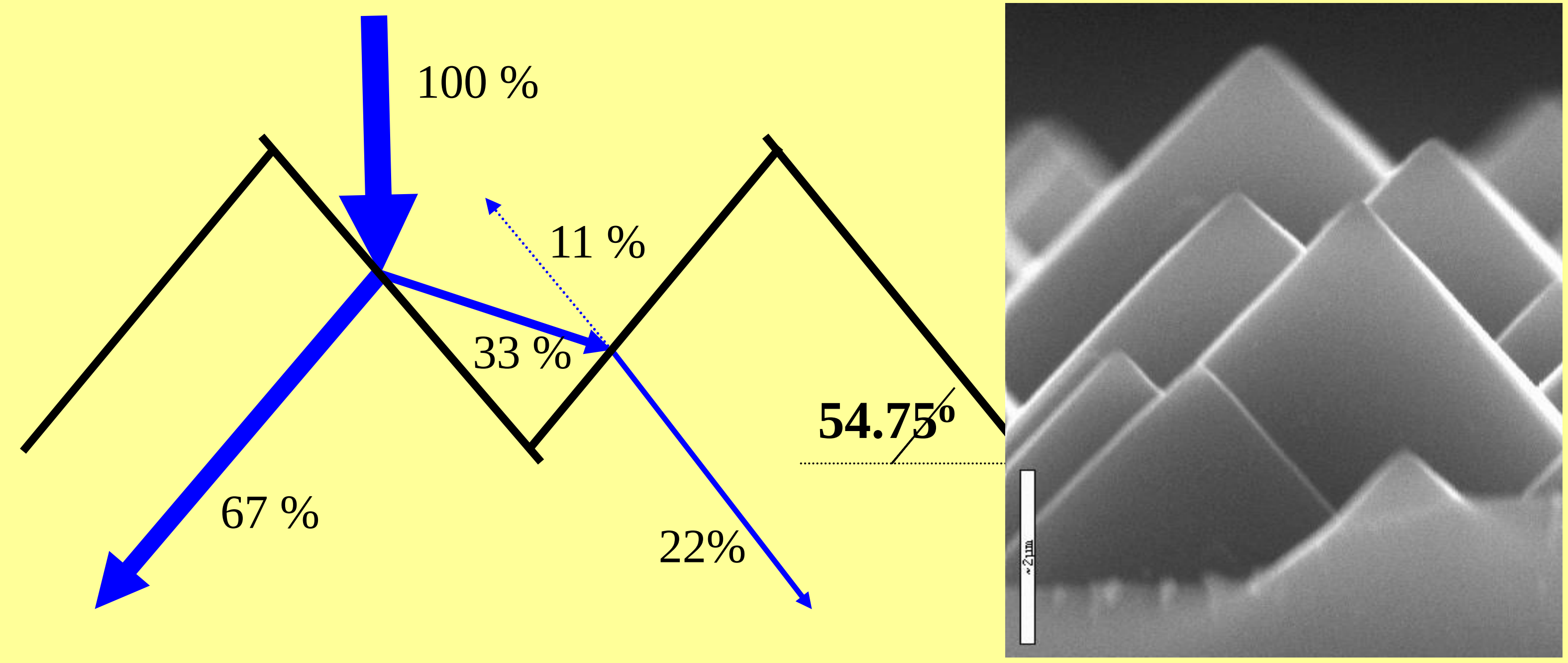
Si p type, resistivity 1 ohmcm, thickness ~ 200 μm, τ - 5 ÷ 25 μs

In order to precisely determine the effect of the ARC layer or the texture of the cell’s surface on the reduction of the radiation reflection, photovoltaics introduces a quantity described as the effective reflection coefficient R_{eff}. It is defined by the following formula:

$$R_{eff} = \int_{400}^{1100} R_{ref}(\lambda) N_{ph}(\lambda) d\lambda \ / \ \int_{400}^{1100} N_{ph}(\lambda) d\lambda$$

$N_{ph}(\lambda)$ – the number of photons falling on a surface unit for a given wavelength per one second for solar spectrum AM1.5

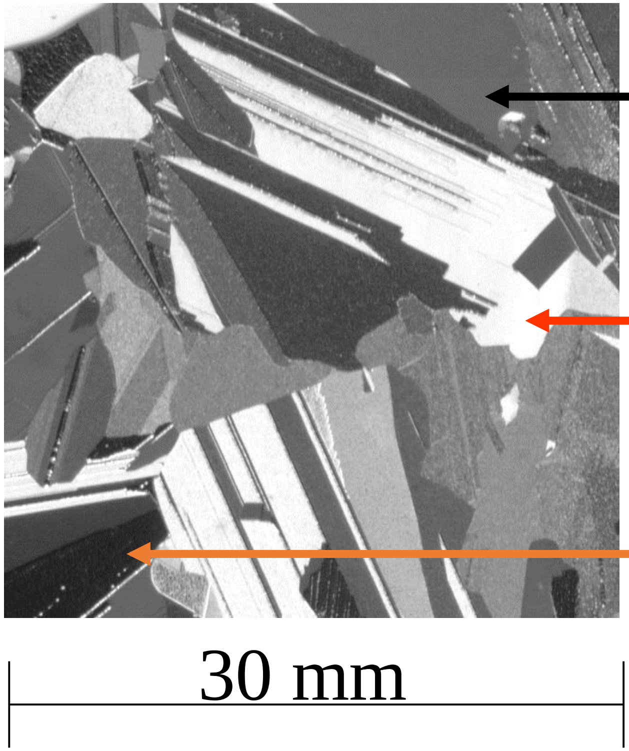
Texturization of mono Si by KOH etching

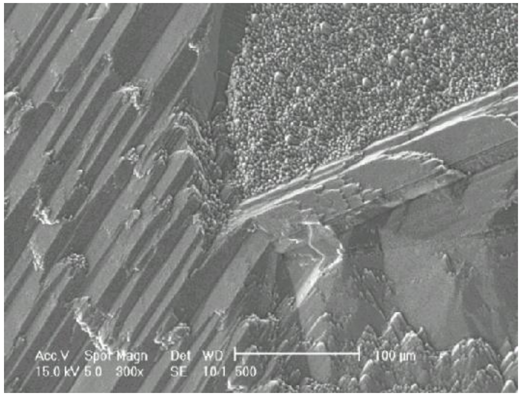


The Si (100) texturized in KOH solution

Texturization

Mc-Si after etching in KOH solution





Orientation (hkl)

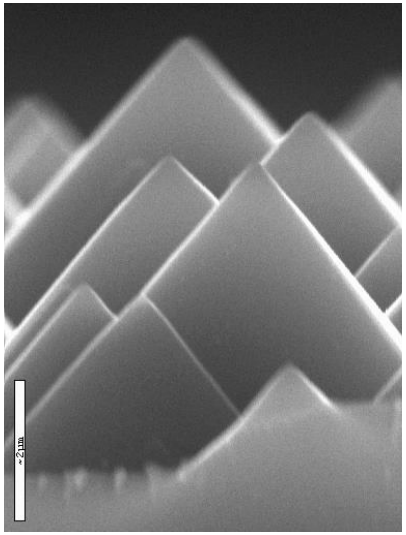
10 %< R_{ref} <33 %

Orientation (111)

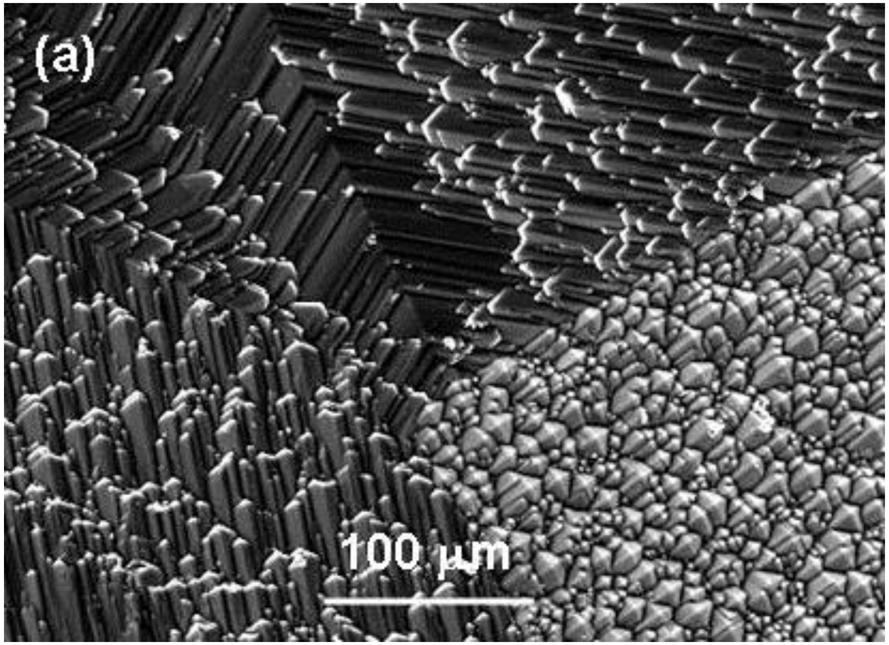
R_{ref} = 33 %

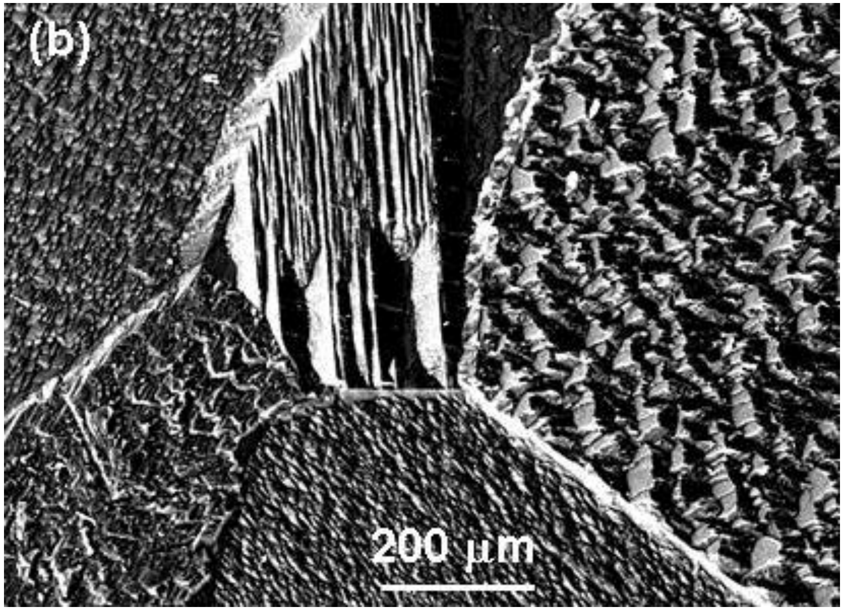
Orientation (100)

R_{ref} = 10 %



~ R_{ref} = 24 %

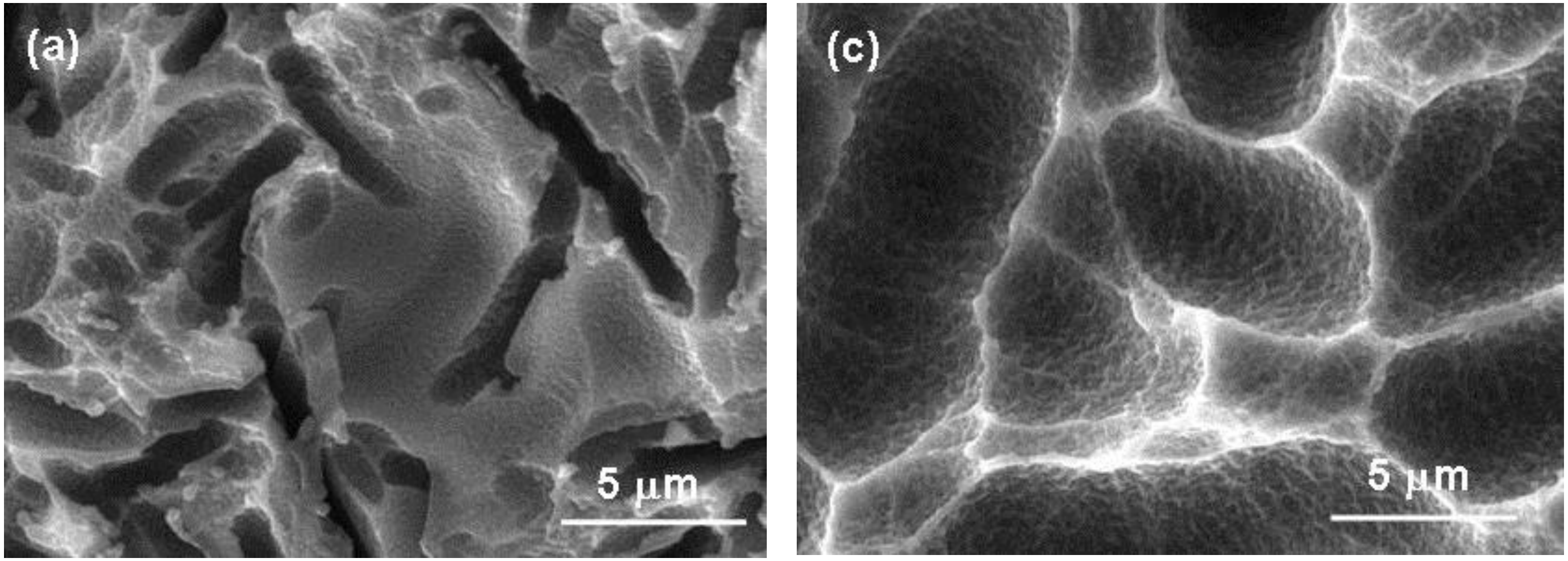




$R_{eff} \approx 24\%$

Texturization of mc - Si in $KOH:H_2O:IPA$

Acidic texturization



SEM micrograph image of mc-Si surface acid texturized in $HF:HNO_3:H_2O$ solution after 15 s (a) and after 60 s (b).

