SOLAR CELLS MANUFACTURING
FABRICATION PROCESS

TP LUMELEC

Table of contents

EVACUATION INSTRUCTIONS FOR TEACHERS 3
SECURITY INSTRUCTIONS 3
HANDLING INSTRUCTIONS 4
CLEANROOM ENTRY PROCEDURE 5
PROCESS SHEET 6
I- SUBSTRATE CHARACTERIZATION 6
II- MASKING OXIDE 6
III- PHOTOLITHOGRAPHY n° 1: "CATHODE OPENING" 8
IV- REAR SIDE PROTECTION 8
V- ETCHING MASK OXIDE 9
CATHODE DIFFUSION (N type) 10
DEOXIDATION OF DIFFUSION WINDOWS 11
XIII- METALLIZATION 11
XIV- PHOTOLITHOGRAPHY n° 2 : "METAL ETCHING" 12
XIII- REAR SIDE METALLIZATION 13
XV- METAL ANNEALING 14
XVII- ASSEMBLY 14
SIDE VIEW OF THE PROCESS STEPS 15
V- WITNESS TREATMENT 1 16
WITNESS TREATMENT 2: DEOXIDATION OF DIFFUSION WINDOWS 17
CHARACTERIZATIONS 18
XXI-Characterization of the photovoltaic cells and modules 20
MEASUREMENT OF JUNCTION DEPTHS 28
MASKS 29

EVACUATION INSTRUCTIONS FOR TEACHERS

REMINDER : Each teacher is responsible for the orderly and calm evacuation of all students under his care at the time of the incident.

IN THE MAIN CLEAN ROOM:

- ⇨ Evacuate the students by the emergency exit which leads directly into the hall.
- ⇨ Do not go through the airlock again; do not undress.
- ⇨ Exit through the main entrance of AIME.

IN THE PHOTOLITHOGRAPHY ROOM:

- ⇨ Evacuate the students by the emergency exit which leads directly into the corridor.
- ⇨ Do not go through the airlock again; do not undress.
- ⇨ Exit through the main entrance of AIME.

IN ASSEMBLY OR CHARACTERIZATION ROOMS:

- ⇨ Evacuate the students through the emergency exit leading to the green space behind the AIME.
- ⇨ Do not go through the airlock again; do not undress.
- ⇨ Take a tour of AIME.

GATHER ALL STUDENTS AT THE GATHERING POINT IN FRONT OF AIME.

TAKE A CENSUS.

DO NOT REINSTATE THE PREMISES WITHOUT THE ADVICE OF THE PERSONNEL IN CHARGE OF EVACUATION

SECURITY INSTRUCTIONS

LOCATE **THE SAFETY EQUIPMENT**:

- emergency exits
- security showers
- fire extinguishers
- self-contained breathing equipment

WEAR PROTECTIVE GLASSES IS MANDATORY FOR:
- CHEMICAL CLEANING (RCA AND H_2SO_4-H_2O_2)
- ALL WET ATTACKS

TRAINEES ARE **FORBIDDEN** TO TRANSPORT CHEMICALS FROM ONE WORKSTATION TO ANOTHER.

Keep in mind that:

- gloves are compulsory but they do not provide sufficient protection against high temperatures or corrosive products,
- some baths give off noxious vapors, normally drawn in by laminar flow hoods,
- overshoes sometimes make the floor very slippery.

HANDLING INSTRUCTIONS

- Throughout the duration of the process, the quality control of each step must be a permanent concern if we want to achieve a final component in working order, as well as a good performance on the whole. For this purpose, we will use in parallel with the "components" wafer, a control/test wafer (“witness”) which will characterize each step carried out.

- Warning: the wafers boxes must be opened by turning the cover clockwise

- For handling a wafer with tweezers:

- take advantage of the flat if the wafer is in the box
- pinch at least 5mm from the edge of the wafer to reduce the risk of breakage.

Any wafer coming out of a wet treatment must at the end undergo a rinsing with D.I. water and mechanical drying before being stored in its box.

- A good rinsing must include a change of tweezer, it is necessary to have a second one available and clean all tweezers.

- The tips of the pliers must not be wiped (neither on the gown, nor on paper), they must be rinsed with water and dried with nitrogen.

- The function of the gloves is to protect the components from contamination. Contamination of gloves should also be avoided. They are absolutely not an effective protection against acids.

- The plastic of the boxes cannot withstand temperatures above 250 ° C. In particular, cool down the wafers coming out from oven, for about 20 seconds in the open air.

- Paper is a source of contamination, make minimal use of it.

CLEANROOM ENTRY PROCEDURE

- Leave street clothes and bags in the seminar room.
- Six lockers, lockable, can be used in the SAS for valuables.
- No more than 4 people in the sas at the same time

Clean room entry:

Lab coat: white: permanent staff
blue: trainees
green: visitors

Overshoes: place the seam inside.
Do not put your foot in the clean part until you have put on your overshoes.

Mob caps: Provision in the wall dispenser.

Gloves: Provision in the wall dispenser. 2 sizes available.

Exit of clean room:

Lab coat/mob caps/goggles: place them in your personal box
Overshoes/gloves: throw them in dedicated trashes.

Recommendations:

- Be careful not to enter the airlock with muddy or wet dress shoes (use the doormat at the entrance of the AIME).
- Limit the number of objects and documents entering the Clean Room (**carbon pencil prohibited**).

PROCESS SHEET

Throughout the process, quality control at each step must be a constant concern if we want to achieve a final component in working order, as well as good performance on the entire wafer. For this purpose, we will use, in parallel with the “components” wafer, a “control” wafer which will make it possible to precisely characterize each step carried out before moving on to the next one.

I- SUBSTRATE CHARACTERIZATION

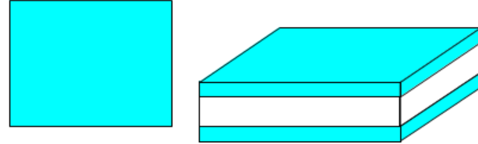
COMPONENTS AND WITNESS WAFERS: The substrates used are P-type silicon (Boron doped), orientation <100>, for which you will first have to determine the characteristics indicated below and report them on the characterization sheet (p.20).
These measurements are taken on the test wafer. Electrical characterizations can be made after Witness treatment n1 (page 9 & 16).

⇨ wafer thickness measurement	e_s =	µm
⇨ 4 probes measurement	V/I =	Ω
⇨ sheet resistance calculation	$R_{\square}$ =	Ω/□
⇨ resistivity calculation	ρ_s =	Ω.cm.
⇨ doping concentration calculation	N_A =	at.cm^{-3}

II- MASKING OXIDE

This step is generally carried out by AIME staff. It consists of cleaning the surface of the wafer to carry out thermal oxidation to form a thick SiO_2 oxide. This oxide, called “masking oxide”, protects the entire wafer. By photoetching we open the different “windows” necessary for the subsequent stages of the process.

masking oxide
Si (P)
masking oxide



1- Cleaning before Oxidation:

Operations	Conditions
⇨ 1°) Degreasing	Acetone
⇨ 2°) Rinsing	DI water
⇨ 3°) Chemical Oxidation	H_2SO_4 + H_2O_2 (1/1) - 2 min
⇨ 4°) Rinsing	DI water

⊂⊃ 5°) SiO_2 etching	BOE HF - 30 s
⊂⊃ 6°) Rinsing	DI water
⊂⊃ 7°) Drying	Spin dryer
⊂⊃ 8°) Washing - Drying	Washer dryer

<u>2- Wet thermal Oxidation:</u> This operation is performed in 5 steps inside oven N° 2-2

Conditions		
⊂⊃ process also test-wafer		
Temperature	**Duration**	**Flow rates**
⊂⊃ from 800°C to 1100°C	25 min	N_2 = 1 l/min
⊂⊃ 1100°C	35 min	H_2 = 2,3 l/min - O_2 = 1,5 l/min
⊂⊃ 1100°C	30 min	O_2 = 2,2 l/min
⊂⊃ 1100°C	5 min	Ar = 1,5 l/min
⊂⊃ from 1100°C to 800°C	60 min	N_2 = 1 l/min

At the end of this oxidation stage, you will recover two wafers:
- a wafer “component” where the photovoltaic cells will be made
- a so-called “witness” wafer used to characterize the main stages of the process.

