Prof. Giuliano Martinelli,

Donato Vincenzi, Marco Stefancich, Cesare Malagù

Università di Ferrara, Dipartimento di Fisica

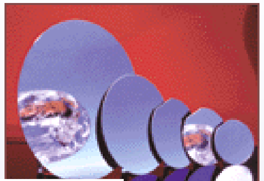
Concentration photovoltaic systems

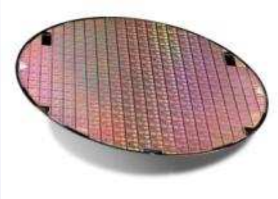
Classical and new approaches to thin film photovoltaics

n.i.s.
Nanostructured Interfaces and Surfaces
Centre of Excellence

Torino, 23 Giugno 2008

Sensor and Semiconductor Laboratory





Prof. Giuliano Martinelli
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Stefano Baricordi	Cesare Malagù
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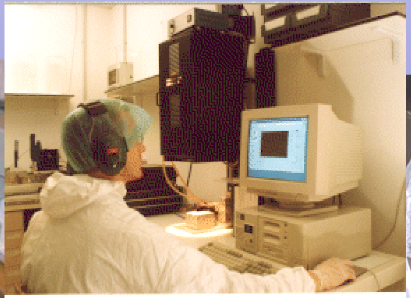
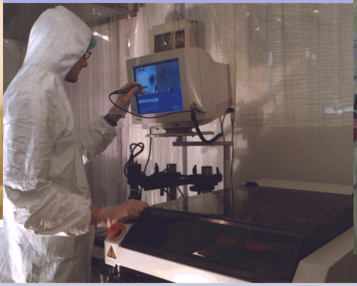
Alan Cervi	Marco Stefancich
Delia Puzzovio	Beatrice Vendemiati
Sandro Gherardi	Donato Vincenzi





Sensor and Semiconductor Laboratory

Prof. G
Prof. V
Maria

Andre
Stefan
Marian
Alan C
Delia I
Sandro

i

SINCERT

CERMET

CERTIFICATO DEL
SISTEMA QUALITÀ

SI DICHIARA CHE IL SISTEMA DI GESTIONE PER LA QUALITA DEL

LABORATORIO SENSORI E SEMICONDUTTORI -
DIPARTIMENTO DI FISICA UNIVERSITA' DI FERRARA
Via Paradiso 12 - Ferrara

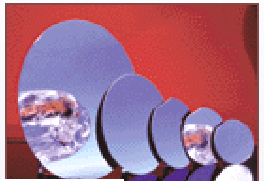
REGISTRAZIONE No. 2530 - A

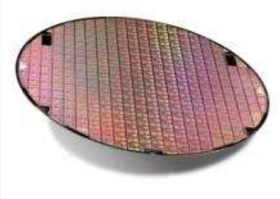
È CONFORME ALLA NORMA

UNI EN ISO 9001 - 2000

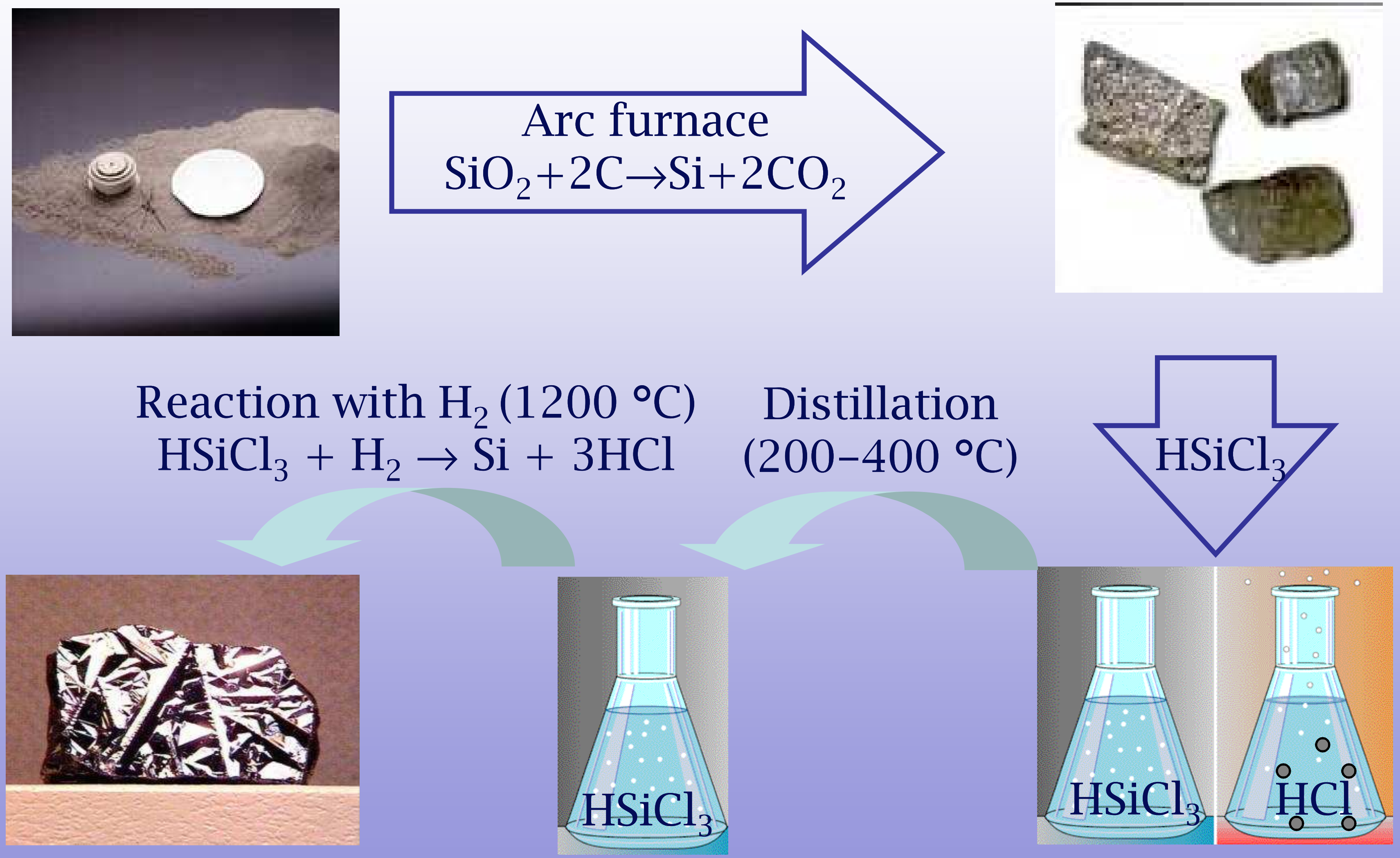
PER I SEGUENTI PRODOTTI/SERVIZI:

PROGETTAZIONE E REALIZZAZIONE DI SENSORI A FILM SPESSO PER GAS
E CELLE FOTOVOLTAICHE





The silicon feedstock production



Quarzite (SiO_2)
18 kg

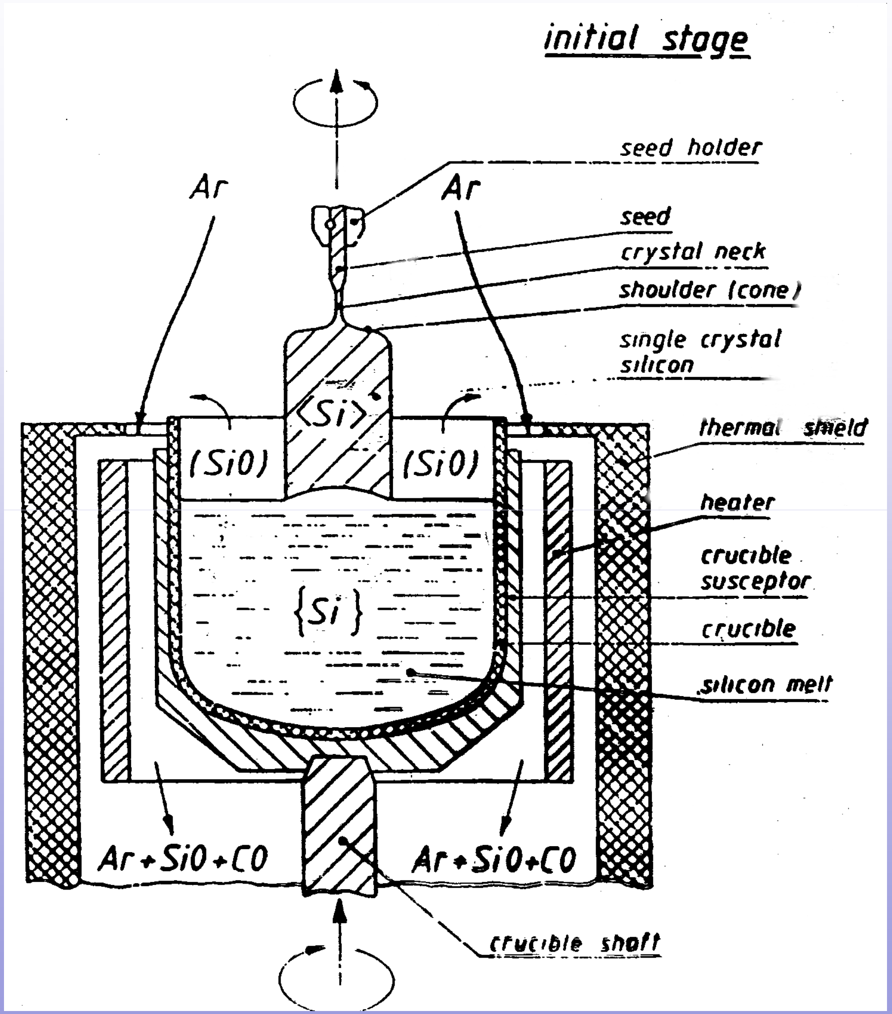
Arc furnace
$SiO_2 + 2C \rightarrow Si + 2CO_2$

$HSiCl_3$

Distillation
(200–400 °C)

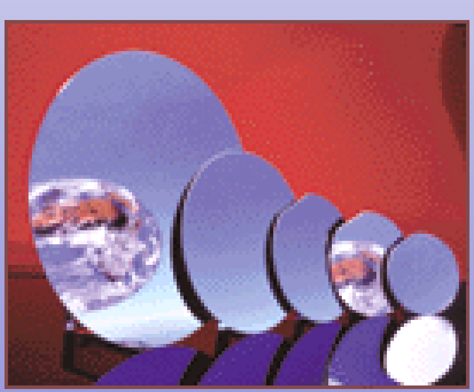
Reaction with H_2 (1200 °C)
$HSiCl_3 + H_2 \rightarrow Si + 3HCl$

Czochralski Growth (1400 °C)



Monocrystal Ingots (up to 300 mm)

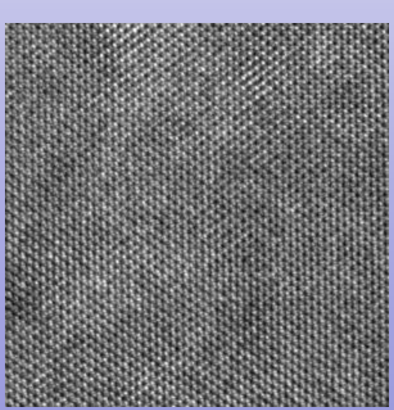
Slicing, grinding, polishing

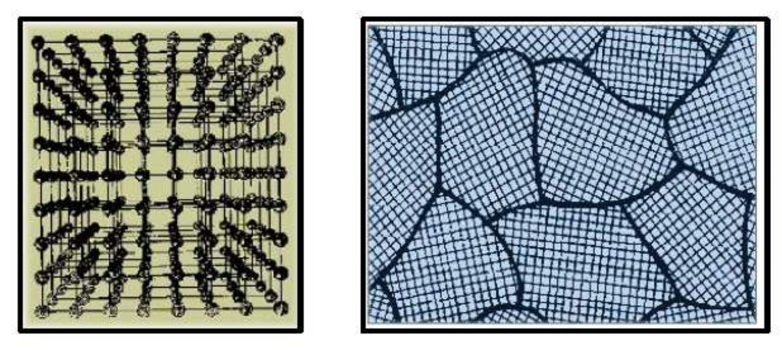


Wafers (1 kg)

Monocristal Silicon

Polycrystal Silicon





The p-n junction at equilibrium

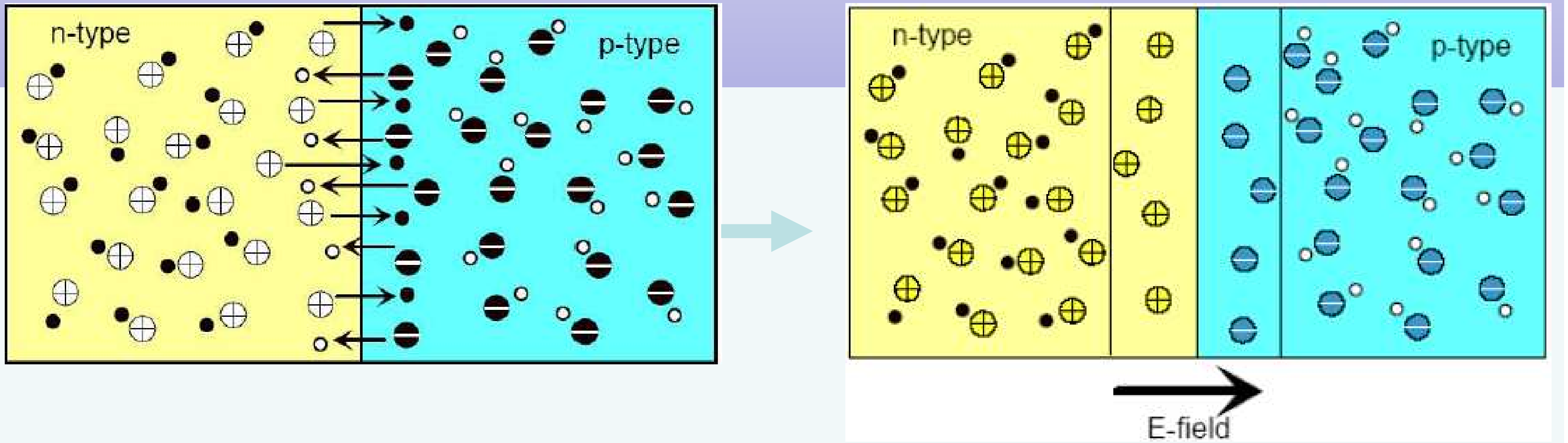
Contact between two differently doped regions.

Majoritary carriers diffuse in the region of opposite doping according to Fick Law.

The equilibrium is reached when two space charge regions are formed.