New method: texturing by metal assisted chemical etching

Pd deposition

Pd nanoparticles deposited from $PdCl_2$ solution

Porous silicon formation

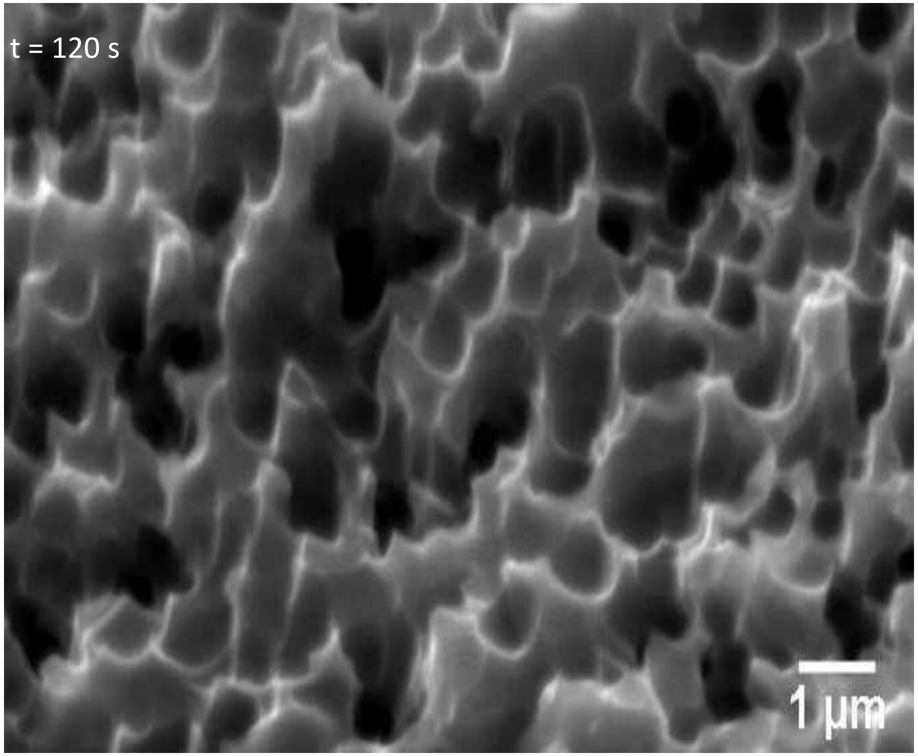
MAE in $HF:H_2O_2:H_2O$ or in $HF:HNO_3:H_2O$

Texturization

Etching by KOH

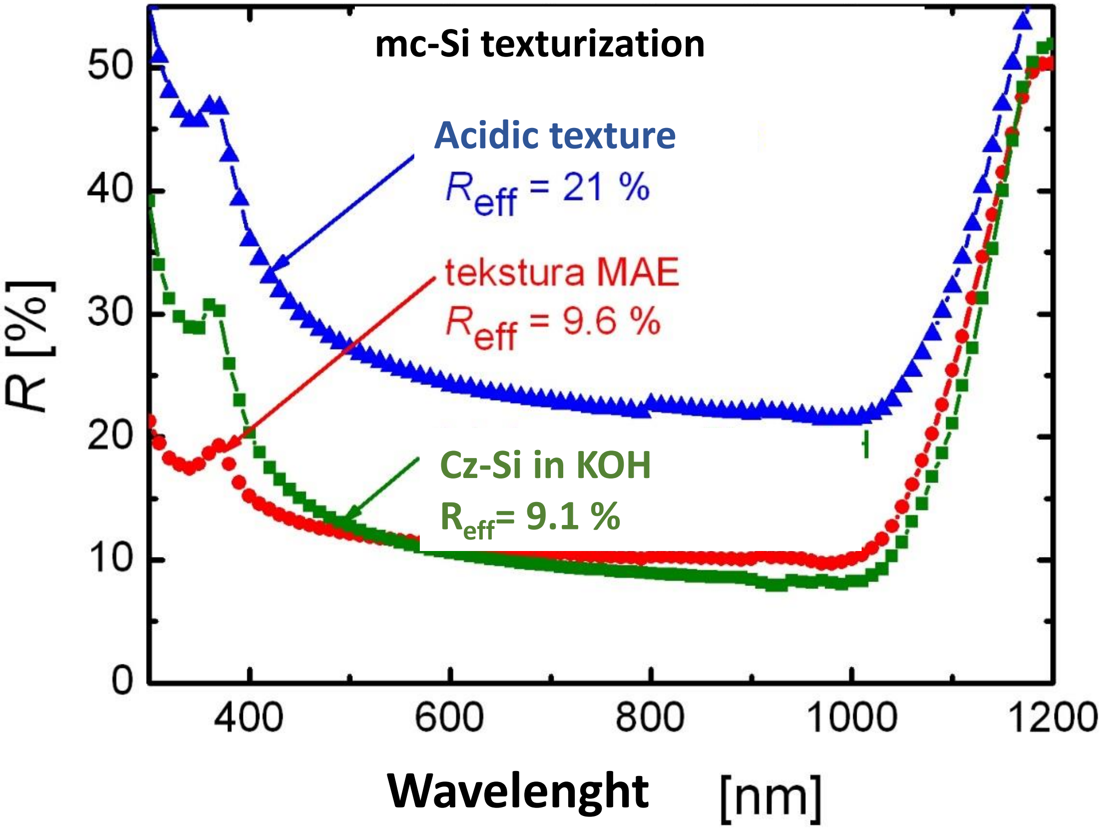
- Time of etching 1-2 min
- Si : „as-cut”, ribbon Si
- Small refelctivity - „Black Silicon”

Texturing by metal assisted chemical etching (MAE)



SEM micrographs of the surface of mc-Si silicon digested by MAE in HF: H_2O_2: H_2O solution, and then in 1M KOH solution for 60 s.

Teksturing by MAE



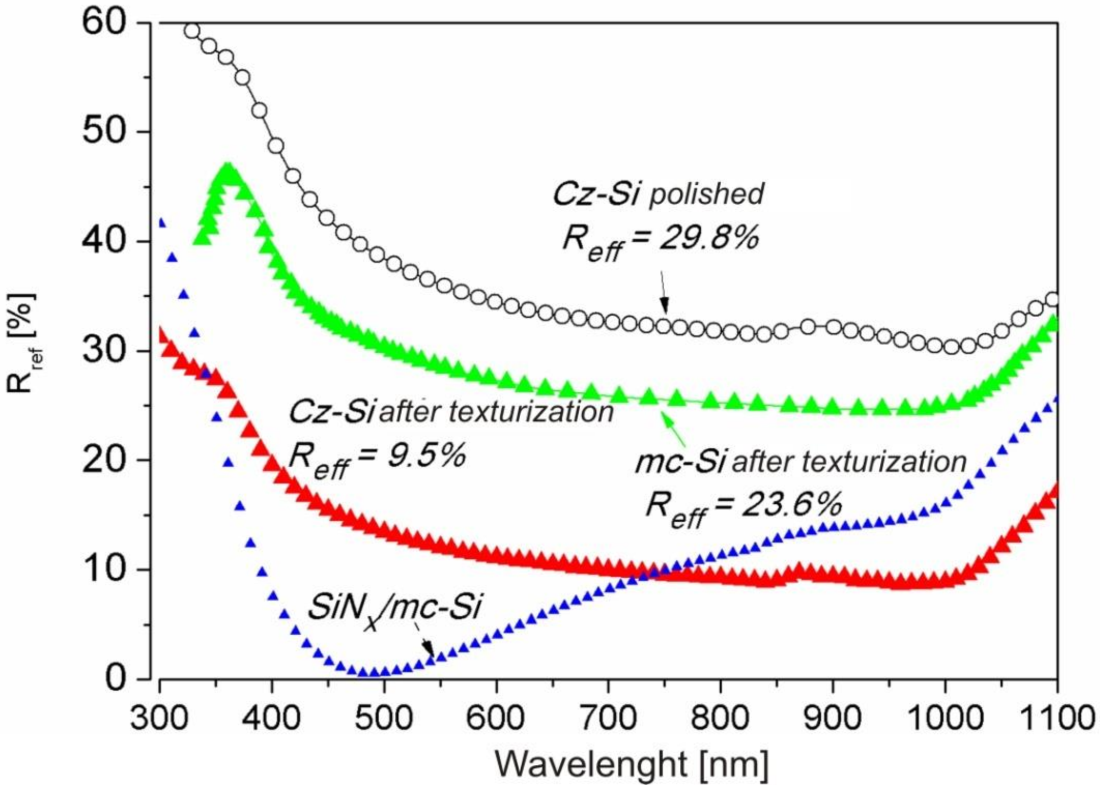
In high efficiency solar cells, the surface texturization is applied simultaneously with the a**nti-reflective coating (ARC**), which allows for a maximum reduction of R_{eff}. The ARC layer of the cell is required to fulfill a few basic conditions. One is to achieve the lowest possible value of the extinction coefficient k, which results in a high value of the transmission coefficient. As regards the value of the refractive index of the layer n_{arc} , it can be determined from the following relation:

$$n_{arc}d = \lambda_{opt}/4$$

where d is the thickness of the layer and λ_{opt} is the length of the wave for which the photon stream reaches its maximum

In the case of the silicon in which the refractive index n equals 3,87 for the wavelength of 632,8 nm, the optimal refractive index in the ARC layer equals 1,97

Texturization + ARC



Dependence of the reflection coefficient on the wavelength for surface-polished silicon Cz-Si and mc-Si, after texturization and deposition of a silicon nitride ARC layer; measurements performed with a spectrophotometer Perkin-Elmer Lambda-19, at AGH, Krakow.

II Diffusion and p-n junction formation

The Si plates in the quartz holder are placed in a heated quartz reactor which is provided with protective gas N_2 and reactive gases $POCl_3$ and O_2. At the temperature above 800 ^oC, in the presence of oxygen, a dissolution of the $POCl_3$ occurs and, at the same time, phosphosilicate glass $xSiO_2 \cdot yP_2O_5$ (PSG) is formed on the Si surface, which further constitutes a local source of phosphorus diffusing in silicon. This process takes place according to the following dependences

$$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6Cl_2$$
$$2P_2O_5 + 5Si \rightarrow 5SiO_2 + 4P$$

Sources of the dopants

STEADY

Emulsion
Filmtronics509
(125 ml – 130 USD)

Paste
Filmtronics SPP-P600
(125 ml – 130 USD)

Paste P101
(500 ml – 100 EUR)

Plate BN

LIQUID

$POCL_3$ (250 ml - 500 zł)

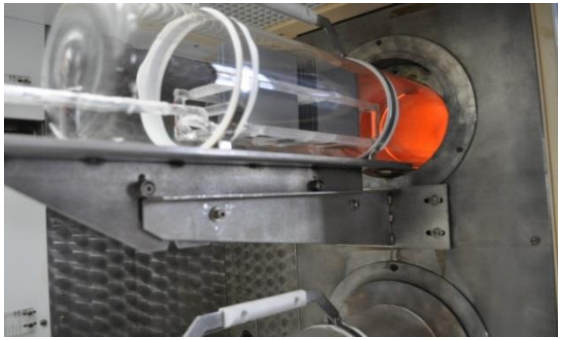
BBr_3 (50 ml – 1000 zł)