III- PHOTOLITHOGRAPHY n° 1: "CATHODE OPENING"

This step is intended to etch the masking oxide previously formed on the front face of the component wafer. It takes place in two successive phases: a first operation called photolithography during which a resist is deposited then developed after exposure through mask no. 1. Added to this is **an intermediate step to protect the rear face** and finally a step called wet etching of the SiO_2. The operations necessary for these different stages are described below:

Supervisor's visa for the continuation of Operations ▼	
Operations	**Conditions**
⊂⊃ 1°) Drying	Hot plate 120°C – 2 min
⊂⊃ 2°) HMDS Deposit (Adhesion promoter)	Spin coater 4000 rpm - 30 s
⊂⊃ 3°) Positive photoresist deposit	Resist Shipley S1813 Spin coater 4000 rpm - 30 s
⊂⊃ 4°) 1st annealing	Hot plate 100°C – 60 s
⊂⊃ 5°) Alignment - Insolation	Mask n°1 – 5 s
⊂⊃ 6°) Development	Bath at 20 °C - 25 s
⊂⊃ 7°) Rinsing	DI water
⊂⊃ 8°) Drying	Spin dryer
⊂⊃ 9°) Observation	Optical microscope
⊂⊃ 10°) 2nd annealing	Hot plate 120° C - 45 s

IV- REAR SIDE PROTECTION

At this stage of the process, protection of the rear face is necessary in order to preserve the thick oxide layer which will prevent the formation of parasitic junctions on the rear face during the diffusion stage. This protection is provided by an adhesive film, resistant to acid attack and solvents, and removed after exposure to UV.

Supervisor's visa for the continuation of Operations	
Operations	**Conditions**
⊂⊃ 1°) Rear side protection	Place UV film

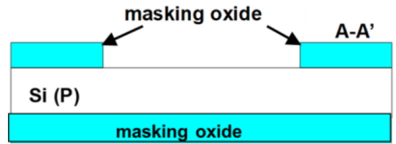
V- ETCHING MASK OXIDE

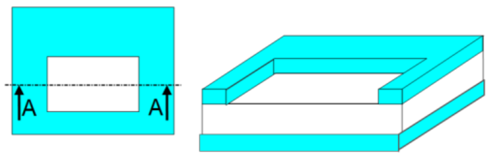
The aim of this step is to etch, through the resin mask, the masking oxide and thus delimit regions of the wafer where the bare silicon appears. These regions are called “diffusion windows” because it is through them that the diffusion of the dopant will take place, the masking oxide acting elsewhere as a barrier to diffusion. This engraving is a so-called wet etching which is carried out by immersing the wafer in an appropriate acid solution. This solution will selectively etch the oxide with respect to the silicon. It is important to know the etching time of the bath used because it can vary from one bath to another or even depending on the temperature and age of the solution. The determination of this speed, and therefore the attack time to be used, will be carried out on the witness wafer using the following operations.

Proceed with witness treatment n°1 in order to determine t1 (Go to Page 16).

	Supervisor’s visa for the continuation of Operations	
Operations	**Conditions**	
⊂⊃ 1°) SiO_2 Etching	Buffer HF (on component wafer during t1 determined according to witness)	
⊂⊃ 2°) Rinsing	DI water	
⊂⊃ 3°) Drying	Spin dryer	
⊂⊃ 4°) Control Etching	Optical microscope	
⊂⊃ 5°) UV Film removal	Remove the back side UV film (by placing the indicator for 4 minutes under the UV lamp or cleaning with acetone)	
⊂⊃ 5°) Resist removal	Acetone	
⊂⊃ 6°) Cleaning	D.I. water	
⊂⊃ 7°) Drying	Spin dryer	

At this stage of the process, the sectional profile of the “component” wafer is as follows:





At this stage, the remaining masking oxide portions on the edges of the window retains the HF liquid by a simple geometric effect. The hydrophilic/hydrophobic transition is therefore difficult to observe. We therefore advise you to check the engraving by immersing the test area located near the flat and thus observe the hydrophobic nature of the surface.

ORGANIC DECONTAMINATION

The control wafer from step 3) will also undergo this decontamination step.

Operations	Conditions
⊂⊃ 1°) Cleaning	H_2SO_4 + H_2O_2 - 2 min
⊂⊃ 2°) Rinsing	DI water
⊂⊃ 3°) Drying	Spin dryer

CATHODE DIFFUSION (N type)

We will now start the manufacturing of the PN junction of the photovoltaic cell.
In our process, the wafer (or the silicon substrate) is of type P (the holes are the majority carriers) and constitutes the anode of the diode. The cathode will therefore be of type N (electrons are the majority carriers) and will be obtained by diffusion of a donor type dopant, such as phosphorus in our case.

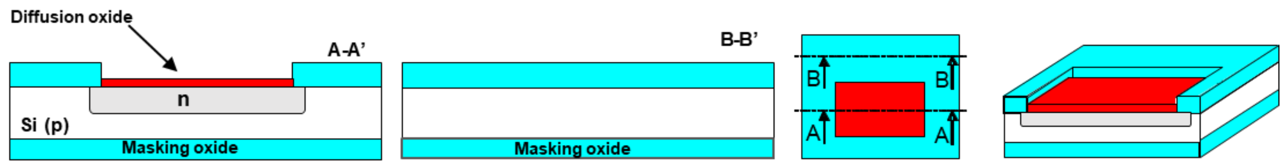
The control wafer from step 3) will also undergo this diffusion.

The large part of the witness wafer resulting from step 3) will also undergo this diffusion. The diffusion takes place in oven n°1-1. It consists of placing, at high temperature, the silicon wafers in a tube swept by:
- a neutral gas N_2,
- oxygen,
- a gaseous compound containing the doping element, here $POCl_3$.

We therefore carry out the diffusion of N-type impurities (phosphorus) in the vicinity of the silicon surface:

Temperature	Duration	Flow Rate
□ 950°C	5 min	N_2 = 2 l/min - O_2 = 0,1 l/min
□ 950 °C	17 min	N_2 = 2 l/min - O_2 = 0,1 l/min $POCl_3$ = 5 mg/min
□ 950 °C	7 min	N_2 = 2 l/min - O_2 = 0,1 l/min

At high temperatures, oxygen reacts with the silicon surface to form a doped oxide (“glass”) which serves as a source for diffusion.

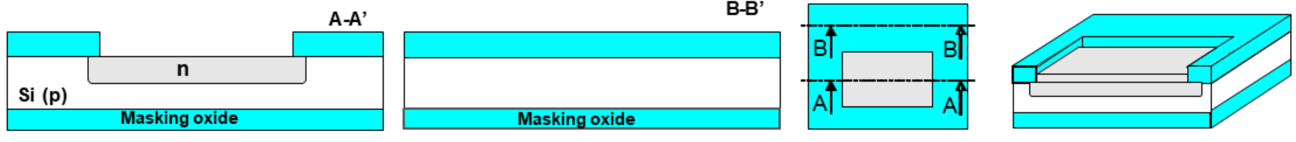


DEOXIDATION OF DIFFUSION WINDOWS

Proceed with witness treatment n°2 in order to determine t2 (Go to Page 17).

Supervisor's visa for the continuation of Operations	

Operations	Conditions	
⊂⊃ 1°) SiO_2 Etching	Buffer HF (on component wafer during t_2 determined according to witness)	
⊂⊃ 2°) Rinsing	DI water	
⊂⊃ 3°) Drying	Spin dryer	
⊂⊃ 4°) Control Etching	Optical microscope	
⊂⊃ 5°) Doping Control	V/I measure on left part of the witness after **witness treatment n°2**	



XIII- METALLIZATION

This operation consists of depositing on the front face of the wafer a layer of aluminum of approximately 4500Å, obtained either by cathodic sputtering or thermal evaporation. In both cases, it is necessary to have a sufficient vacuum in the deposition chamber to guarantee the purity of the metallic layer.

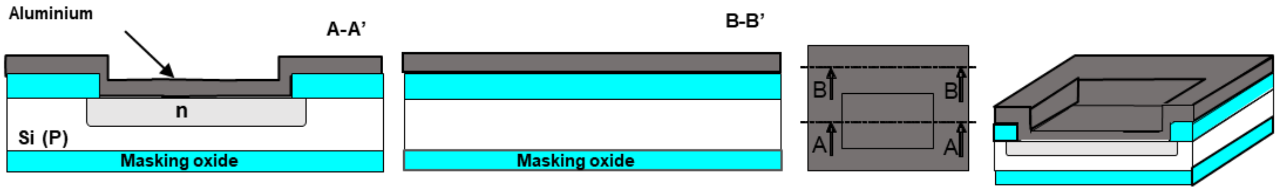
You will need to write down the parameters in of the corresponding tables:

Either by RF magnetron sputtering	⊂⊃ Deposit	Pressure before Deposit = 10^{-7} mbar Pressure during Deposit = 2.10^{-3} mbar RF Power = 150 W Target-substrate distance = 90 mm Duration of the Deposit = 15 min