As a consequence an electric field is formed at the junction

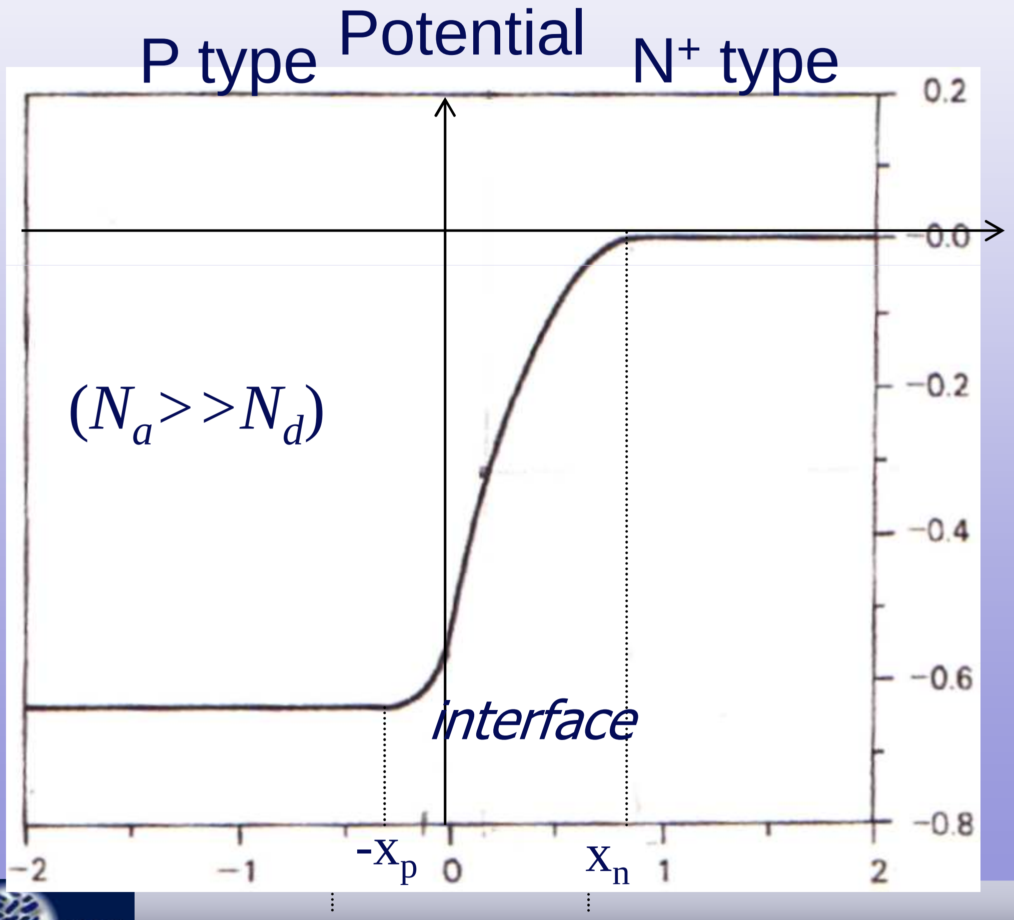
The region where the built–in field is present is known as DEPLETION REGION



np+ junction

$$\begin{cases} \Phi(x) = \dfrac{eN_a}{2\varepsilon}(x+x_p)^2 - V \; if \; -x_p \le x < 0 \\ \Phi(x) = -V \; if \; x \le -x_p \end{cases}$$

$$\begin{cases} \Phi(x) = -\dfrac{eN_d}{2\varepsilon}(x-x_n)^2 \;\; 0 < x \le x_n \\ \Phi(x) = 0 \;\; x \ge x_n \end{cases}$$

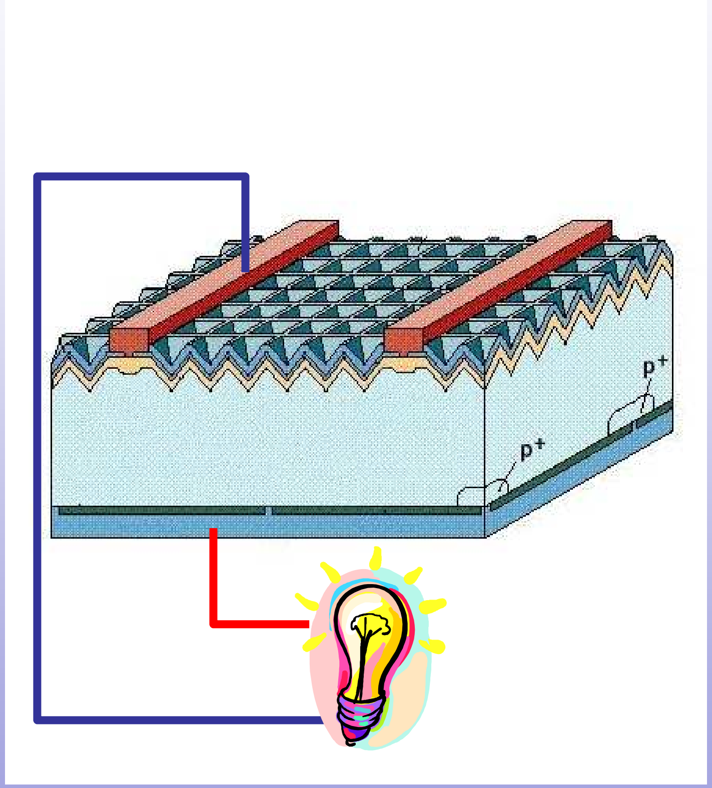


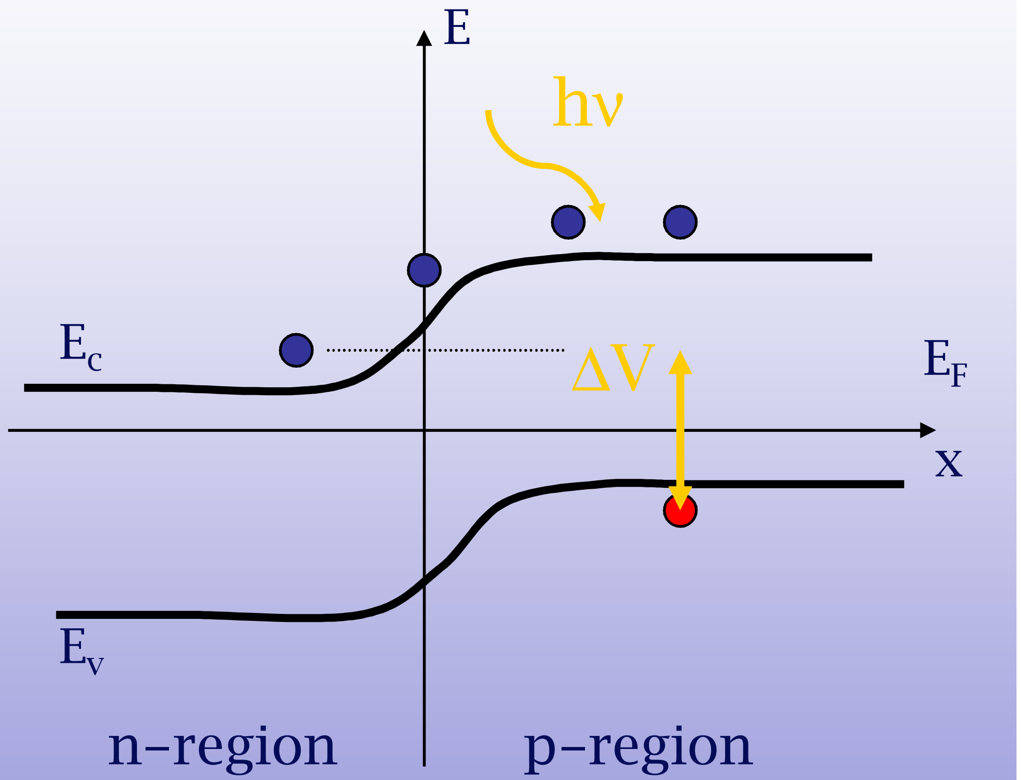
The continuity of the potential and of the field at x=0 (junction) leads to:

$$x_n = \sqrt{\frac{2\varepsilon V}{qN_d\left(1+\dfrac{N_d}{N_a}\right)}}$$

$$x_p = \sqrt{\frac{2\varepsilon V}{qN_a\left(1+\dfrac{N_a}{N_d}\right)}}$$

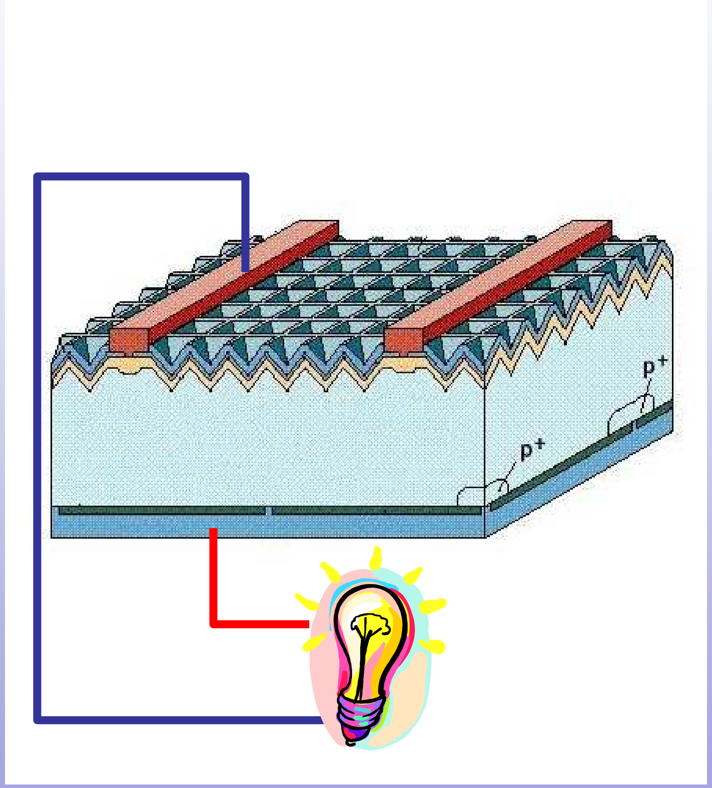
The photovoltaic convertion and the separation of photo-generated carriers

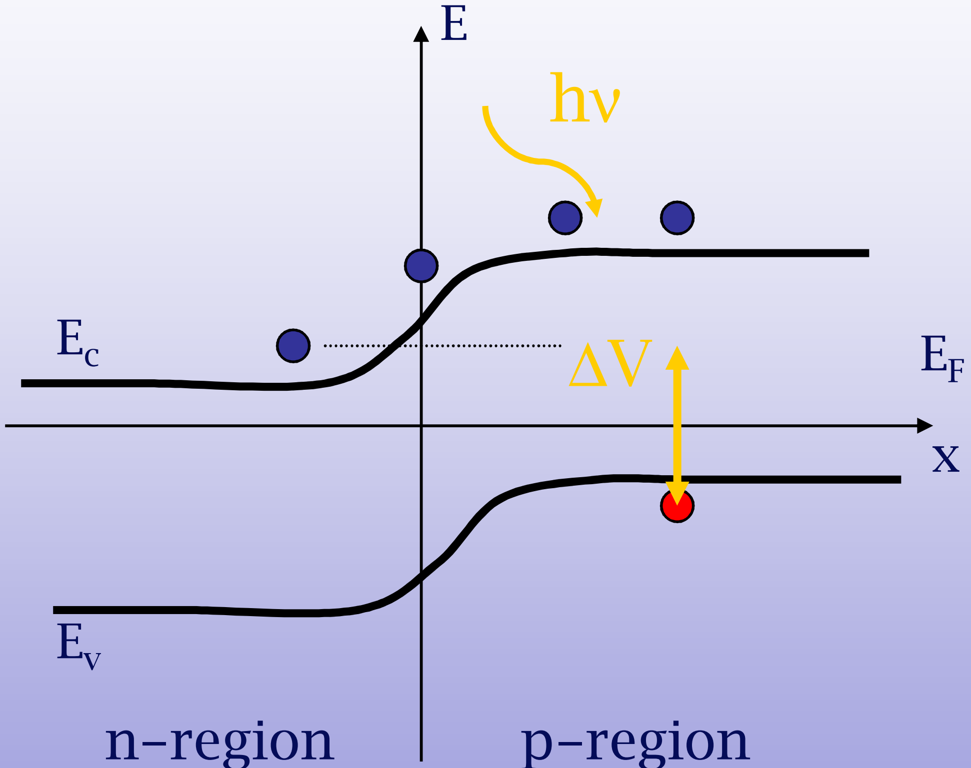




The solar irradiance at the Earth surface is about 1000 W/m^2, but standard photovoltaic cells can convert up to 15 % of it

The photovoltaic convertion and the separation of photo-generated carriers

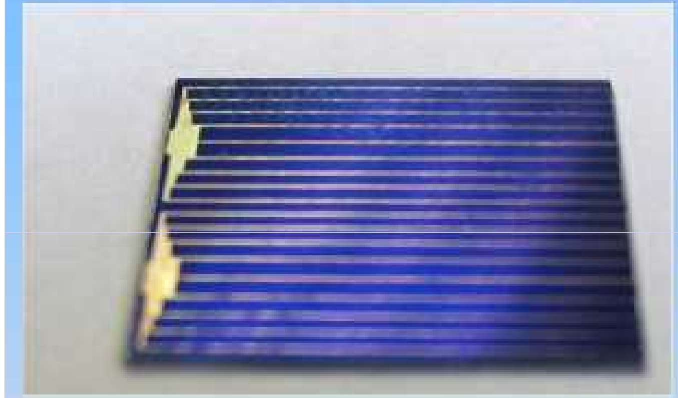




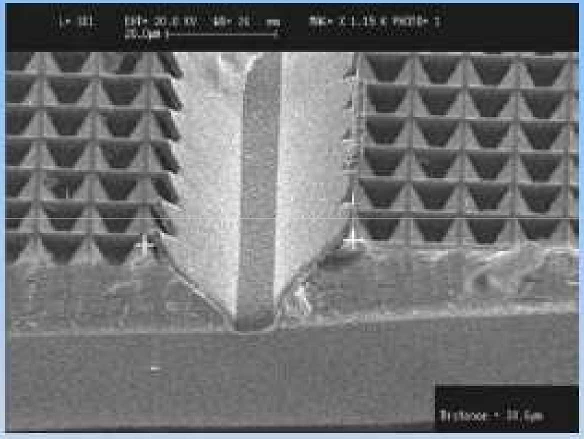
The solar irradiance at the Earth surface is about 1000 W/m^2, but standard photovoltaic cells can convert up to 15 % of it

The photovoltaic cell

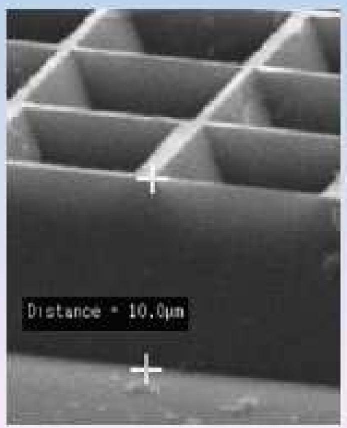
With optical concentration of 100 X each cm² of silicon material will produce approximately 3 Amps of current.
Electrical resistances in the cell circuit MUST therefore be keept to a minimum but, at the same time, the front cell contact must be as small as possible to limit shading effects.
Cell dimension, at the same time, must be reduced to avoid too large currents.



Anti-reflection coatings are used to reduce light reflection at the air to cell interface (caused by the high refraction index of silicon)



Micromachining techniques are used for light trapping in the material.



Contacts are deposited in deep grooves to obtain thck electric pathes with low cell shading.