H_3PO_4

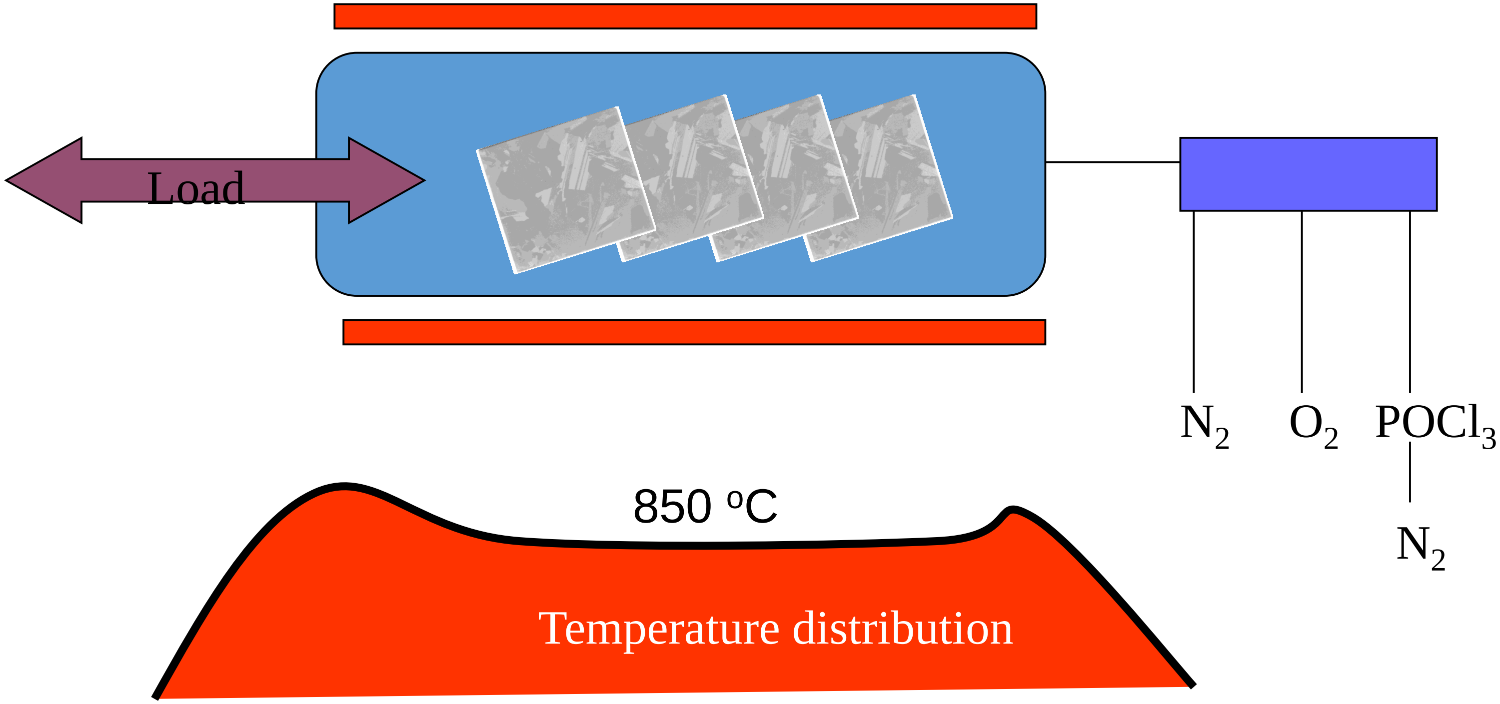
GASEOUS

10%BF_3 in N_2
(40 l – 7464 zł)

The industrial diffusion furnace



Quartz reactor



Load

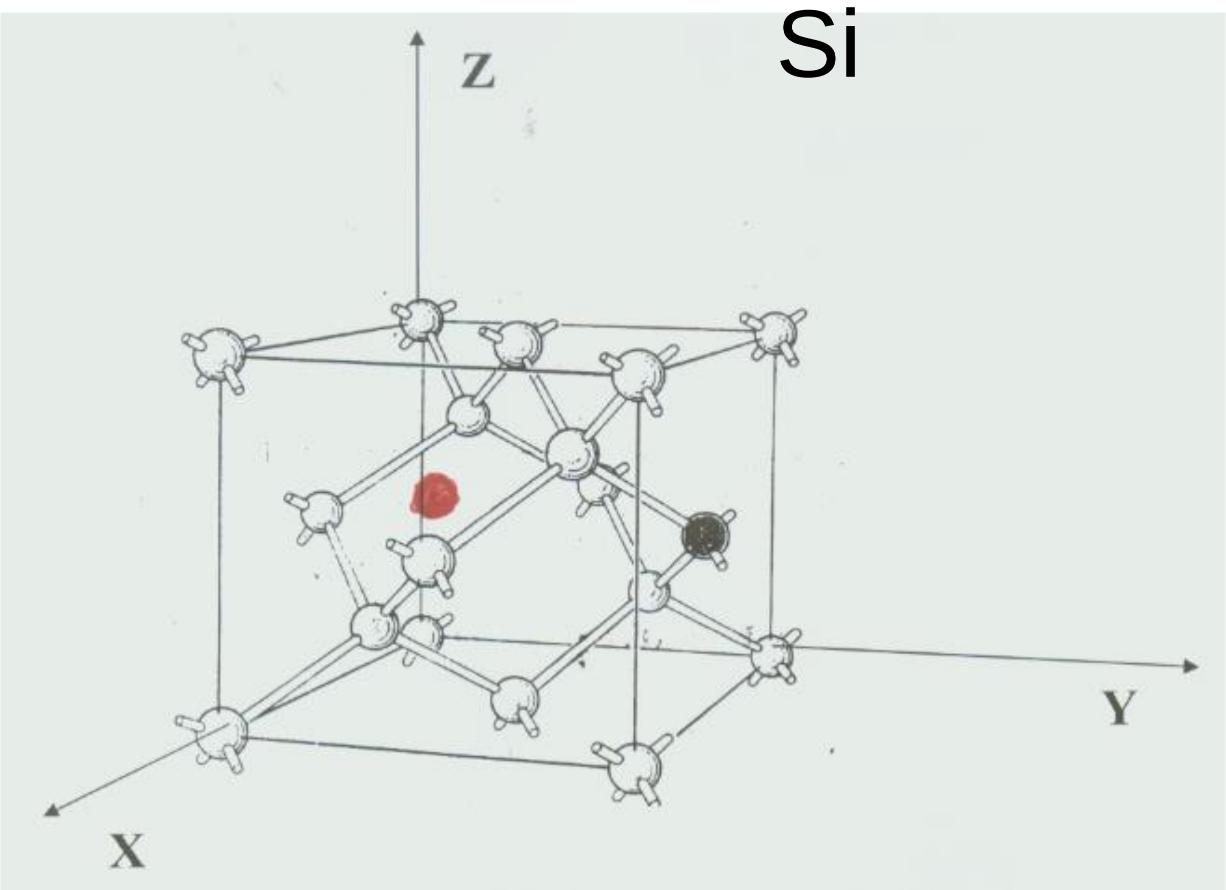
N_2 O_2 $POCl_3$

N_2

850 °C

Temperature distribution

During diffusion, the doping atmosphere must be supplemented with oxygen, so that the partial pressure P_2O_5 is sufficient to saturate PSG with phosphorus atoms. As a result of the diffusion process, some of the impurity atoms do not assume the substitution sites in the crystalline silicon structure, but instead they assume the interstitial sites, thus forming an electrically inactive layer, the, so called, dead layer. The concentration and the profile of the impurity are affected by the temperature, time and concentration of the reactive gases. The measurement of the layer resistance, performed with a four-point probe, is a control measurement after each diffusion process, which provides information not only on the value of Rρ but also on the homogeneity of the impurity distribution on the whole surface of the Si plate. Most of the producers currently perform doping of the n-type area with the value of Rρ at the level of 40 ÷ 50 Ω/□, where the fast development of paste production technologies and metallization processes of front electrode contacts makes it possible to produce a cell with the thick film technology for Rρ ~ 80 Ω/□.



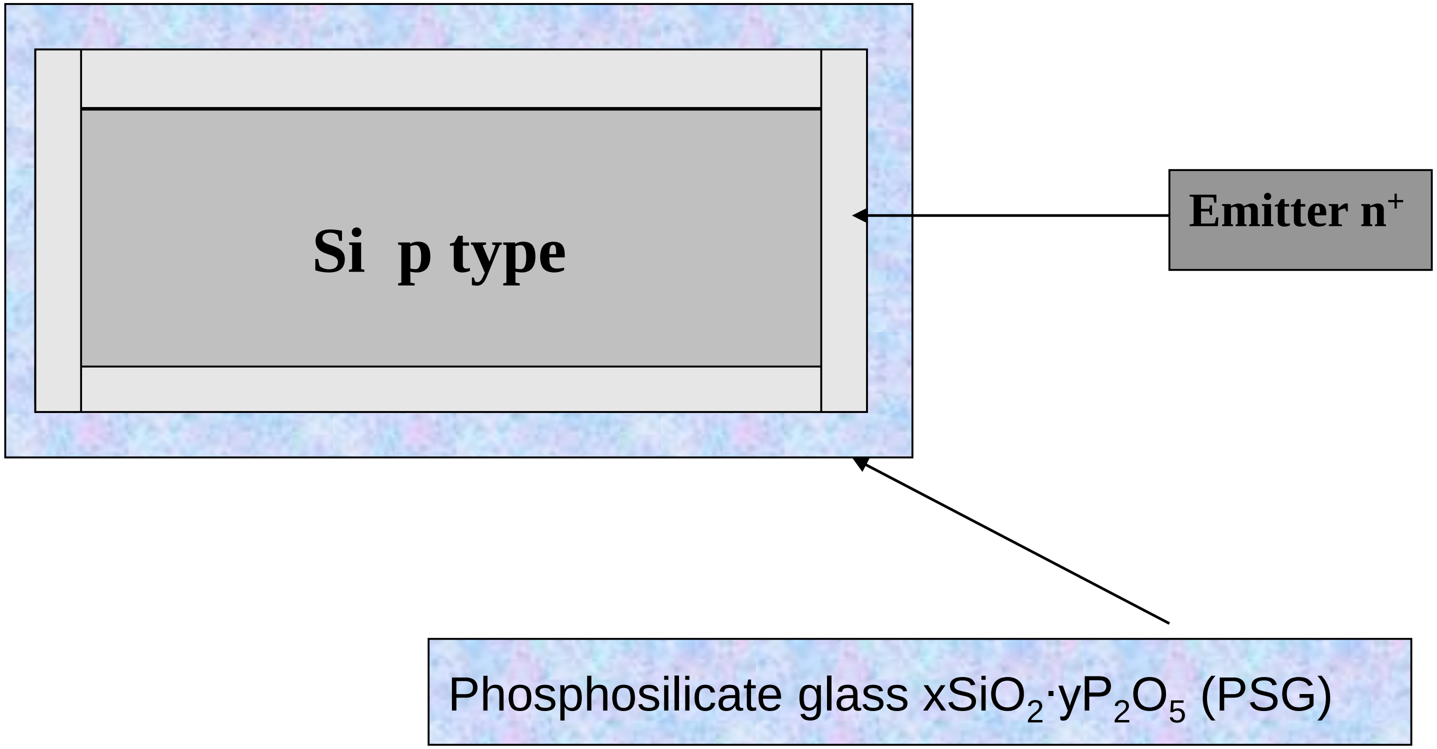
● - Dopant element in substitution position

SR

● - Dopant element in interstitial position

SIMS

In the diffusion process, the doping takes place on all sides of the plate.