OR

by thermal evaporation	⊂⊃ Degassing	T(subst.) = °C Duration = min

⊂⊃ Deposit	Pressure before Deposit = mbar Pressure during Deposit = mbar

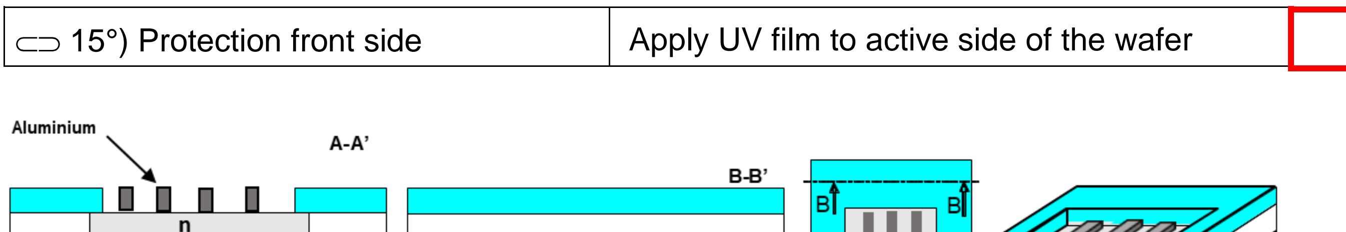


XIV- PHOTOLITHOGRAPHY n° 2 : "METAL ETCHING"

The second level of masking aims to protect the regions of the component where we wish to preserve the aluminum deposit (on the cathode). The photolithography conditions are summarized below:

Operations	Conditions	
Supervisor's visa for the continuation of Operations		▼
⊂⊃ 0°) Aluminum etching bath homogenization.	Switch on the ultrasonic cleaner containing the Al etching bath.	☐
⊂⊃ 1°) Drying	Hot plate 120°C – 2 min	
⊂⊃ 2°) Resist deposit	Resist Shipley S1813 Spin coater 4000 rpm - 30 s	
Supervisor's visa for the continuation of Operations		▼
⊂⊃ 3°) 1st annealing	Hot plate 100°C – 60 s	
⊂⊃ 4°) Alignment - Insolation	Mask n°2 – 5 s	
⊂⊃ 5°) Development	Bath at 20 °C - 20 s	
⊂⊃ 6°) Rinsing	DI water	
⊂⊃ 7°) Drying	Spin dryer	
⊂⊃ 8°) Observation	Optical microscope	☐
⊂⊃ 9°) 2nd annealing	Hot plate 120° C - 45 s	
⊂⊃ 10°) Bath of Al etching	Stop the ultrasonic cleaner, and take out the Al etching bath	
⊂⊃ 11°) Al ETCHING	Al etching bath (40vol. H_3PO_4 + 7vol. HNO_3 + 7vol. H_2O) using **final control with naked eye** + 30 s of supplementary etching	
⊂⊃ 12°) Rinsing	DI water	
⊂⊃ 13°) Drying	Spin dryer	
⊂⊃ 14°) Observation	Optical microscope	☐

⊂⊃ 15°) Protection front side	Apply UV film to active side of the wafer



⊂⊃ 16°) Desoxidation rear side	HF BOE
⊂⊃ 17°) UV Film removal	Remove the back side UV film (by placing the indicator for 4 minutes under the UV lamp or cleaning with acetone)
⊂⊃ 18°) Resist removal	Acetone
⊂⊃ 19°) Cleaning	D.I. water
⊂⊃ 20°) Cleaning	Spin dryer

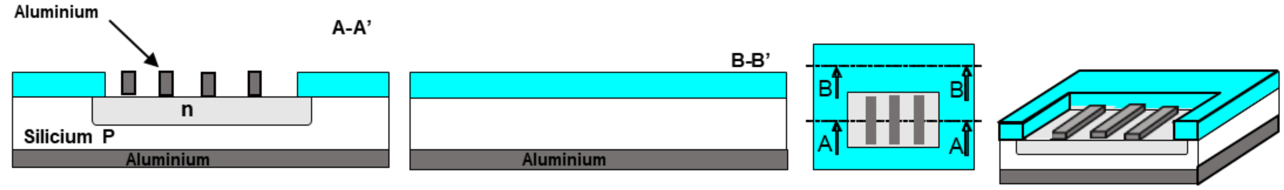
XIII- REAR SIDE METALLIZATION

This operation consists of depositing a layer of aluminum on the rear face of the wafer in order to be able to recover the contact of the P zone (anode). This layer will be obtained by cathode sputtering or by thermal evaporation. In both cases, it is necessary to have a sufficient vacuum in the deposition chamber to guarantee the purity of the metallic layer.
You will need write down parameters in one or other of the following tables:

Either by RF magnetron sputtering	⊂⊃ Deposit	Pressure before Deposit = 10^{-7} mbar Pressure during Deposit = 2.10^{-3} mbar RF Power = 150 W Target-substrate distance = 90 mm Duration of the Deposit = 15 min

OR

by thermal evaporation	⊂⊃ Degassing	T(subst.) = °C Duration = min
	⊂⊃ Deposit	Pressure before Deposit = mbar Pressure during Deposit = mbar



XV- METAL ANNEALING

This Operation is carried out in oven n ° 3-2 according to the conditions:

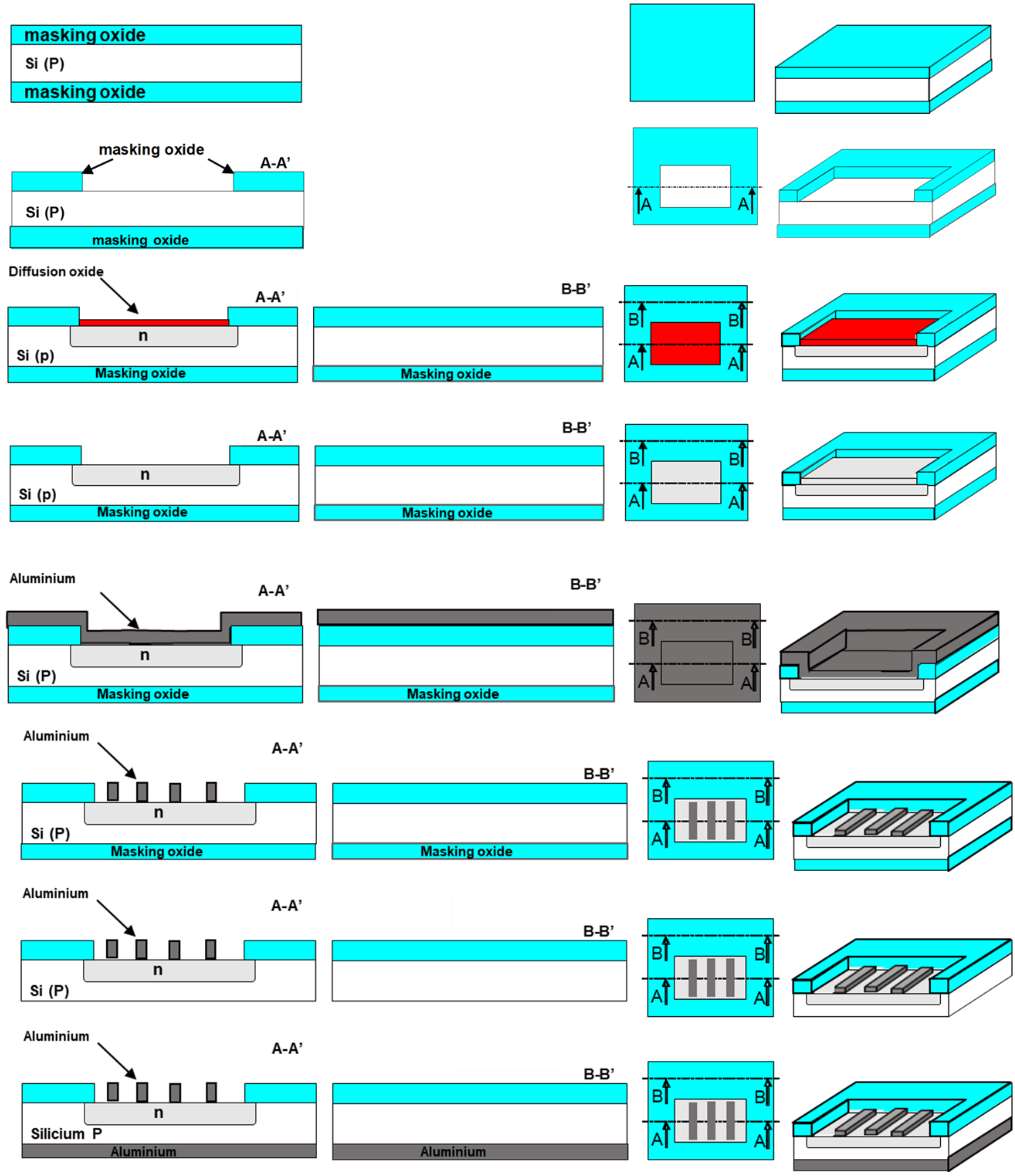
Temperature	Duration	Flow rates
⊂⊃ 400°C	20 min	$N_2 + H_2$ (5%) = 1 l/min

⊂⊃ Aluminum thickness measurement on "components" wafer using the profilemeter
⊂⊃ Fill in the 1st part of the results sheet before the wafer probing test