ANNUAL ITALIAN POWER CONSUPTION:

330 milions of MWh
(about 60000 MW installed)

Annual polysilicon (feedstock) production in the world :

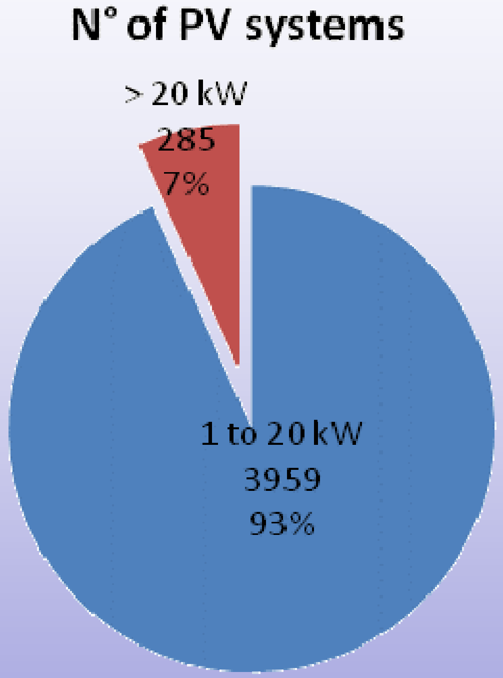
30.000 ton

CONSIDERATION: *With the present technology 10 Ton are needed to manufacture solar panels with a peak power of 1 MWp. If the worldwide polysilicon production would be dedicated to PV (no silicon for microelectronics !) it would be possible to get only* ***3000 MWp.***

For an annual production of ***1000 MWh*** */ year for each MWp installed, it would be possible to reach just* ***3 millions MWh/year, which is less than 1% of the Italian annual power consumption.***

PV Panels installed in Italy since government grants

Fonte: Solon S.p.A



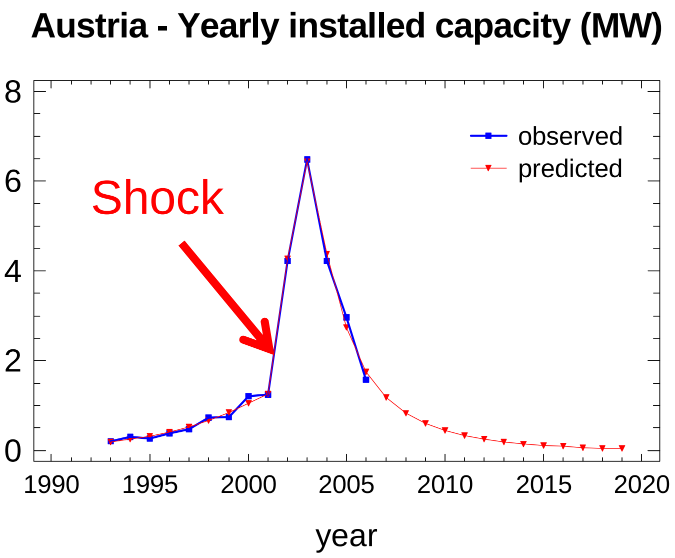
83 MW installed since 2005 until march 2008

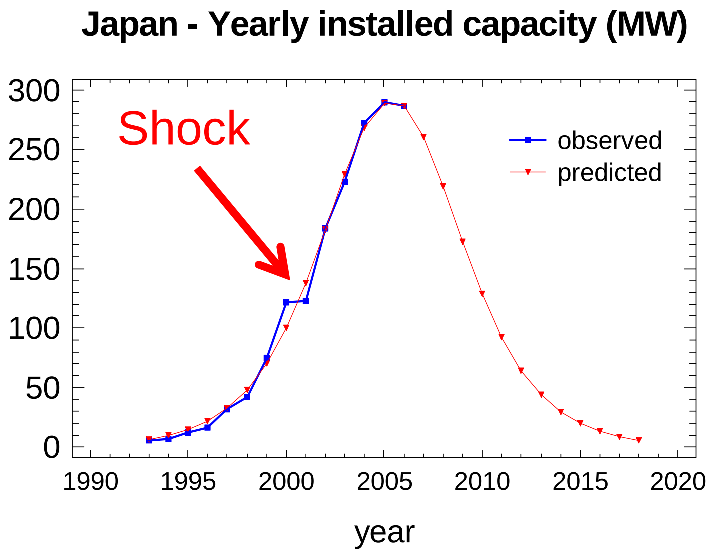
The big portion of the plants is below the 50 kW size

Comment: 83 MW can generate about 85.000 MWh each year, equal to 0.024 % of the Italian request.

The perspectives of present technology

Fonte: Mortarino e Guidolin, Università di Padova*





Generalized Bass Model seems to suggest that the current available PV technology is going to complete its life cycle and that new solutions for solar energy should become available in the short term.

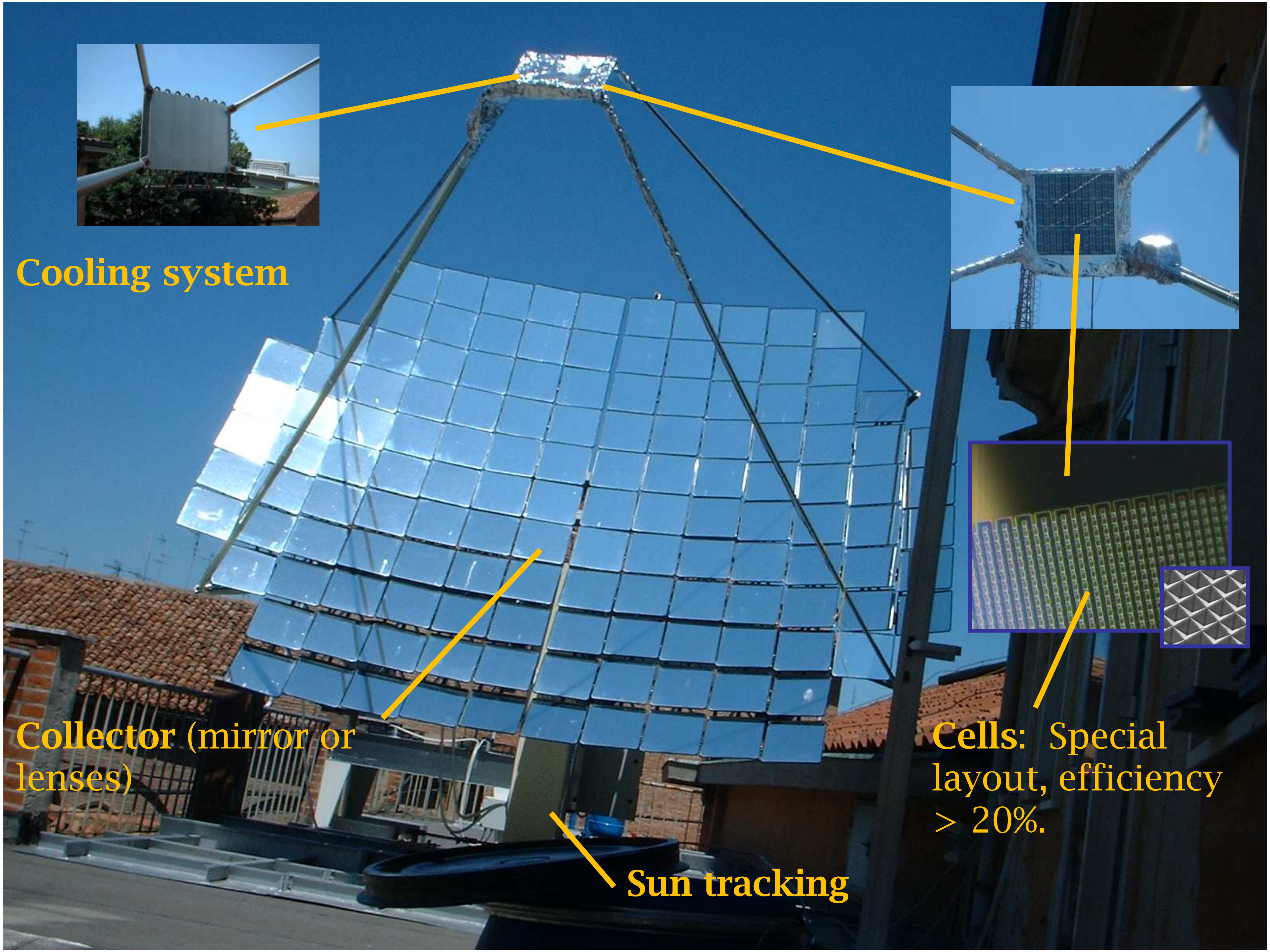
***(Cross-country diffusion of photovoltaic systems: modelling choices and forecasts for national adoption patterns. WPseries, N.18/2007. Dipartimento di Scienze Statistiche. Università di Padova)**

New technologies are mandatory

An alternative approach: solar concentration systems

With ***solar concentration systems****, at 200x ratio, just* ***1500 ton*** *of polysilicon would be enough to* ***cover the 10%*** *of Italian energy needs*

This approach can be sustained from both **economic** and **energy payback** point of view



Cooling system

Collector (mirror or lenses)

Cells: Special layout, efficiency > 20%.