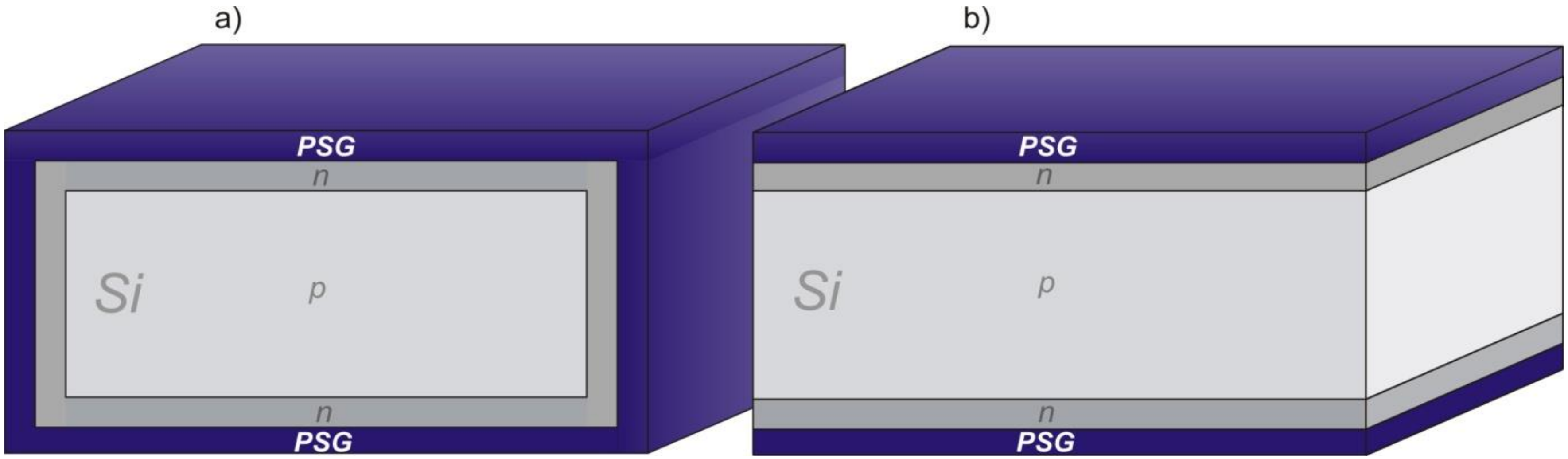


Si p type

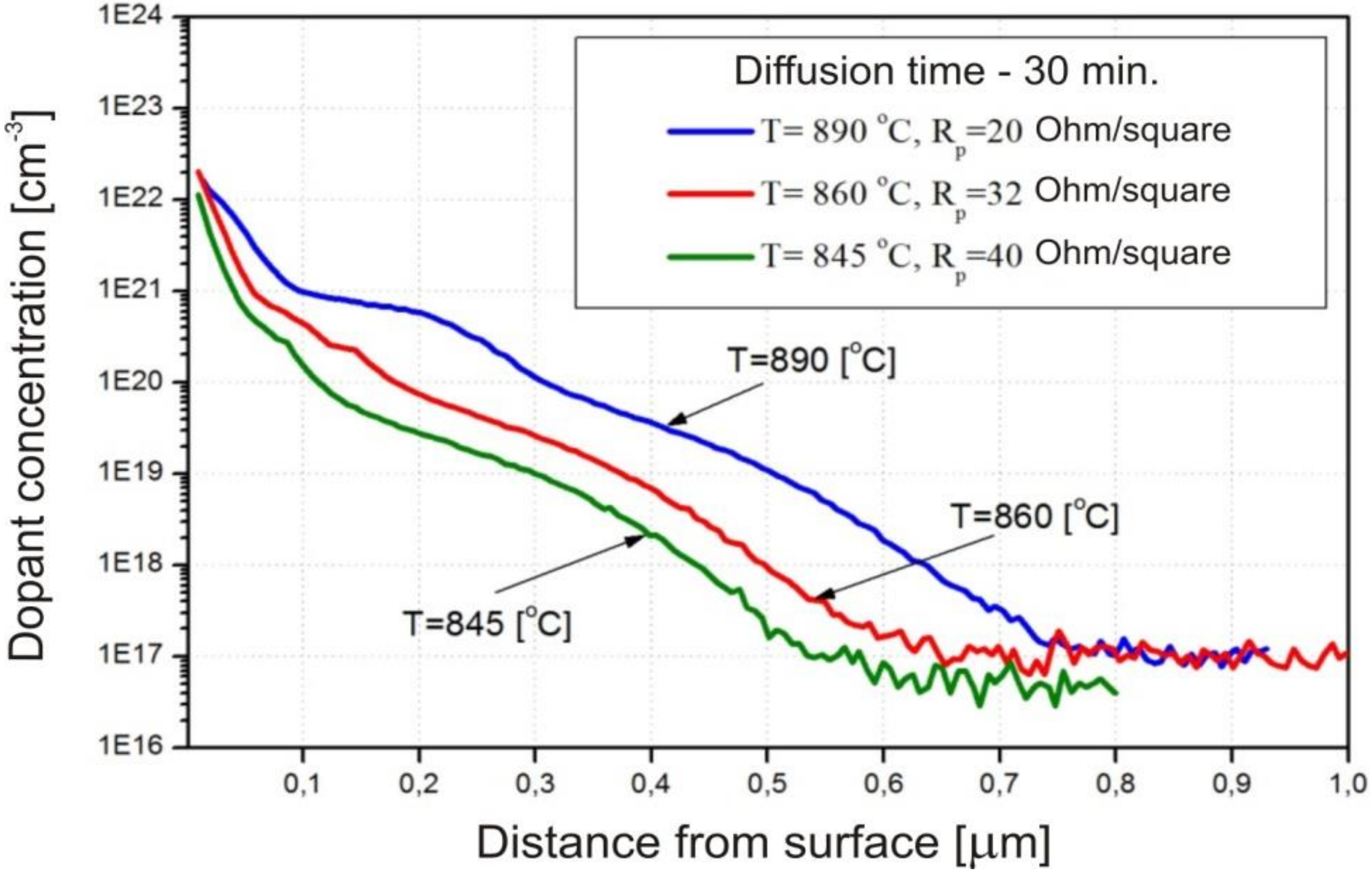
Emitter n^+

Phosphosilicate glass $xSiO_2 \cdot yP_2O_5$ (PSG)

The elimination of the short-circuit on the edges in the thick film technology is performed in the process of chemical etching of the edges, cutting the latter off with the use of laser or plasma etching.



Cross-section of a plate after diffusion (a) and after edge separation (b)



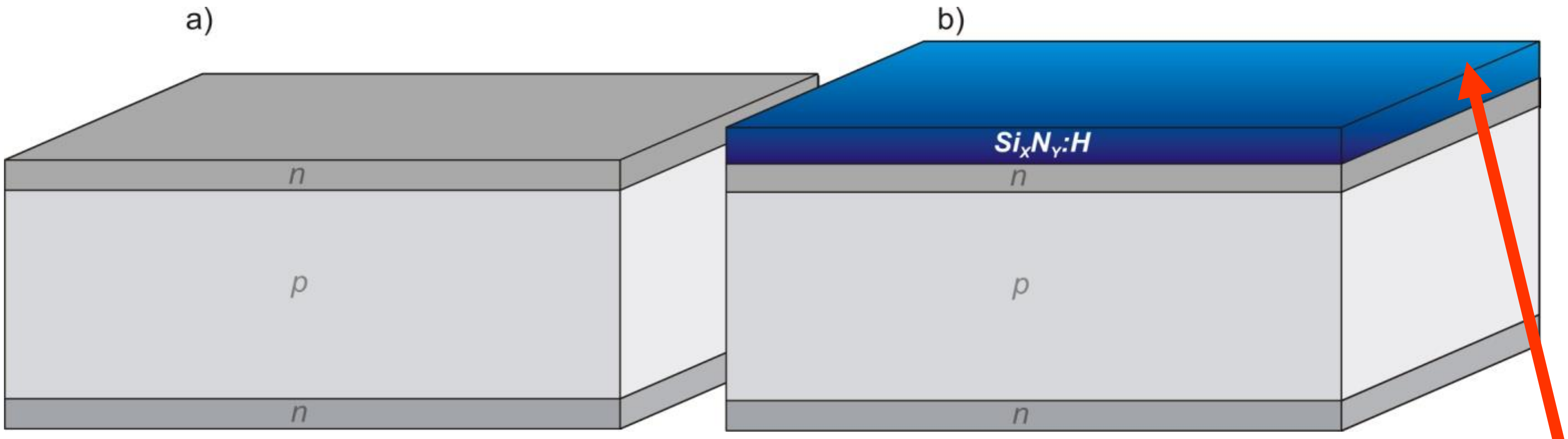
Profiles of donor impurity distribution from source $POCl_3$ through secondary ion mass spectrometry (SIMS) at the Physics Institute PAS in Warszawa; together with the temperature value for the given diffusion process. The diagram also gives the surface resistance value Rρ of the donor impurity layer.

In-line diffusion process from H_3PO_4

III Deposition of passivation and antireflection coating

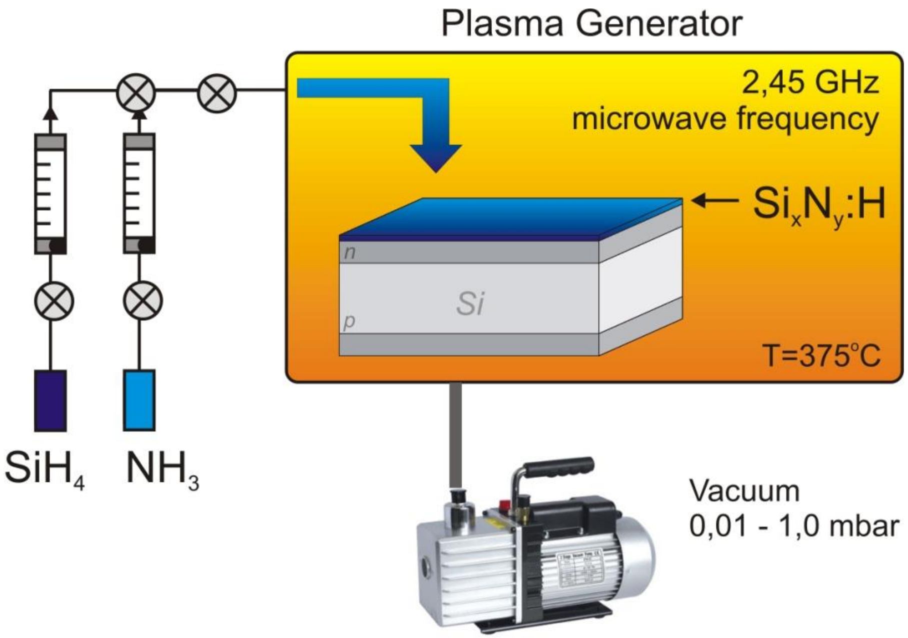
After separating the edge and eliminating the PSG glass layer in a 5% HF solution, a passivation and an antireflection coating (ARC) is deposited on the front surface of the plate. As the passivation coating, we can apply a SiO_2 layer, produced in dry oxygen at the temperature of 800 ^{o}C, and next, as the ARC coating, one can deposit e.g. a titanium oxide TiO_2 layer. The mass production of solar cells currently involves the application of only one layer which plays both functions, i.e. a coating of hydrogenated silicon nitride deposited with the method of RPECVD (Remote PECVD)

III Deposition of passivation and antireflection coating



Scheme of a plate section after the elimination of phosphosilicate glass (a) and after the deposition of a hydrogenated silicon nitride $Si_xN_y:H$ (b)

The optimal $Si_xN_y:H$ layer is of the thickness d ~ 85 nm and its refractive index has the value of n ~ 2,05. The above layer also has 10 ÷ 15 % at. H, and this hydrogen, in the process of contact metallization, passivizes the broken surface bondings, and in the case of m-Si – also the grain boundary areas