XVII- ASSEMBLY

⊂⊃ DICING of the “components” wafer with a diamond blade
⊂⊃ MOUNTING on base: welding on printed circuit board
⊂⊃ MICRO-WELDING by ultrasound (wedge bonding of Al-Si wire 5%, ∅ 25µm)

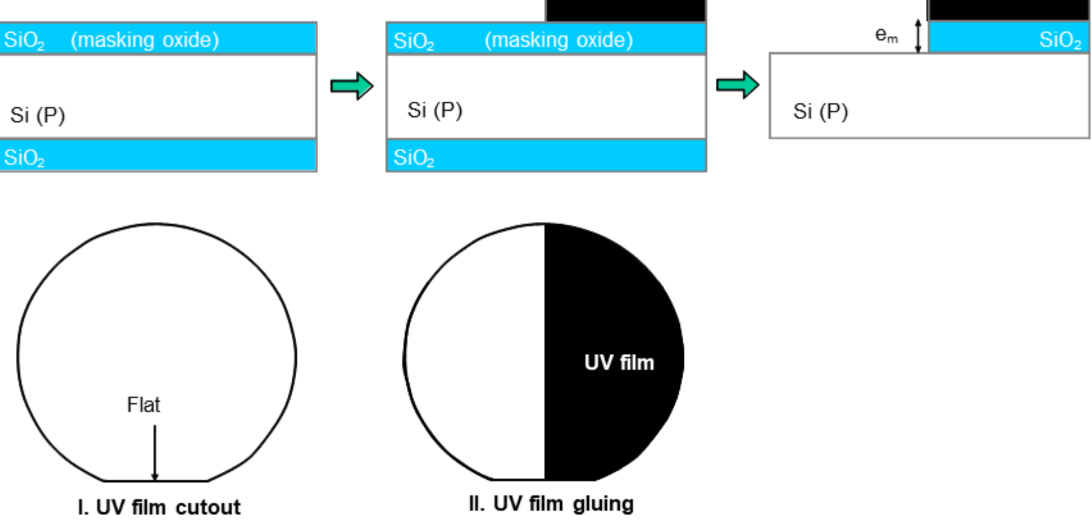
SIDE VIEW OF THE PROCESS STEPS



V- WITNESS TREATMENT 1

The aim of this step is to etch, through the resin mask, the masking oxide and thus delimit regions of the wafer where the bare silicon appears. These regions are called “diffusion windows” because it is through them that the diffusion of the dopant will take place, the masking oxide acting elsewhere as a barrier to diffusion. This engraving is a so-called wet etching which is carried out by immersing the wafer in an appropriate acid solution. This solution will selectively etch the oxide with respect to the silicon. It is important to know the attack time of the bath used because it can vary from one bath to another or even depending on the temperature and age of the solution. The determination of this speed, and therefore the attack time to be used, will be carried out on the witness wafer using the following operations.

Operations	Conditions
⊂⊃ 1°) UV Film on witness	Apply the UV film to the right half of the witness (flat side down)
⊂⊃ 2°) HF Etching	Immerse the witness in the HF buffer by determining the attack time of the thick oxide
⊂⊃ 3°) UV Film removal	Remove the UV film (by placing the indicator for 4 minutes under the UV lamp or cleaning with acetone)



Nota :

1 - Any aqueous solution slides on the Si while it wets on the SiO_2. The attack will therefore be completed when we visually notice that the HF no longer holds on the wafer.

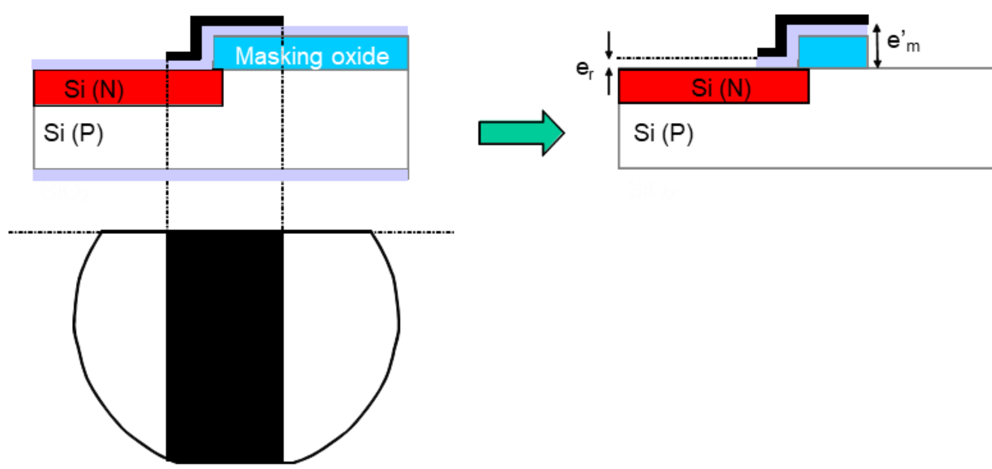
2 – How to apply the UV film:

- Cut a portion of film slightly larger than the surface to be covered
- Remove the film protecting the sticky side and apply the film to the surface, taking care above all that it adheres perfectly to the edges of the surface to be covered. It is advised to place first the UV film, sticky side up, and then set down the polish side of the witness in contact with the sticky side of the film (unpolished side of the wafer up).
- After the wet etching step, place the piece of wafer for about 4 minutes under the UV lamp in order to degrade the glue, and then lift the film which should hardly offer any resistance.

The thickness of the initial masking oxide (e_m) will be measured on the control wafer using the profilometer (TENCOR) and the ellipsometer, and will be reported on the characterization sheet (p.20).

WITNESS TREATMENT 2: DEOXIDATION OF DIFFUSION WINDOWS

In order to take the cathode contacts on the front face, the pre-deposition oxide will be etched so as to return to the level of the silicon surface in the diffusion windows. It will therefore first be necessary to measure the attack time t2 necessary for this engraving on the left part of the witness wafer. In reality, a slight over-etching will be carried out to be sure to eliminate all the oxide and thus obtain good quality contacts.



Operations	Conditions
⊂⊃ 1°) UV Film on witness	Apply the UV film to the right half of the witness (flat side down)
⊂⊃ 2°) HF Etching	Immerse the witness in the HF buffer by determining the attack time of the thick oxide
⊂⊃ 3°) UV Film removal	Remove the UV film (by placing the indicator for 4 minutes under the UV lamp or cleaning with acetone)

*** MATERIAL CHARACTERIZATION STEP (values to be reported in the MATERIAL CHARACTERIZATION SHEET – p.20):**

-the thicknesses of e'_m and e_r oxides will be measured on this witness wafer using the profilometer (TENCOR) and the ellipsometer,
- the phosphorus concentration of the diffused zone will be deduced from the junction depth xj and the V/I ratio obtained from measurements carried out on the left part of the witness,
- the boron concentration of the starting substrate will be deduced from the measurements carried out either on the deoxidized strip of the control plate from step 3), or on the right part of the witness wafer.

CHARACTERIZATIONS

I- SUBSTRATE CHARACTERIZATION:

At the start of the process, we measure:
- the four points measurement: V/I = ...Ω
- the thickness of the slices: e_s = ...µm

We deduce:
→ $R_{\square s}$ = ...Ω
→ ρ_s = ...Ω.cm
→ N_A = ...at/cm^3

II - MEASUREMENTS OF OXIDE THICKNESSES:

a- Masking oxide after Operation II e_m = ...µm

b- Diffusion oxide after Operation X e_d = ...µm

c- Final masking oxide $e_{m'}$ = ...µm

III- CHARACTERIZATION OF THE DIFFUSION:

After step X (diffusion of the substrate), Measurements of:

V/I = ...Ω → $R_{\square d}$ = ...Ω

X_j = ...µm → ρ_d = ...Ω.cm

→ C_s = ...at /cm3

ELECTRICAL CHARACTERIZATION OF SOLAR CELLS

The photovoltaic effect discovered by Edmond Becquerel in 1839 highlighted the fact that materials such as silicon emit electricity when they receive light. It is used in photovoltaic cells, small silicon-based electronic components. Without mechanical parts, without noise, without producing pollutants, they directly convert solar energy into electricity, in the form of direct current.

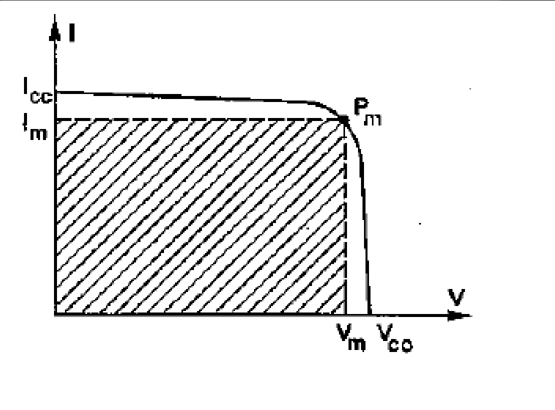
There are three main grades of silicon cells:

- monocrystalline silicon: it is the most expensive but its yield (from 12 to 17%) is higher than the other qualities,
- polycrystalline silicon: it is the most common currently on the market because it is less expensive even if its efficiency is a little lower,
- amorphous silicon: less efficient, it is significantly less expensive because it can be manufactured by vaporization on a support (plastic, glass, etc.)