Sun tracking

Concentrating Photovoltaics

Concentrator developed at Sandia National Laboratories in '70s

Point focus hybrid silicone-glass Fresnel lenses which casts the sunlight onto a circular cell of about 5 cm in diameter. The concentration ratio is in the range of 40X and rated power is about 1 kWp
IES-UPM(1980)

350 kW Soleras Plant installed in Saudi Arabia by Martin Marietta.

The modules include Point focus Fresnel lenses

World record (2003) module efficiencies were achieved by Ioffe Institute (St.-Petersburg, Russia) and Fraunhofer Institute for Solar Energy Systems (Freiburg, Germany):

24.9% at module aperture area

S = 200 cm^2

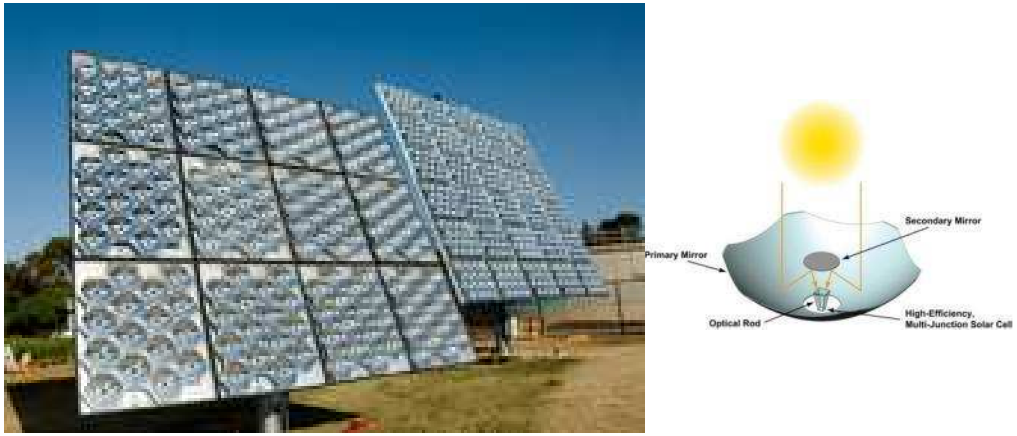
Dual-junction cells made of $Ga_{0.65}In_{0.35}P/Ga_{0.83}In_{0.17}As$ have been used in the modules

Ioffe Physico-Technical Institute

Euclides (30x, parabolic trough; Si solar cells)

PV concentration systems


Amonix, Tempe, AZ

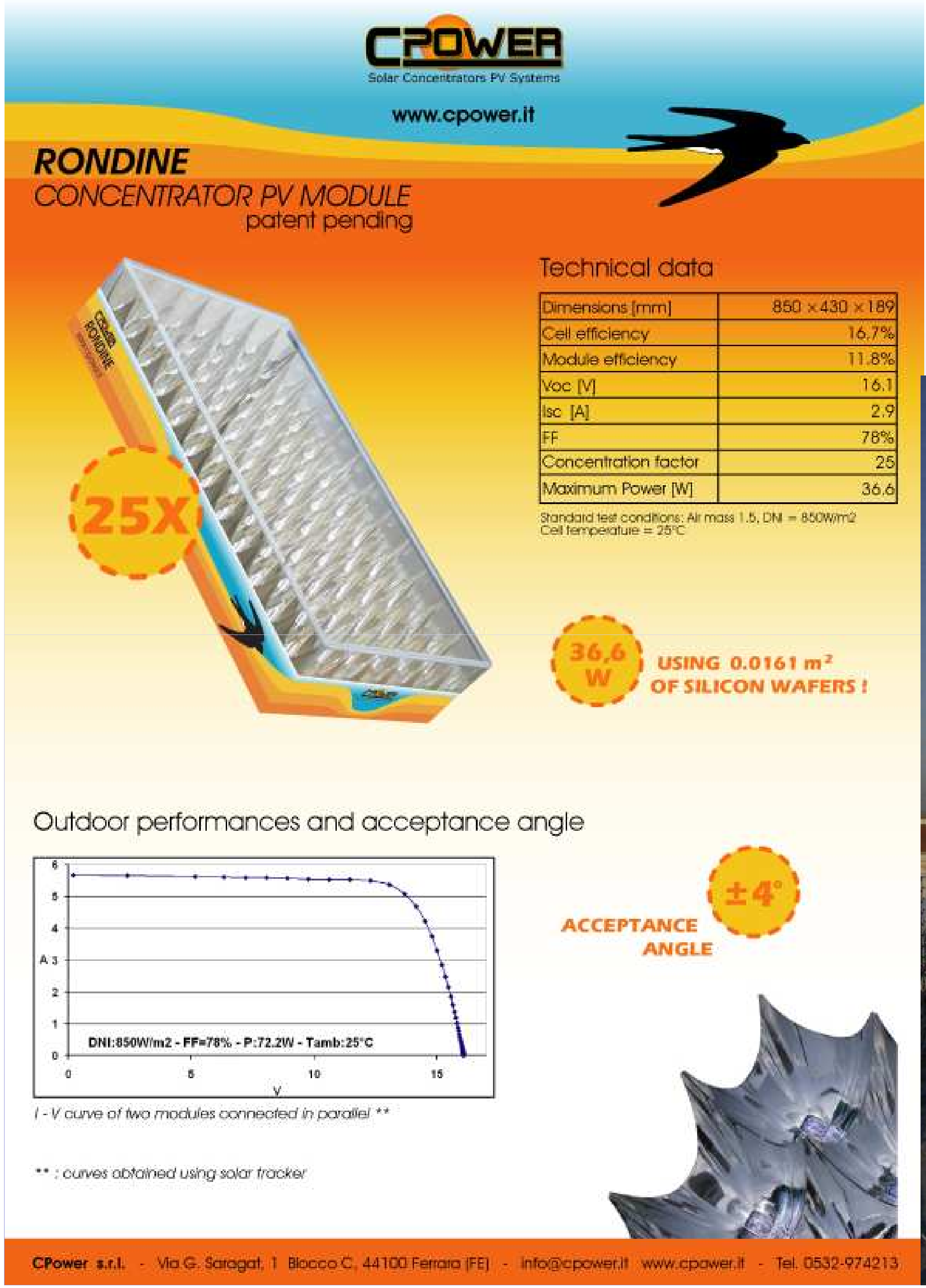


Solfocus, Mountain View, CA


UC Merced, Merced CA

Concentrix Solar GmbH

“Rondine”: Si based PV concentration system



CPOWER
Solar Concentrators PV Systems

www.cpower.it

RONDINE
CONCENTRATOR PV MODULE
patent pending

Technical data

Dimensions [mm]	850 × 430 × 189
Cell efficiency	16.7%
Module efficiency	11.8%
Voc [V]	16.1
Isc [A]	2.9
FF	78%
Concentration factor	25
Maximum Power [W]	36.6

Standard test conditions: Air mass 1.5, DNI = 850W/m2
Cell temperature = 25°C

25X

36,6 W USING 0.0161 m² OF SILICON WAFERS !