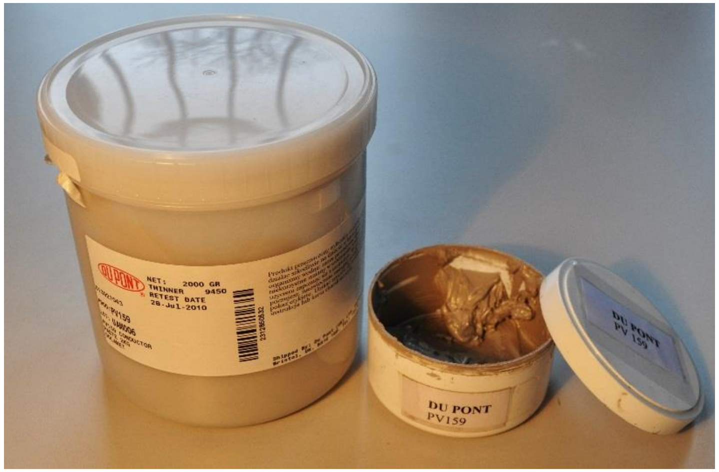


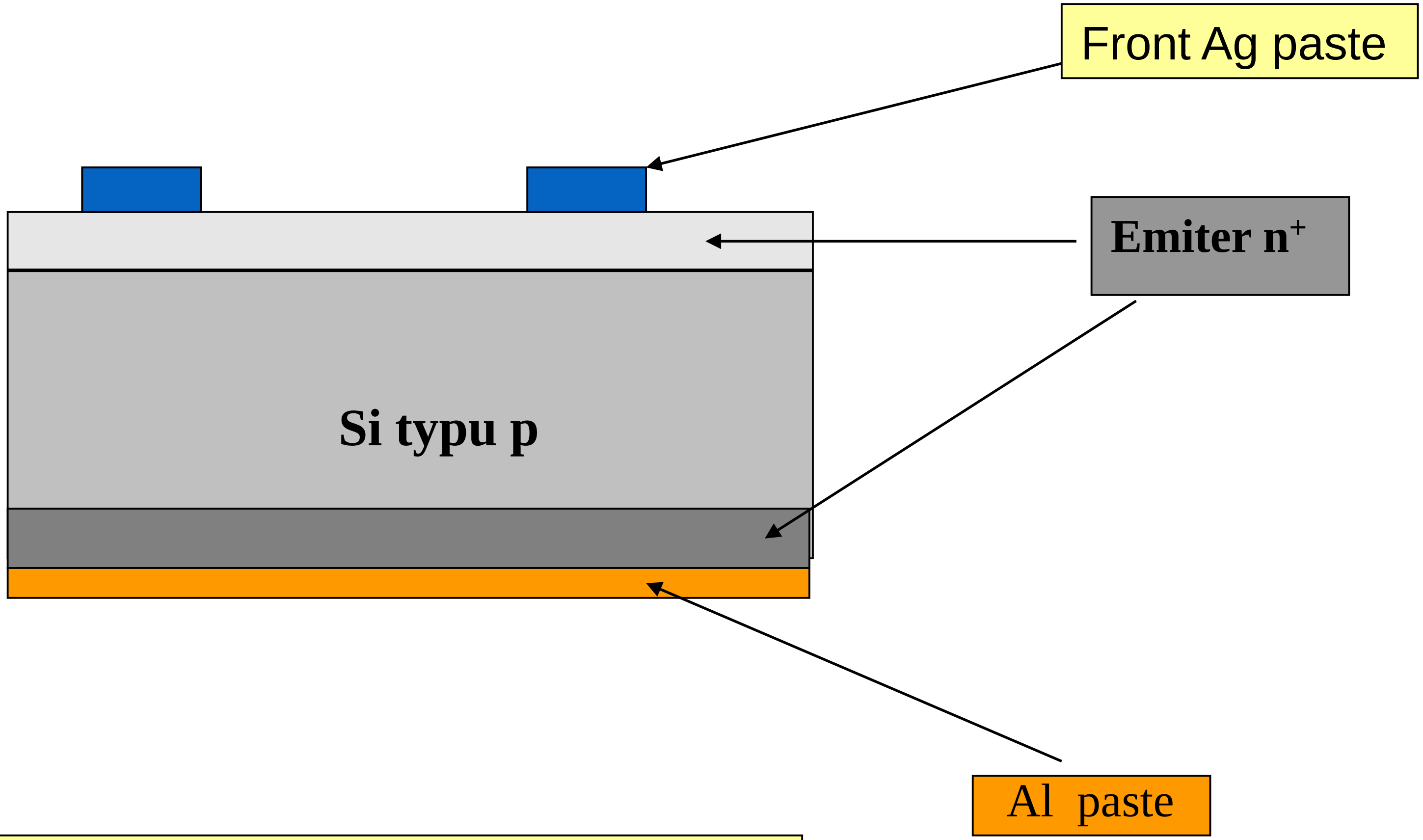
Scheme of the PECVD method of deposition a Si_xN_y:H layer formed as a result of decomposition of silane SiH_4 and ammonia NH_4, in which only the ammonia is decomposed into plasma, in the generator located outside the reaction chamber

The silicon nitride layer deposited by means of PECVD allows for a passivation of the Si surface, but at the same time, it plays the role of an antireflection coating. The Si_xN_y:H layer, due to its electron affinity, is appropriate for the n-type Si. In the case of the p-type Si surface, more suitable seems to be an Al_2O_3 layer, which is deposited with the method of ALD (Atomic Layer Deposition).

Layer type	**Deposition method**
SiO_2	**Thermal**
Si_xN_y:H	**PECVD**
Al_2O_3	**ALD**

Metallization by screen-printing





Front Ag paste

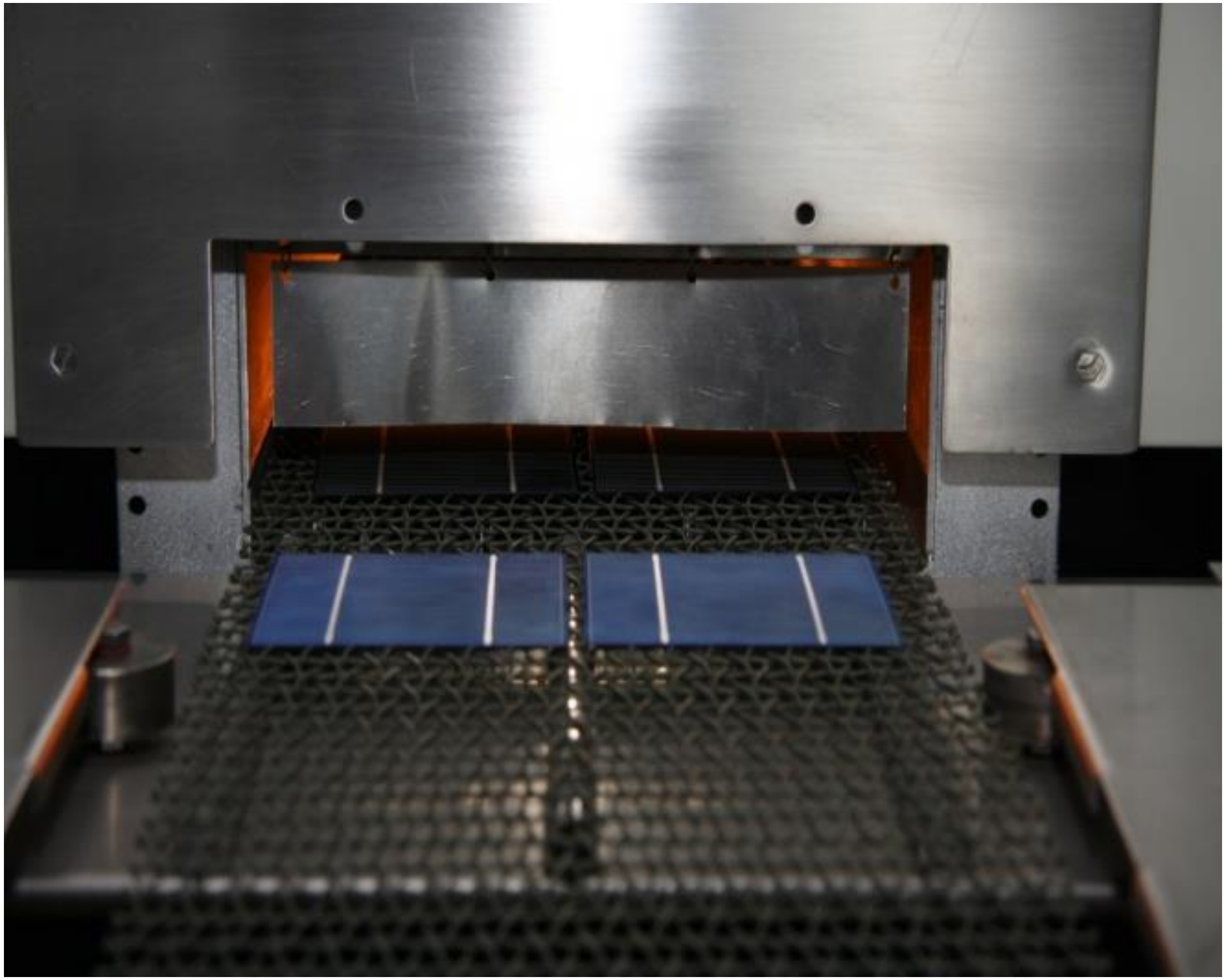
Emiter n$^+$

Si typu p

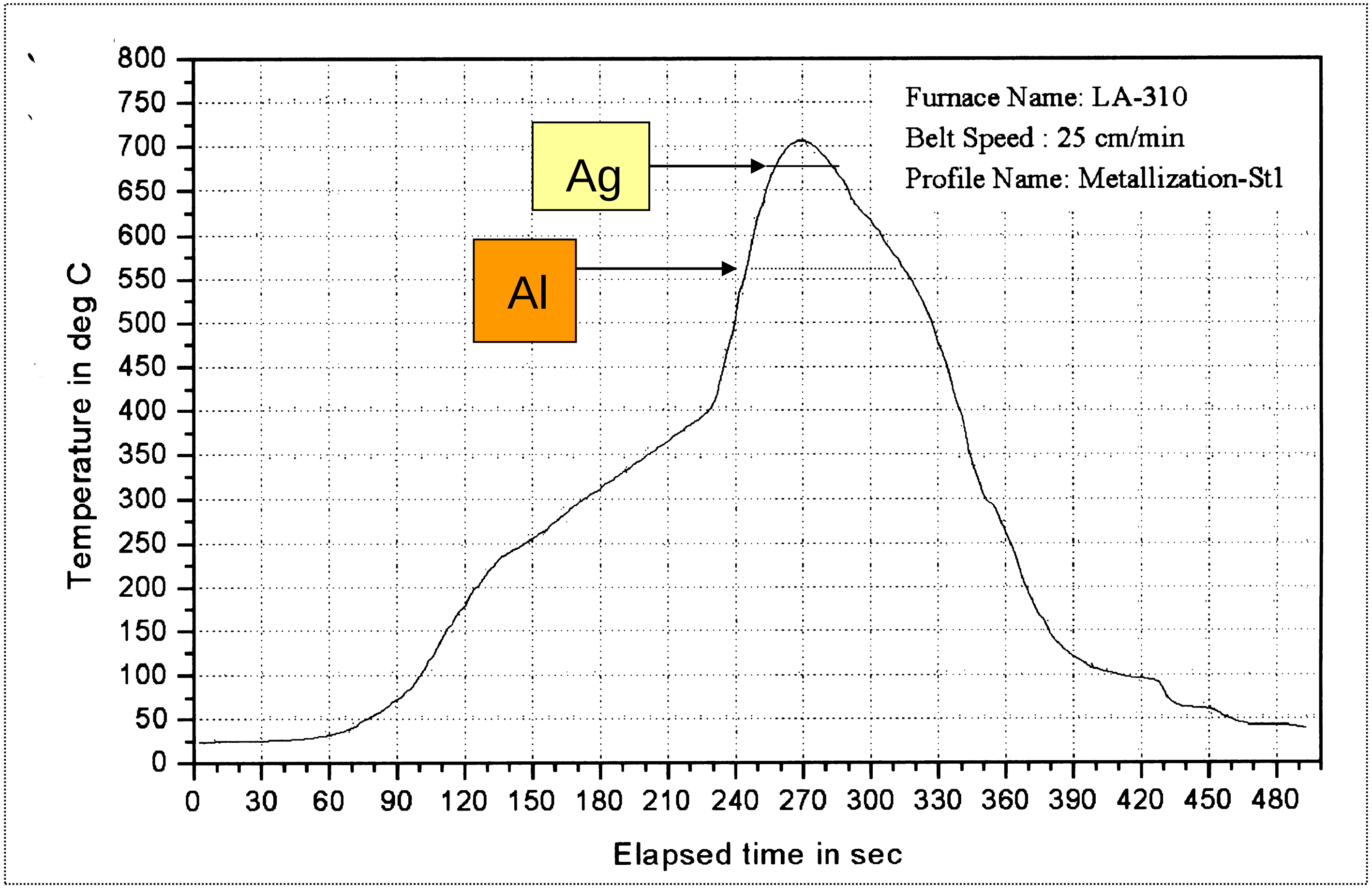
Al paste

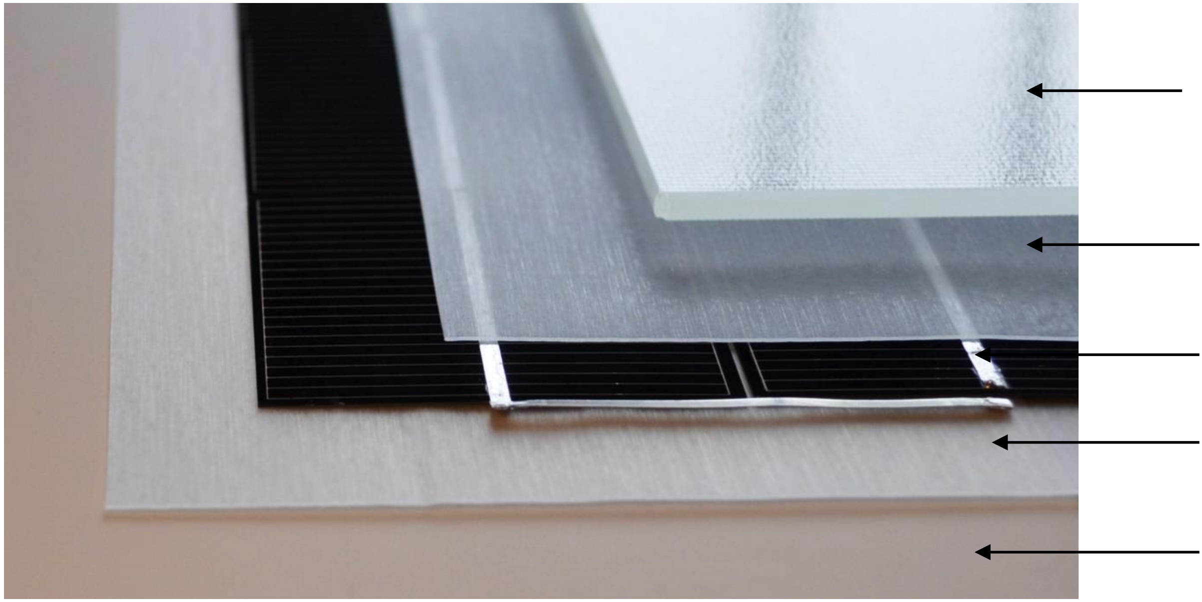
Scheme of solar cell section after screen-printing process