Each photovoltaic cell delivers a current under its own voltage. Its voltage when no current flows at its poles is called "open circuit voltage" (V_{CO}) and the current flowing when there is no voltage is the "short circuit current" (I_{CC}). These are the two extreme situations of the cell for which no power is delivered by the cell. We always seek to avoid this situation by operating the photovoltaic solar panel with voltage and current at maximum power (V_m and I_m). These two parameters are used to determine the nominal efficiency of the photovoltaic panel, the power of which is then expressed in Wc (peak Watt).

Each cell is therefore attached to precise characteristics obtained in the factory under "normal" conditions and listed below:

- **Short circuit current: I_{cc} (A)**
- **Open circuit voltage: V_{co} (V)**
- **Form Factor (filling factor): FF**
- **Operating point: (V_m, I_m) => P_m**
- **Optimum conversion efficiency:** η



- The FF parameter is the filling factor or form factor, it measures the rectangular nature of the I(V) curve. It can vary from 0.25 for a low efficiency cell to 0.9 for an ideal cell. It can be defined by :

$$FF = \frac{V_m . I_m}{V_{CO} . I_{CC}}.$$

- The optimum conversion efficiency is defined by the ratio of the maximum available electrical power to the incident light power:

$$\eta = \frac{Pmax}{Psolar} = \frac{FF . I_{CC} . V_{CO}}{Psolar}$$

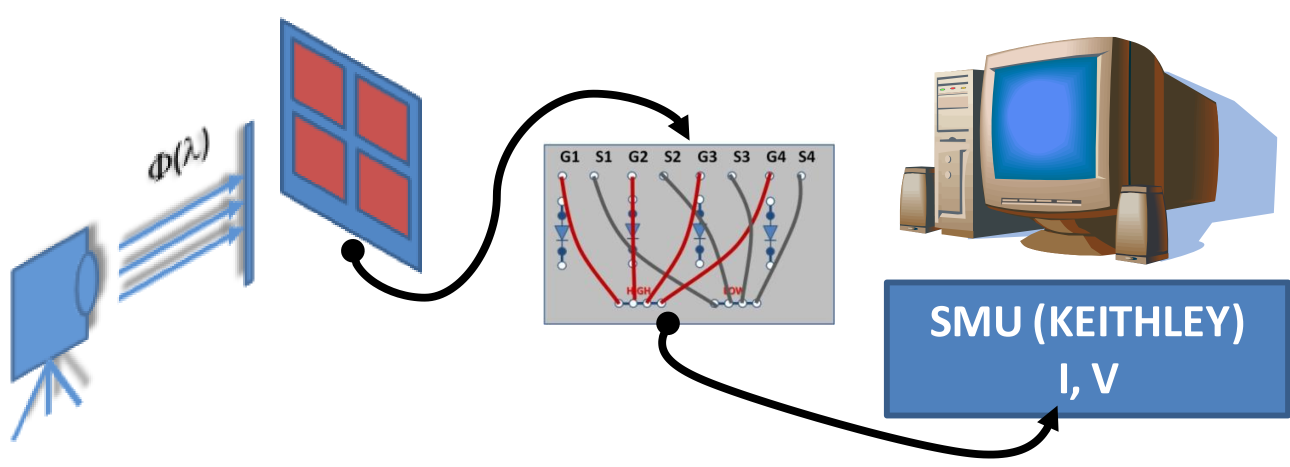
Assembled in series, the cells provide the useful voltage and electric current, thus obtaining photovoltaic modules. They are the ones we market. The material used being very fragile, it is necessary to protect it from bad weather with transparent and solid glass. The envelopes currently used are designed to resist environmental attacks for twenty to thirty years.

The purpose of this characterization session is to introduce you to solar cells, solar panels (modules) and to acquire some notions of radiometry.
The experiments installed in the characterization room will allow you to address several issues related to the production of electrical energy from light energy:

- Trace and understand a solar cell characteristic,
- Mount solar cells in series and in parallel to create a module,
- Highlight shading effects.

On the characterization program:
- Initially, we will draw and comment on the characteristics I=f(V) and P=f(V) of a photovoltaic cell (abbreviated as "PV cell").
- In a second step, we will study the series and parallel associations of cells in order to increase the electrical power available.

XXI- Characterization of the photovoltaic cells and modules



- Reading of the I=f(V) characteristics is done with the SMU (Source Measure Unit) of KEITHLEY controlled by the PC. You will then use the TP LUMELEC software.

- You will place the "Solar" measuring bench so that the cells are illuminated evenly and with maximum light. The assembly should not be moved throughout the measurement phase.

1 - Using the luxmeter, measure the light intensity IL of your source expressed in lux,
2 - Measure the surface illuminated by the lamp expressed in cm^2,

2 - Characteristic of a single PV cell:

a) Adjust the handling bench,
b) Carry out the I(V) measurements from 0 to 100% illuminance in steps of 20%,
c) Complete the following table for the maximum incident light power (100%):

- **- Short circuit current: I_{cc} (A)**
-
- **- Open circuit voltage: V_{co} (V)**
-
- **- Form Factor (filling factor): FF**
-
- **- Operating point: (V_m, I_m) => Pm**
-
- **- Optimum conversion efficiency: η**

Open circuit voltage: Voc (mV)	**V_{CO} =**
Short circuit current: Icc (A)	**I_{CC} =**
Maximum electrical power P_{MAX} (mW)	**P_{MAX} =**
Optimum conversion efficiency (%)	**η =**

a) What parameter of the characteristic I=f(V) of the cell does the illumination vary?
b) Give the coordinates (V, I, P) as well as a name at this particular point where this power is maximum.
c) According to the range of variation around this point, does the cell behave like a current or voltage generator?

3 - Characteristic of the other PV cells:

a) Complete the following table for the maximum incident light power (100%) for each of the other cells.

Open circuit voltage: Voc (mV)	**V_{CO} =**
Short circuit current: Icc (A)	**I_{CC} =**
Maximum electrical power P_{MAX} (mW)	**P_{MAX} =**
Optimum conversion efficiency (%)	**η =**

4 - 4 - Association of cells : solar module

We want to increase the available power of the generator. To do this, we create an association of several cells called a “module”. Throughout the rest of the TP, we will place ourselves in maximum lighting conditions.

4.1 - Serie :

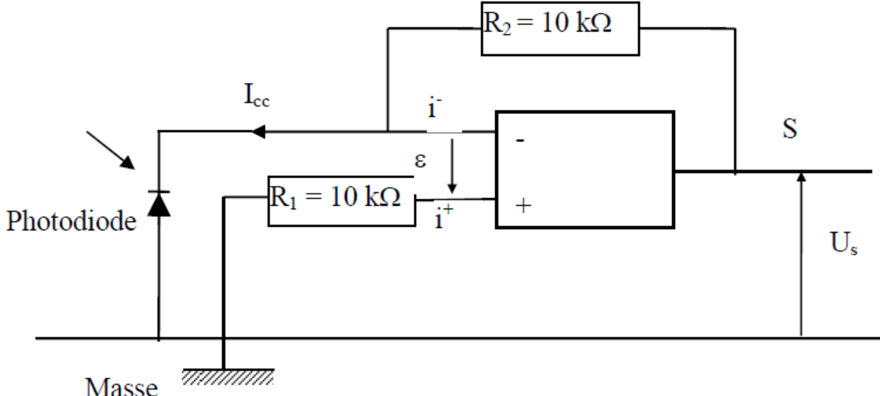
a) When generators are associated in series, what is the common electrical quantity?
b) What electrical quantity is increased by associating generators in series?
c) Carry out the serial association of two cells and repeat the same measurements as in question 2:

Open circuit voltage: Voc (mV)	V_{CO} =
Short circuit current: Icc (A)	I_{CC} =
Maximum electrical power P_{MAX} (mW)	P_{MAX} =

4.2 -Parallel :

4.2.1 – Simple assembly :

a) When generators are associated in parallel, what is the common electrical quantity?
b) What electrical quantity is increased by combining generators in parallel?
c) Carry out the parallel association of two cells, illuminate them simultaneously with the same light intensity and measure V_{CO} using a multimeter and I_{CC} using the following setup:



Open circuit voltage: Voc (mV)	V_{CO} =
Short circuit current: Icc (A)	I_{CC} =
Maximum electrical power P_{MAX} (mW)	P_{MAX} =

d) What can you deduce about the mode of operation of a photovoltaic cell?

4.2.2 - Association with anti-return diode:

When the solar panels are associated in parallel, it is necessary to place an anti-return diode (ARD) in series with each cell or module. In fact, in the event of an imbalance in sunlight between panels, the most illuminated modules must not discharge current into the less illuminated modules (at the risk of damaging them). If the cells would charge a battery, these diodes also protect against the current that the battery could deliver during periods of low sunlight.