Outdoor performances and acceptance angle

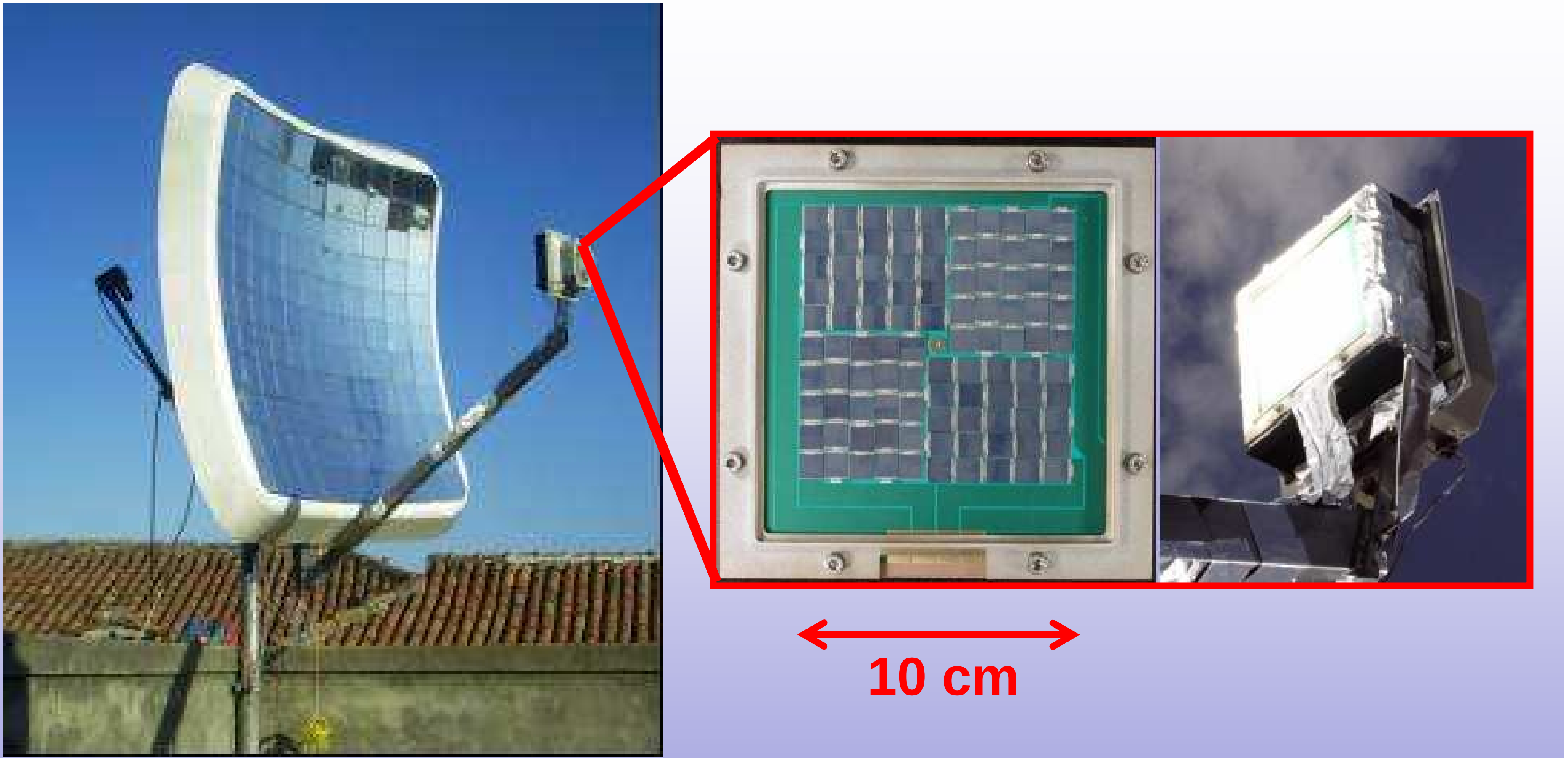
*I - V curve of two modules connected in parallel ***

*** : curves obtained using solar tracker*

±4° ACCEPTANCE ANGLE

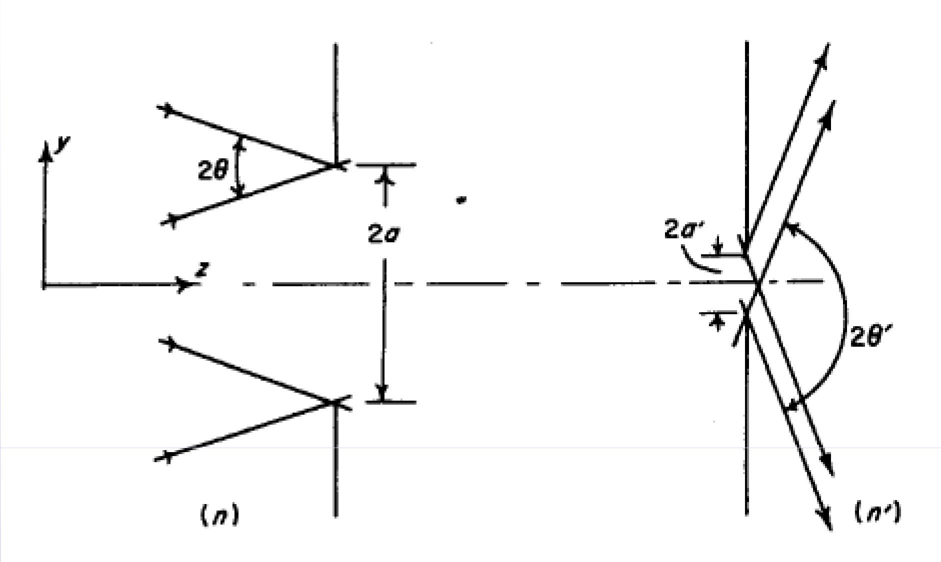
CPower s.r.l. - Via G. Saragat, 1 Blocco C, 44100 Ferrara (FE) - info@cpower.it www.cpower.it - Tel. 0532-974213

Test installation at the University of Ferrara



Example of PV concentration system
(collection area 2.5 m², concentration factor 100x)

Maximum concentration ratio and angular acceptance



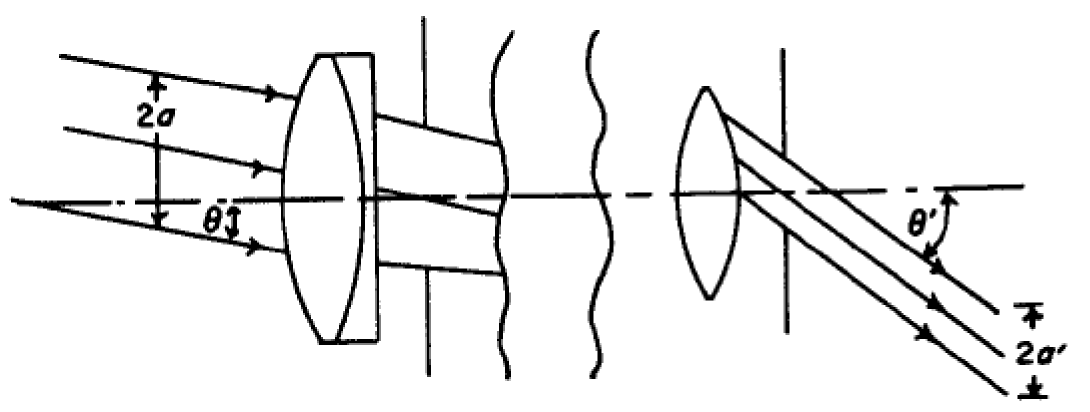
The maximum theoretical concentration is a function of the source divergence

$$C_{\max} = \left(\frac{a}{a'}\right)^2 = \left[\frac{n'}{n\sin(\theta)}\right]^2$$