Metallization process



Temperature at IR furnace





Glass

EVA foil

Solar cells

EVA foil

PVF foil
(backsheet)

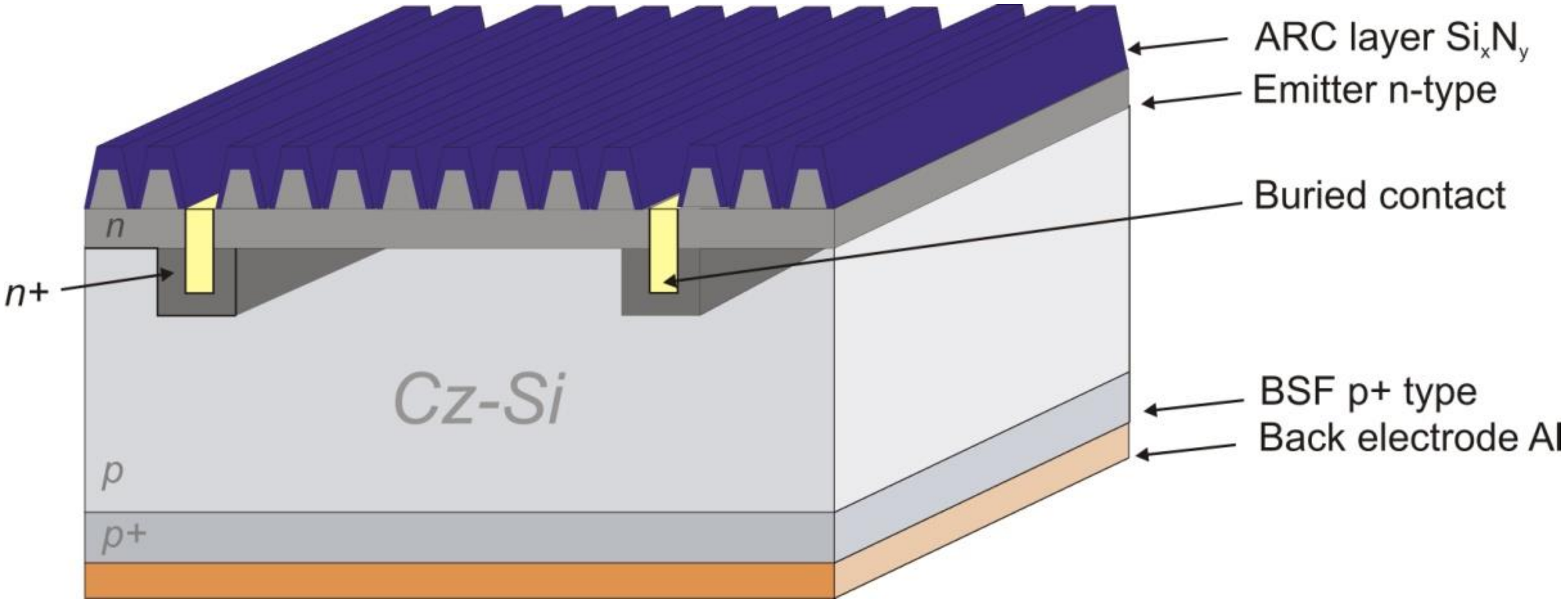
EVA – ethylene-vinyl acetate
PVF – polyvinyl fluoride (tedlar)

Industrial laminator L200 P.Energy

Directions of silicon solar cell development

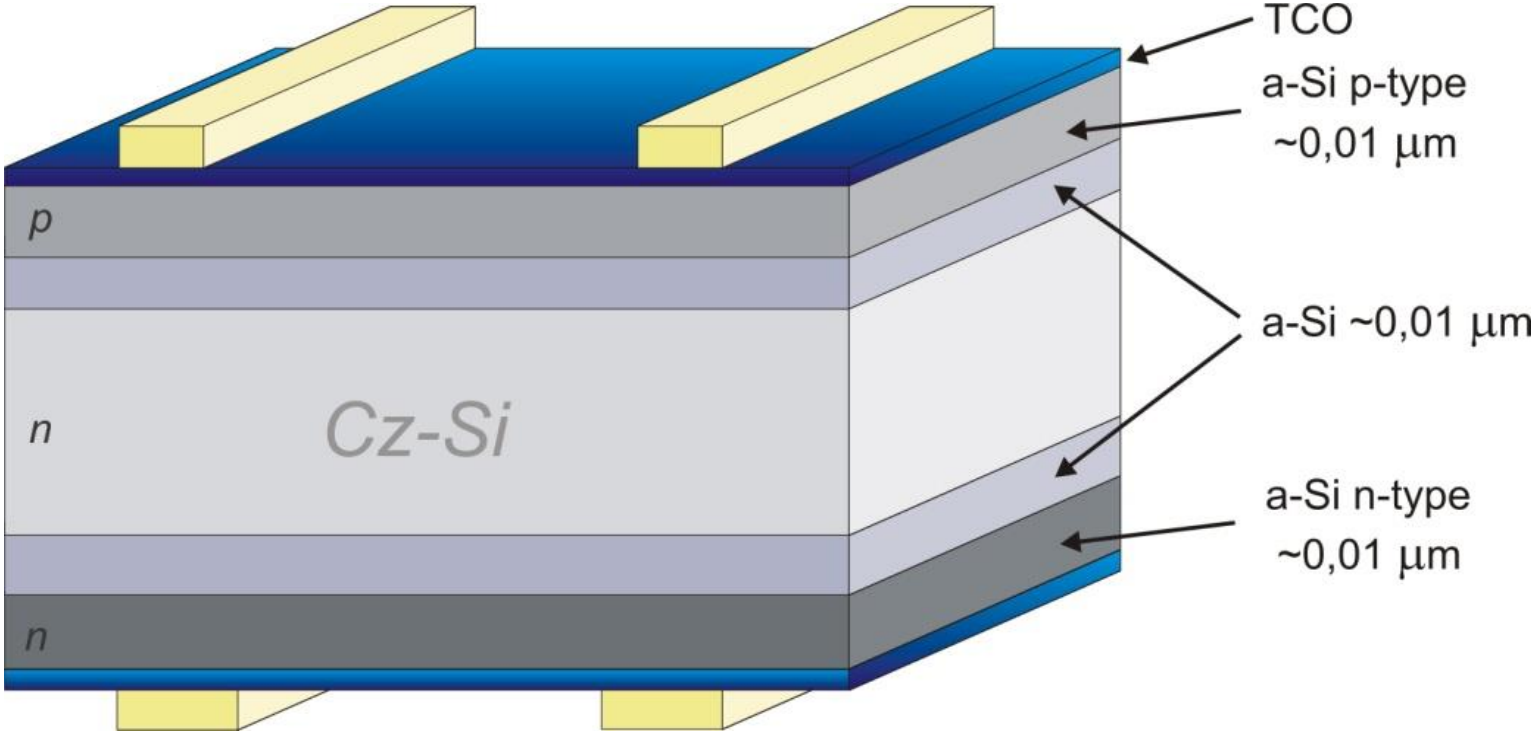
The basic trend in the research and development work is the reduction of the thickness of the solar cell’s base plate, from the currently applied 200 ÷ 150 µm down to 80 ÷ 120 µm, with a simultaneous reduction of the material lost in the process of cutting a single plate from a block, from the present 150 ÷ 120 µm down to 80 µm. This requires a full automatization of the production processes. This leaves a significant space for the concepts of solar cells allowing for a greater conversion efficiency Eff than that of the cells currently manufactured in the mass production, with the efficiency of 16 ÷ 19 %.

The basis for achieving such a high efficiency is the application of the front electrode contacts made of a nickel-copper-silver layer, deposited by means of a chemical bath in the ~ 30 ÷ 50 μm deep laser-cut grooves. Applying a second donor diffusion through the mask makes it possible to create a strongly doped n+-type area under the contacts, with the laminar resistance at the level of 20 Ω/□, which affects the reduction of the series resistance. The high-resistant emitter Rρ ~ 120 ÷ 200 Ω/□, between the thin leading electrodes, reduces the disadvantageous effect of the Auger recombination process and allows for a significant improvement of the cell's current density.



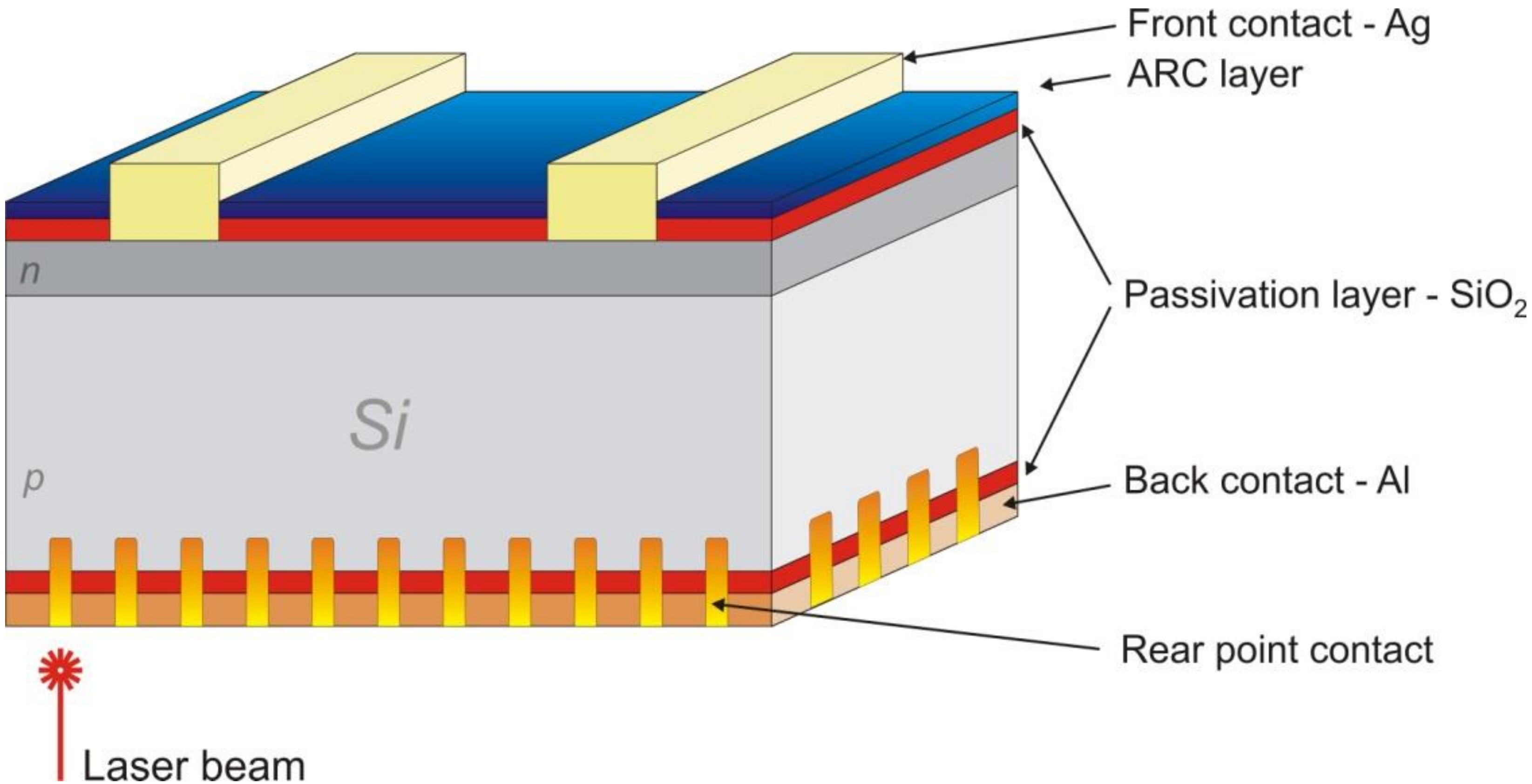
Cross-section of a mono-crystalline silicon solar cell with buried contacts (BCSC). Efficiency 22 %.

The efficiency of the HIT-type cells (*Heterojunction with Intrinsic Thin layer)* is the result of the excellent passivation of the silicon's surface, provided by the non-doped layer of hydrogenated amorphous silicon, which reduces SRV down to the level of 30 – 50 cm/s . What is more, the whole of the technological processes of the solar cell production is performed at the temperature below 200 °C, which does not cause the generation of additional recombination centers or silicon defects.