Carry out the association in parallel with ARD of two cells and redo the same measurements as in question 4.2.1 in conditions of maximum illumination:

a) Note the characteristics I=f(V) and P=f(V) of the two cells associated in parallel with DAR.

Open circuit voltage: Voc (mV)	V_{CO} =
Short circuit current: Icc (A)	I_{CC} =
Maximum electrical power P_{MAX} (mW)	P_{MAX} =

b) What is the maximum electrical power here?
c) Compare it to that of a single cell and that of the series assembly. Where do the differences come from?
d) What is the threshold voltage of the ARDs? Check it if necessary, with the multimeter in the "diode test" position.
e) What is the electrical power lost PP due to the DAR diodes?

4.3 - Series and Parallel Association:

a) When generators are associated in series and in parallel, what are the common electrical quantities?
b) Make the association in parallel of two branches each containing a series association of two cells, illuminate them simultaneously with the same light intensity and redo the same measurements as in the previous question:

Open circuit voltage: Voc (mV)	V_{CO} =
Short circuit current: Icc (A)	I_{CC} =
Maximum electrical power P_{MAX} (mW)	P_{MAX} =

5 - Operation of the solar module:

We offer you :
- A motor topped with a fan
- A "classic" red LED

Find and create the assembly(s) to operate:
1 - the engine
2 - the LED

3 - the motor and the LED at the same time.

Extract from the Datasheet of a red LED from VISHAY:

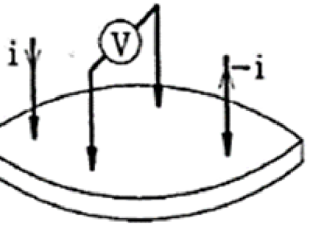
TLHK5800

Vishay Semiconductors

OPTICAL AND ELECTRICAL CHARACTERISTICS [1] RED						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Luminous intensity [2]	I_F = 20 mA	I_V	1000	5500		mcd
Dominant wavelength	I_F = 10 mA	λ_d		630		nm
Peak wavelength	I_F = 10 mA	λ_p		643		nm
Angle of half intensity	I_F = 10 mA	φ		± 4		deg
Forward voltage	I_F = 20 mA	V_F		1.9	2.6	V
Reverse voltage	I_R = 10 µA	V_R	5			V
Junction capacitance	V_R = 0, f = 1 MHz	C_j		15		pF

4 points probe

1. V/I measurement on a thin layer of thickness e and resistivity ρ



If the thickness is negligible compared to the other dimensions, we can construct a two dimensional model of the conduction which gives :

$$\frac{V}{I} = K\,\frac{\rho}{e} \quad (1)$$

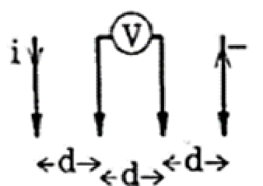
K being a dimensionless coefficient characteristic of 2D geometry (shape of contours, position of contacts).

ρ/e ration characterizes the layer, we call it $R_\square$ We then obtain :

$$\frac{V}{I} = KR_\square \quad (2)$$

(NB: $R_\square$ is expressed in Ohms)

2. Value of K (special case)



The coefficient K can be calculated analytically in some very simple particular cases, for example for 4 points aligned equidistant on a layer without limits (infinite):

$$K = \frac{\ln(2)}{\pi} \quad (3)$$

Practical value $1/K = 4.532$

3. Case of a doped layer

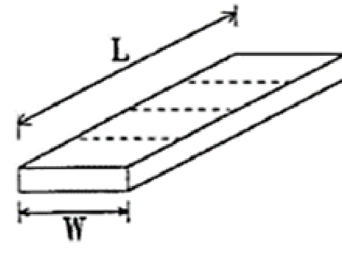
The resistivity is not uniform over the thickness e, but formulas *(2)* and *(3)* are still applicable, by generalization of the use of $R_\square$

We then defined an average resistivity ρ_m such that :

$$R_\square = \frac{\rho_m}{e} \quad (4)$$

If the dopant distribution law is known, we can deduce from ρ_m the concentration at the surface and for different depths (see charts)

4. Relationship with mask drawing



Resistance of a conductive track of length L and width W (parallelepiped) :

$$R = \rho\frac{L}{S} = \rho\,\frac{L}{eW} = \frac{L}{W}\,R_\square \quad (5)$$

Where L and W characterizes the design of the masks while R characterizes the the technology. The L/W ratio can be considered as a « number of squares » hence the name of resistance per square or commonly sheet resistance,

5. Case of significant thickness

If the thickness of the layer is not negligible but still reasonably small, we can apply formulas (2) and (3) by replacing K by a corrected coefficient K', a function of the ratio between the thickness and the other dimensions . In the case of the 4 equidistant points of distance d, the correction is negligible as long as:

$$\frac{e}{d} < 0.25$$

Practical method for measuring 4 points:

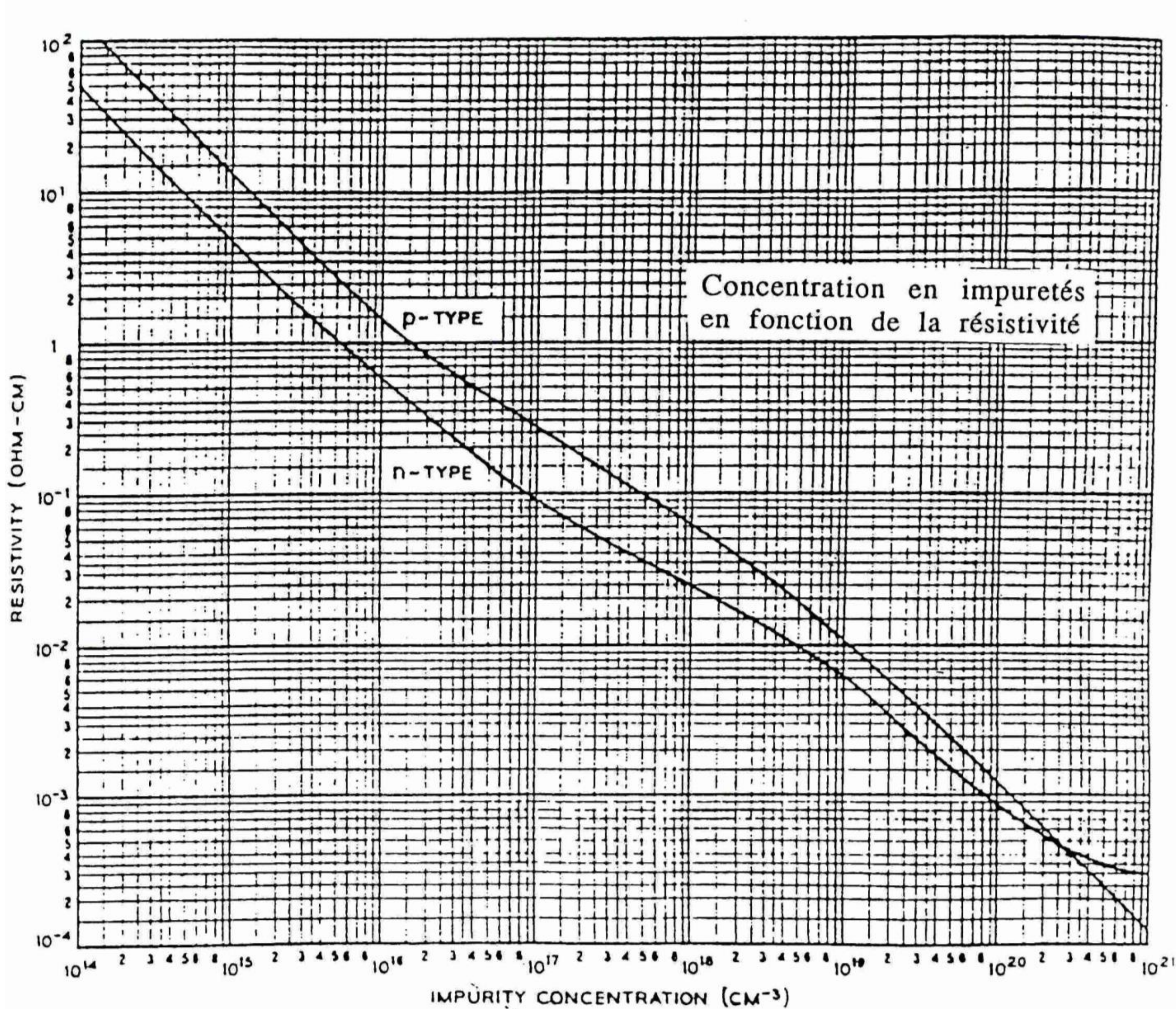
- perform a V/I measurement not too close to the edges of the sample
- express the measurement in Ohms
- multiply by 4.532 to obtain $R_\square$, report this result (always in Ohms)

(the distance between 2 points being 1.59 mm, the thickness correction is not necessary)

- express the thickness e of the layer in cm
- multiply $R_\square$ by e to obtain the resistivity ρ or ρ_m, note this result (in Ohm.cm)
- use an abacus to deduce the dopant concentration (after possibly calculation of the conductivity).