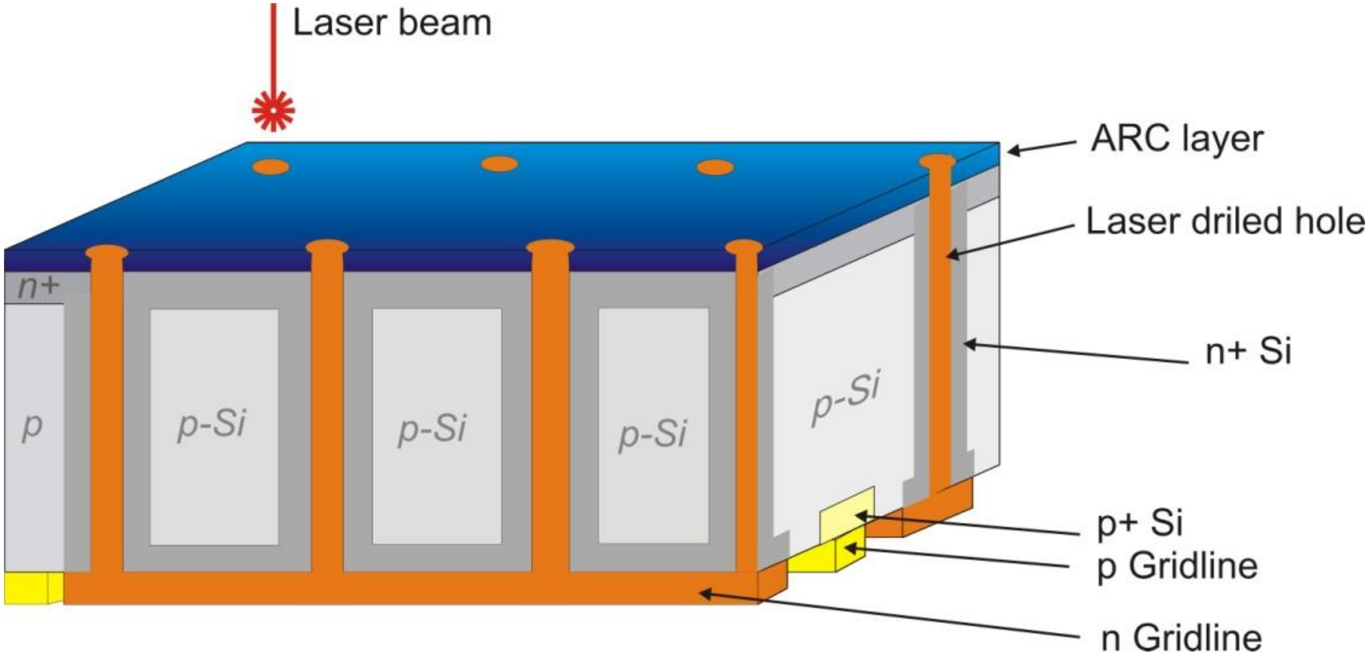
Cross-section of a mono-crystalline solar cell with double-sided layers of amorphous silicon (HIT)

The direction of research aiming at the achievement of the highest possible photovoltaic conversion coefficient with the minimum thickness of the crystalline plate, generates a significant problem resulting from the fact that the 10 μm-thin alluminium layer, used to obtain the rear contact, deposited with the screen printing method, causes the thin Si plates to bend and break, due to the difference in the thermal expansion coefficient, which equals $2{,}35\mathrm{x}10^{-6}$ K^{-1} for Si and $25{,}3\mathrm{x}10^{-6}$ K^{-1} for Al. What is more, the generated back Al layer has its reflection coefficient, within the longwave range, only at the level of 70 – 80 % and it allows for the SRV reduction on the back surface only down to the value of about 500 cm/s. Considering the above facts, one of the solutions is the passivation of the back surface of the cell and the creation of point contacts with the use of laser, which will allow to maintain a large fraction of the rear surface with the passivizing layer. This is implemented in the case of the LFC cells. A single contact point is a few hundred micrometers in diameter, and the distance between the consecutive points is within 1 mm.



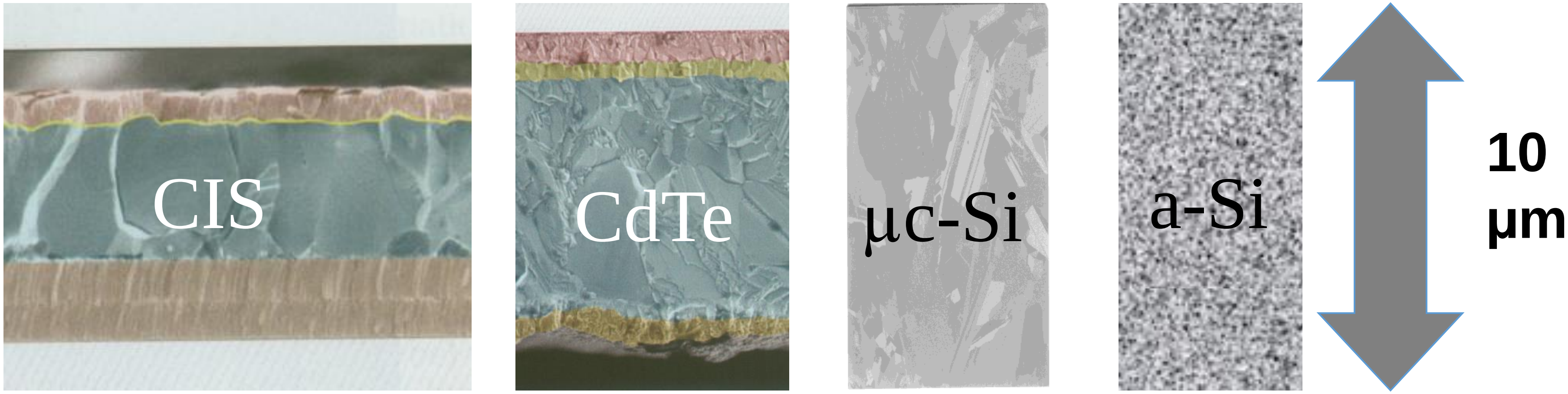
Cross-section of a solar cell with rear point contacts, produced with the laser LFC *(Laser Fired Contact)* method

Their most important distinguishing mark is the few hundred holes, ~ 100 µm in diameter, produced with the use of laser, whose wall-doping is the same donor type as that of the emitter, and this allows to localize the electrode contacts exclusively on the back side of the cell. This reduces the cover coefficient down to zero, which, in turn directly affects the increase of the short-circuit current's density Jsc of the cell. An additional advantage of the cells with the contacts localized only at their back side is the possibility of their assembly into a module without the sequential interweaving of the connection strips, which allows for a better packing of the cells and also creates the possibility of an integrated module assembly, that is soldering the cell layer with the previously prepared rear matrix of the module.



Cross-section of a solar cell with rear point contacts, produced with the laser LFC *(Laser Fired Contact)* method, and cells with an EWT *(Emitter Wrap Through)* emitter

Thin film solar cells



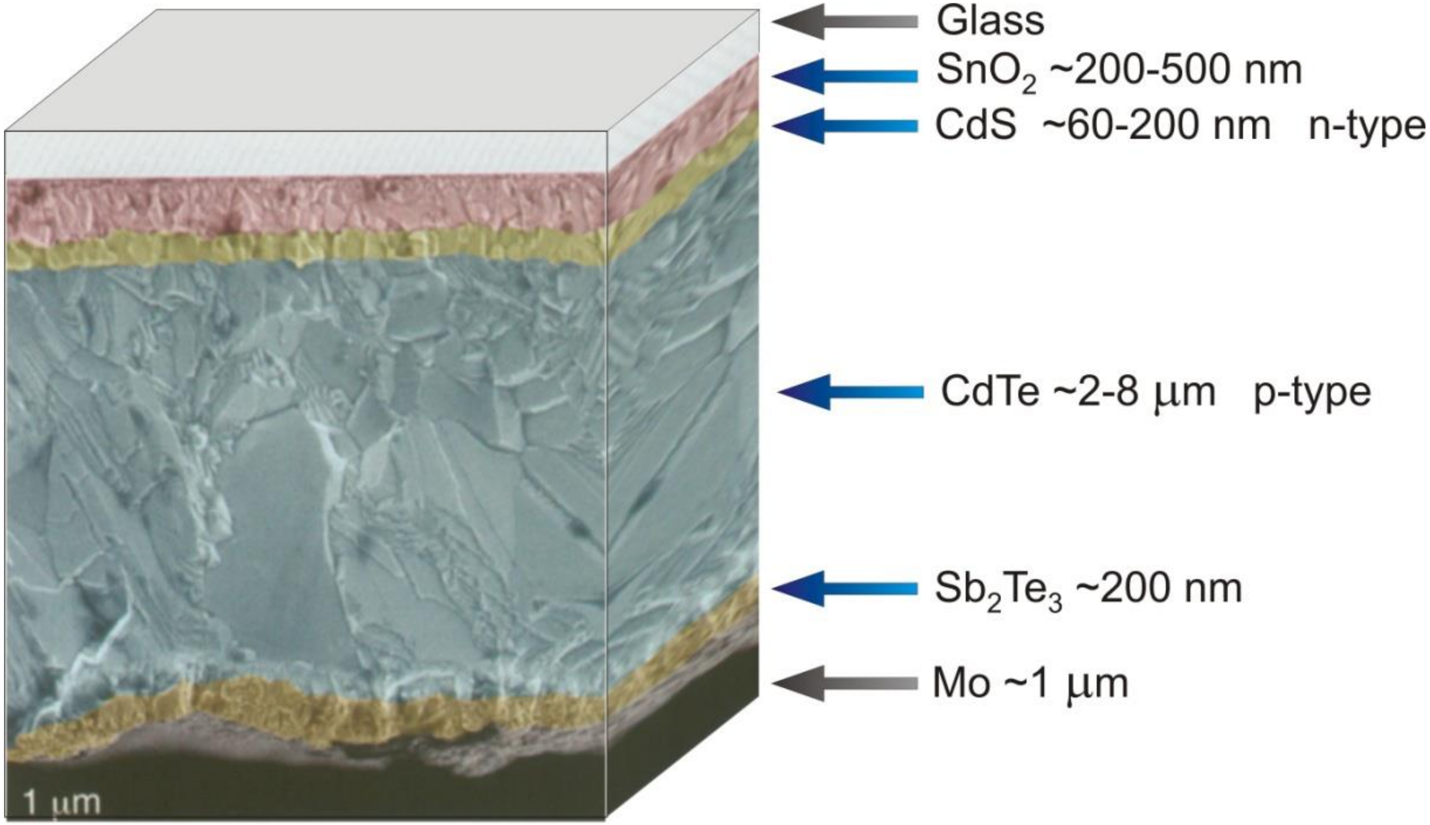
Thin film solar cells

Solar cells can be divided into two main groups: wafer based and thin films. The major drawbacks of wafer solar cells are that the Czochralski or casting process consumes a large amount of electrical power and when the wafers are cutting, there is a considerable wastage of crystal of about 33 %. Unlike crystalline silicon solar module manufacturing, in which the cells are constructed first and later interconnected, the creation of thin-film modules in the process in reverse. First, the absorber and conductive layers are deposited on the substrate and than separated so that they are monolithically connected in series. The interconnection is necessary to convert the high current and low voltage output into a low current and high voltage. This minimizes ohmic power losses, which scale as the square of the current. The most prominent thin film solar cells are: CdTe, CIS and a-Si/µc-Si or a-Si/mc-Si. Today thin film solar cells have a market share of about 12 %.