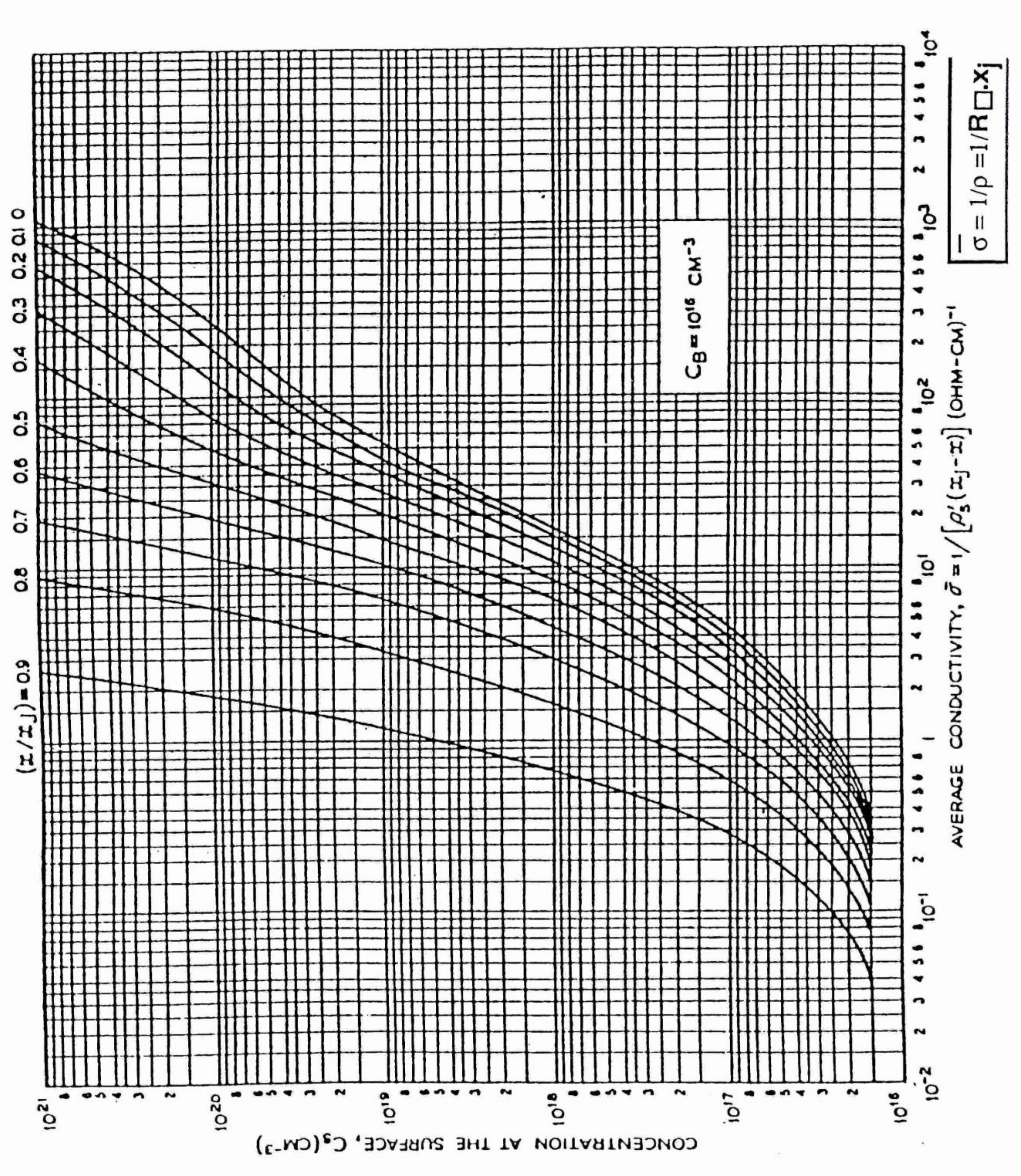
ATTENTION: this is not the same chart depending on whether the doping is uniform (substrate, deposited polysilicon) or not (diffused or implanted layer).

DOPING CONCENTRATION OF STARTING WAFER



Resistivity of silicon at 300°K as a function of acceptor or donor concentration.

DOPING CONCENTRATION AS A FUNCTION OF CONDUCTIVITY AFTER PREDEPOSIT



MEASUREMENT OF JUNCTION DEPTHS

DEFINITION:
Xj is the distance counted from the silicon surface such that C (Xj) = C_B
C (x) corresponding to the doping profile of the diffused zone and C_B to that of the substrate.

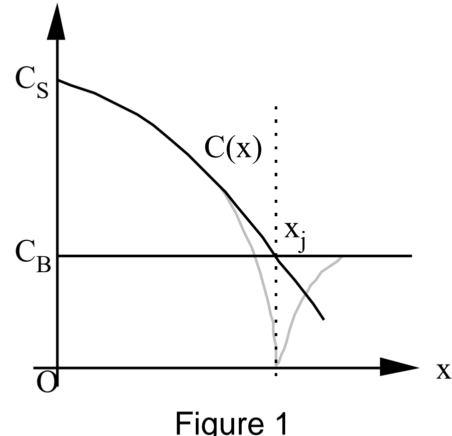


Figure 1

PROCEDURE:
a- Mechanical digging of the sample by a cylinder of radius R coated with diamond paste to obtain an imprint with a depth greater than Xj.

b- Chemical revelation which colors the N zone and the P zone differently.

c- Observation under Optical microscope and measurement of quantities x and y (fig. 3).

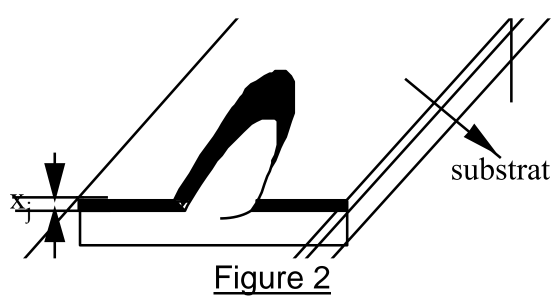


Figure 2

CALCULATION OF X_J :
With the notations in the figure, the measured lengths x and y are such that:

$$\left.\begin{array}{l} x = a - b \\ y = a + b \end{array}\right\} \quad xy = a^2 - b^2$$

In addition, simple geometric considerations lead to:

$$x_j = \{R^2 - b^2\}^{\frac{1}{2}} - \{R^2 - a^2\}^{\frac{1}{2}}$$

$$8 \; R \left\{ \left(1 - \frac{b^2}{2R^2}\right) - \left(1 - \frac{a^2}{2R^2}\right) \right\} = \frac{xy}{2R}$$

$$= \frac{xy}{2R}$$

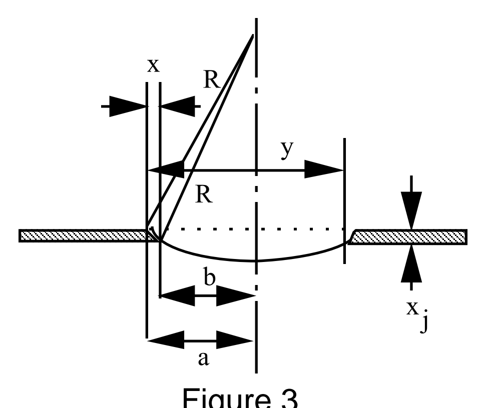


Figure 3

Taking into account the radius of the cylinder R = 1.25 cm and the magnification of the microscope, we have:

objective X 3,2 1 division of Vernier screw → 1 μm and

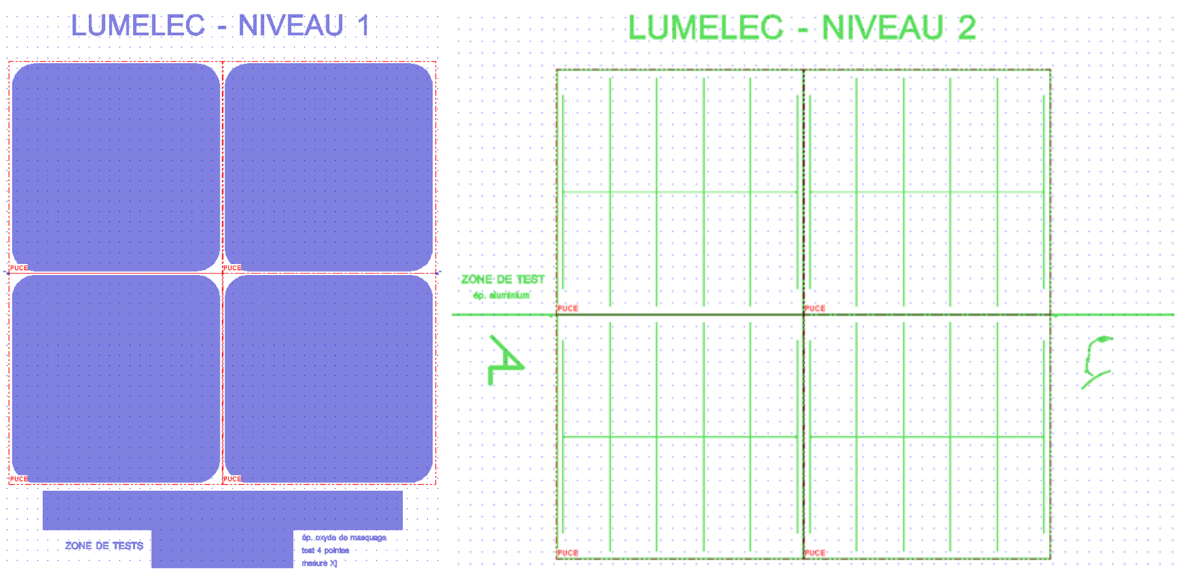
$$x_j\,(\mu m) = 39{,}9 \;.\; 10^{-6} \; x_{(div)} \cdot y_{(div)}$$