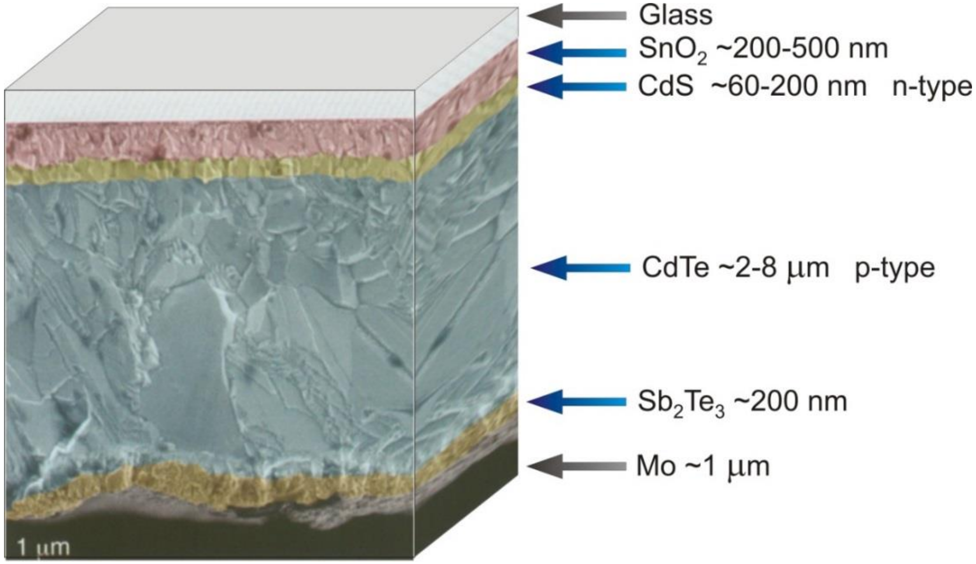
CdTe solar cell

Among the thin-layer solar cells, those of the greatest importance are currently the cells with a cadmium telluride base (CdTe), the latter having a simple energy gap Eg = 1.48 eV and a high value of the absorption coefficient $\alpha \sim 10^5$ cm^{-1}, within the wavelength range of 300 ÷ 820 nm, which makes the layer, only a few micrometers thick, provide the absorption of almost all the radiation in the above range. The above cells are made with the method of depositing successive layers on a glass base covered with a thin layer of a transparent conductive oxide (TCO). The rear contact is achieved through a thin layer of metal. The significant advantage of such cells is the possibility to produce their successive construction layers by means of such techniques as a chemical bath, vapour deposition, electrolysis, magnetron sputtering, spraying or close space sublimation (CSS)

CdTe solar cell

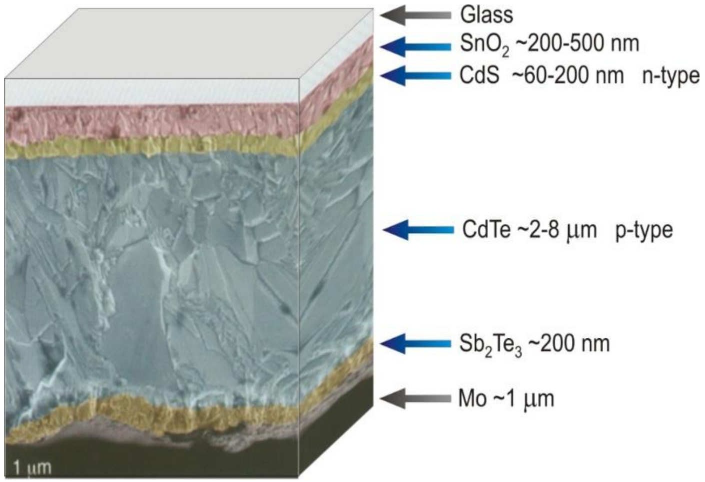


Cross-section of a thin-layer CdTe cell with a typical kind of conductivity and thickness of particular layers



The SnO_2 layer, fluorine doped, is the transparent contact that provides current collection from the front side of the device. In thin film solar cells the TCO front contact needs a high transmission ~ 90 %, high bandgap ~ 3 eV, and high conductivity for use as a transparent contact in the top cell. The CdS layer serves as the window layer. The heart of the cell is CdTe layer, serves as the absorber for incident light. The Sb_2Te_3 layer produces an ohmic contact to the CdTe, and the Mo decreases the series resistivity of the back contact. The thickness of the CdS layer can strongly affect device performance. The cell with a CdS layer of 60 nm has lower open circuit voltage (Voc).

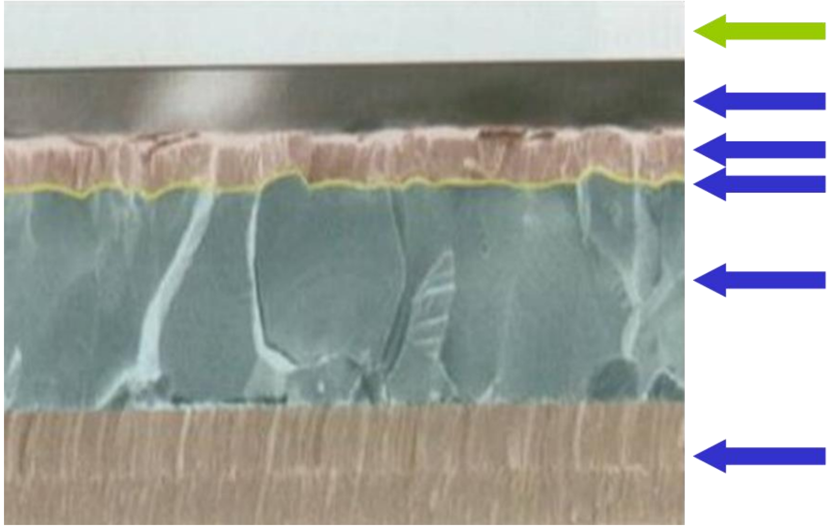
CdTe solar cell



Molybdenum is metal layer that is regularly used as a back contact layer for inorganic thin film solar cells, such as CIGS and CdTe. The most common method used to deposit Molybdenum is sputtering, especially in high volume manufacturing environments.

The advantages of a sputtered process include precise process control with scalable processes while still maintaining the ability to tune molybdenum layer properties for structure optimization. Reactive sputtering of molybdenum oxide has also been used as a buffer layer to improve the efficiency of thin film organic solar cells

CIGS solar cell



Glass

ITO ~ 300 nm

ZnO ~ 250 nm, n-type

CdS ~ 70 nm, n-type

CuInGaSe ~ 2 μm, p-type

Mo ~ 0.5 – 1.0 μm

The basic schematic cross sectional view of CIGS thin film solar cell

The CIGS layer stack is most commonly deposited on Soda Lime Glass (SLG); however, many companies are also looking at lighter, more flexible substrates such as polyimide or metal foils.

CIGS solar cell

- Technology process

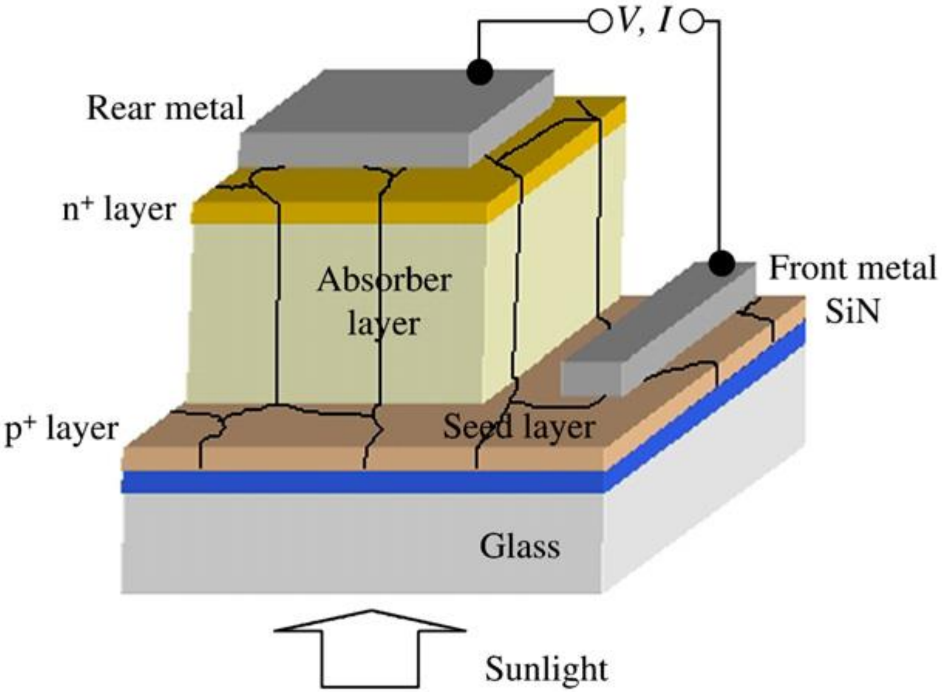
Step 1: Glass preparation
Step 2: Sputter deposition of molybdenum
Step 3: Patterning of the molybdenum conductor
Step 4: Compound formation to create CIGS
Step 5: Patterning to open up the CIGS material
Step 6: Sputter deposition of the zinc oxide transparent conductor
Step 7: Patterning of the zinc oxide
Step 8: Encapsulation
Step 9: PV module testing

CIS ($CuInSe_2$) is a one of the most light absorbent semiconductor and only 0.5 µm can absorb 90 % of the solar spectrum but on the other hand it is very complex material what makes it difficult to manufacture. Its bandgap of 1 eV is rather low and it is usually replaced by an alloy of indium and galium and it is found as CIGS ($Cu(In,Ga)Se_2$) cells. Its bandgap can be varied continuously between 1,0 – 1,68 eV, depending on the Ga/InGa ratio. Many applications require high specific power and CIGS cells on light weight and flexible substrates can yield more than 1,5 kW/kg specific power. The industrial methods for CIGS synthesis employ: DC magnetron sputtering, Nd:YAG laser pattering, vacuum deposition and chemical bath deposition. The Indium is also used in flat screens, light emitting diodes and touchscreens and its exploited resources know today are approximately 11 000 tons what has a negative effect on the future ability of the CIGS technology. Long life CIGS modules have only been possible when encased between glass. This is because the front contact made of zinc oxide is very susceptible to humidity. The main producer of CIGS modules is Wurth Solar (Germany).

CIGS solar cell

- Technology process

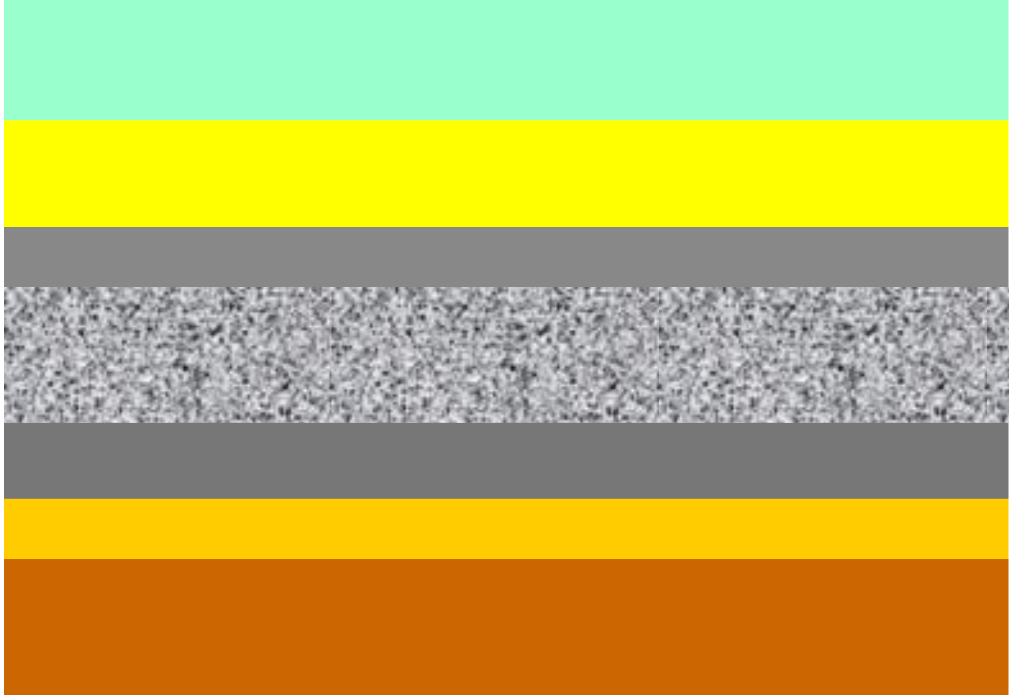
The Mo layer is deposited on the glass by DC magnetron sputtering. This process is carried out in a multi-chamber, in-line sputtering system, where properties of the Mo are sensitive to the sputtering conditions. After laser patterning of the Mo, the glass substrate is transferred to another in-line vacuum system where extensive use is made of sources capable of downward evaporation. Three custom designed sources are employed to supply the Cu, In, Ga and Se needed to form the $Cu(In,Ga)Se_2$ compound. During this process the glass is heated. After deposition of the CdS and scribing of the CIGS, a second in-line sputtering system is used to deposit highly conducting zinc oxide as the top transparent electrode. This electrode is then patterned by scribing, and the plate is ready for testing.



Schematic of a Mesa-type ALICIA poly-Si thin-film solar cell on glass
The sunlight enters the solar cell through the glass

The device is known as the ALICIA solar cell (ALuminium Induced Crystallisation, Ion Assisted deposition), A thin polycrystalline Si seed layer is made on a silicon nitride coated glass substrate by aluminium-induced crystallisation.
This seed layer is about 200 nm thick, has an average grain size of about 20 μm, and is heavily p+ doped with aluminium. Using this thin layer as a crystal template, an n-type layer about 1.8 μm thick is epitaxially grown on top, thus forming the p-n junction and the absorber layer of the solar cell. A heavily n+ doped layer is finally grown as a back surface field and contact region.

a-Si:H



Glass

TCO 900 nm

a-Si:H 10 nm, p-type

i a-Si:H 300 nm

a-Si:H 20 nm, n-type

ZnO 80 nm

Ag, Al

Eg = 1.7 – 1.8 eV

Thank you for your attention