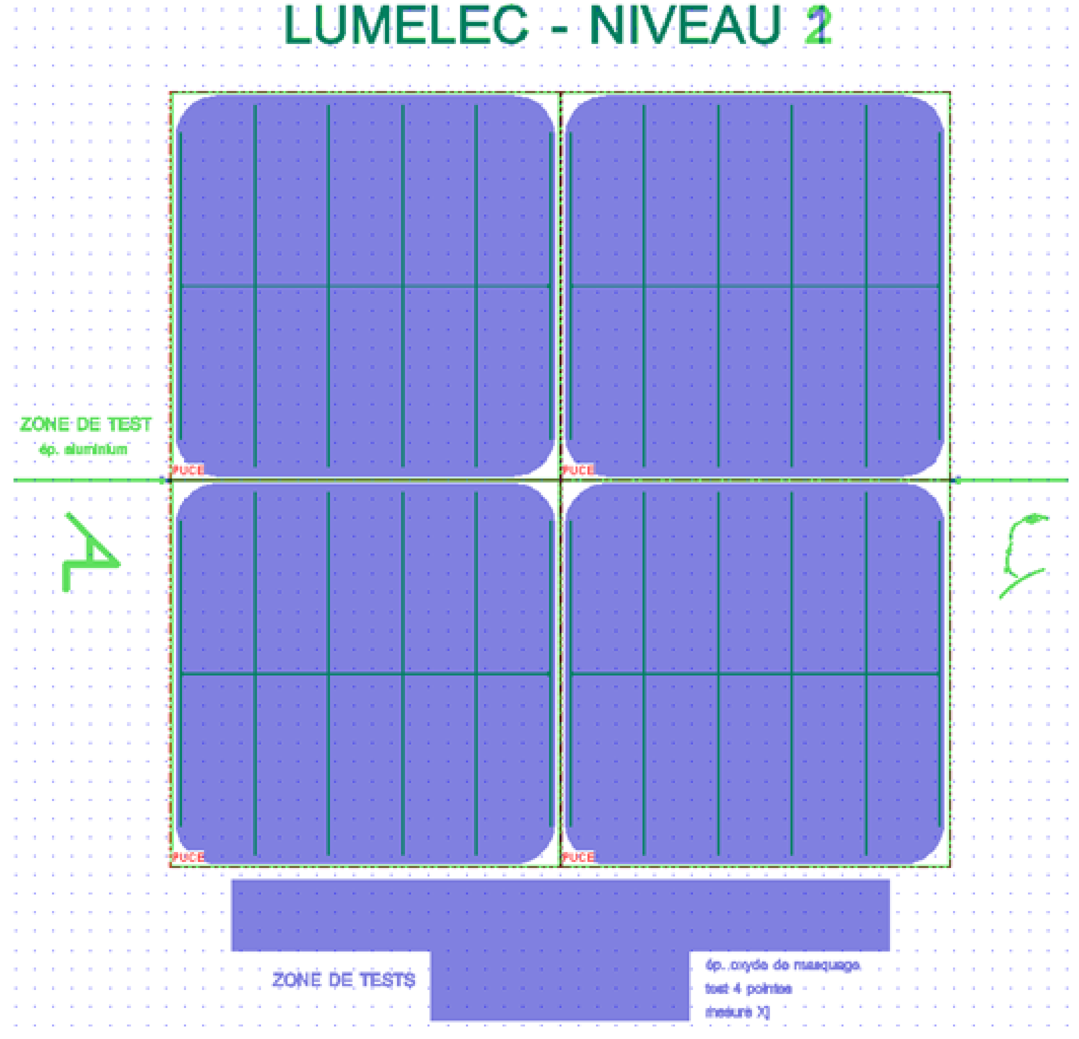
objective X 5 1 division of Vernier screw→ 0,6 μm and

$$x_j\,(\mu m) = 14{,}40 \;.\; 10^{-6} \; x_{(div)} \cdot y_{(div)}$$

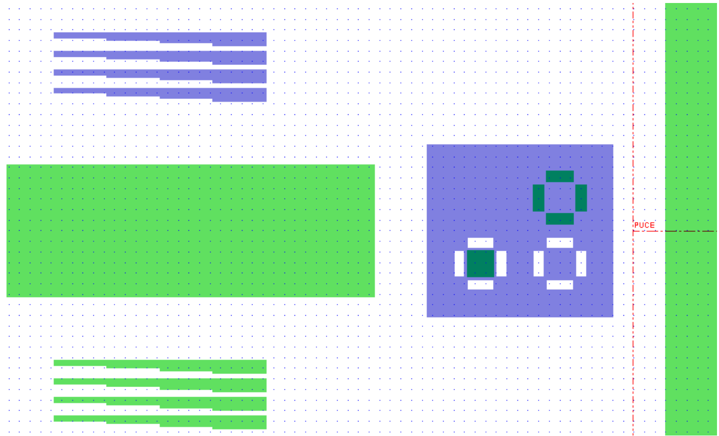
MASKS

1 – MASKS LEVEL 1 AND 2

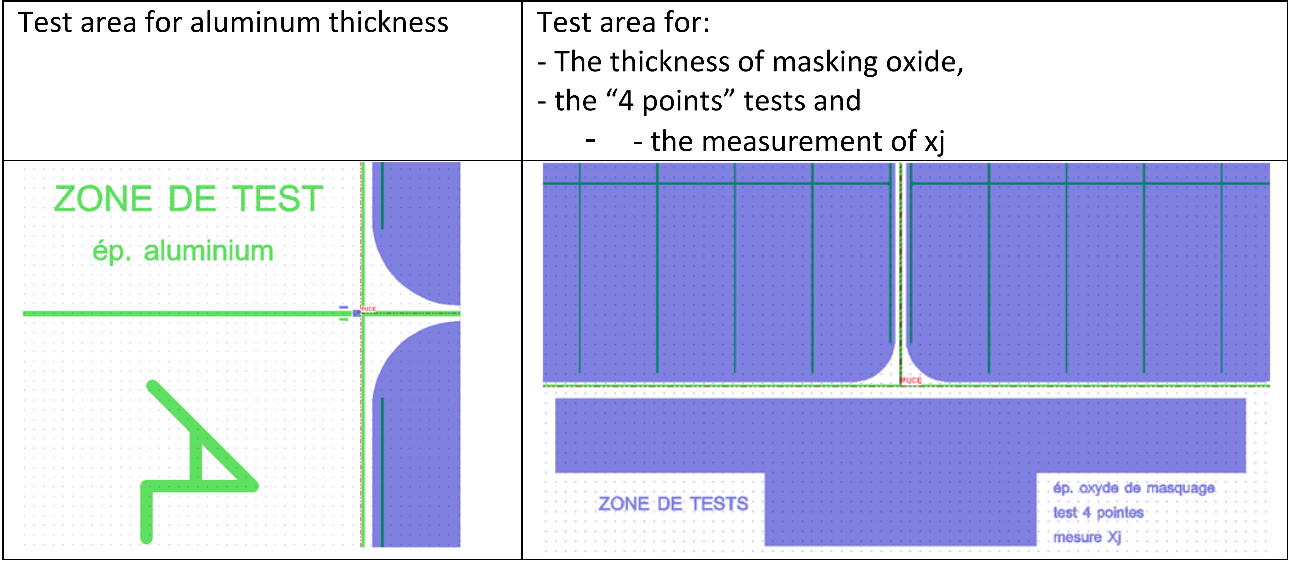




2 – ALIGNEMENT MARKS:



3 – TESTS ZONE :



Test area for aluminum thickness	Test area for: - The thickness of masking oxide, - the “4 points” tests and - - the measurement of xj