Sun divengence is 0.26° and thus the maximum concentration ratio in air is 48.500

Image forming optical system always have a concentration ratio lower than C_{max}

Generalized Etendue



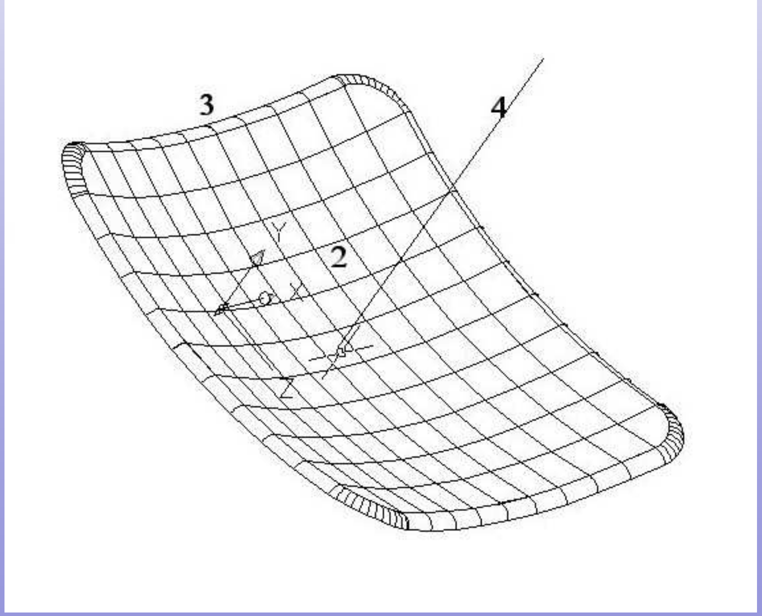
Generalized Etendue is the Lagrange Invariant in paraxial axisymmetric optical systems

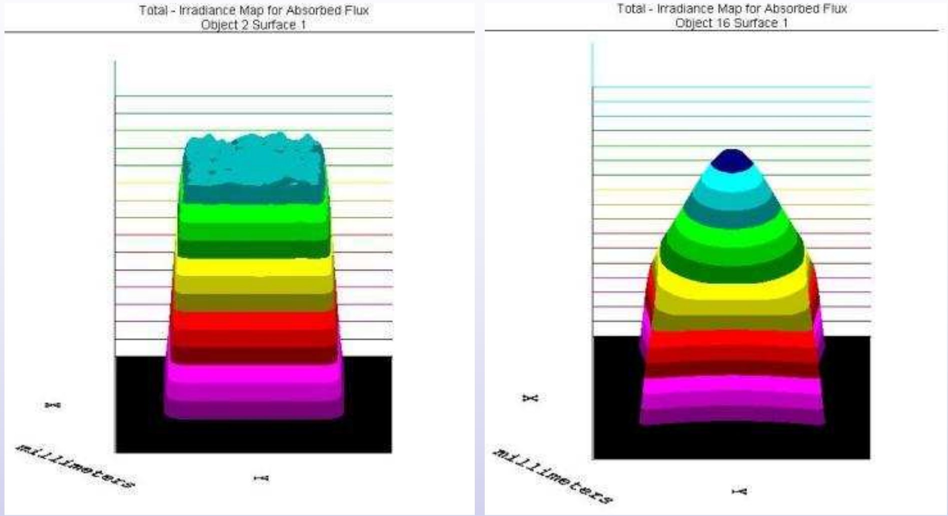
$$E = n^2 a^2 \theta^2$$

The uniformity issue

A single flat mirror does not concentrate sunlight.

But several flat mirrors can overlap their reflection generating a concentrated illuminations spot.





Irradiance profile of flat faceted concentrator (left) vs parabolic concentrator (right)

• Concentration can never excede the mirror number (no hot spots)
• Secondary beam omogenizer may be avoided.
• Flat surfaces are easier to be coated

Non-uniformity in PV dense arrays

The global current generated by a N cells array (I_t) is given by

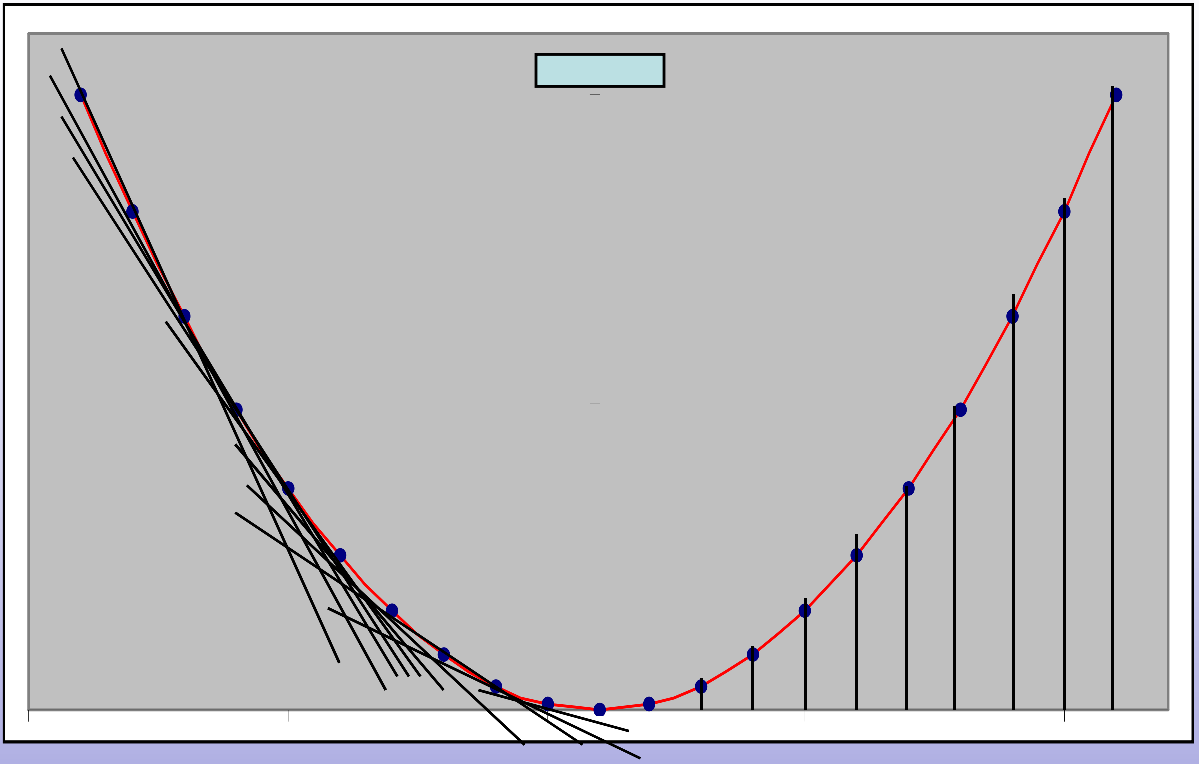
$$I_t = \frac{N}{\sum 1/I_j}$$

For a 50 cells array fluctuations of 10% over 10 cells implies a 2.2% loss in panel performance.

Irradiance non–uniformity may cause overheating (resistive losses) and possibly device failure.

Bypass diode needed to avoid the reverse breakdown of shaded devices.

Flat Faceted concentrator: a working hypothesis



Starting from a parabolic profile a set of equally spaced points is defined (right) and the tangents to the profile are extracted on each point (left)

Then a segment of each tangent is taken centered on the tangence point. Its width coincides with the target dimension.
These segments are the actual mirrors and their projected image coincides, in a first order approximation, with the receiver.

A general Problem: Illumination Efficiency

Flat mirrors suffer from a geometrical effect that causes the image from lateral mirrors to be larger than the image from central mirrors.

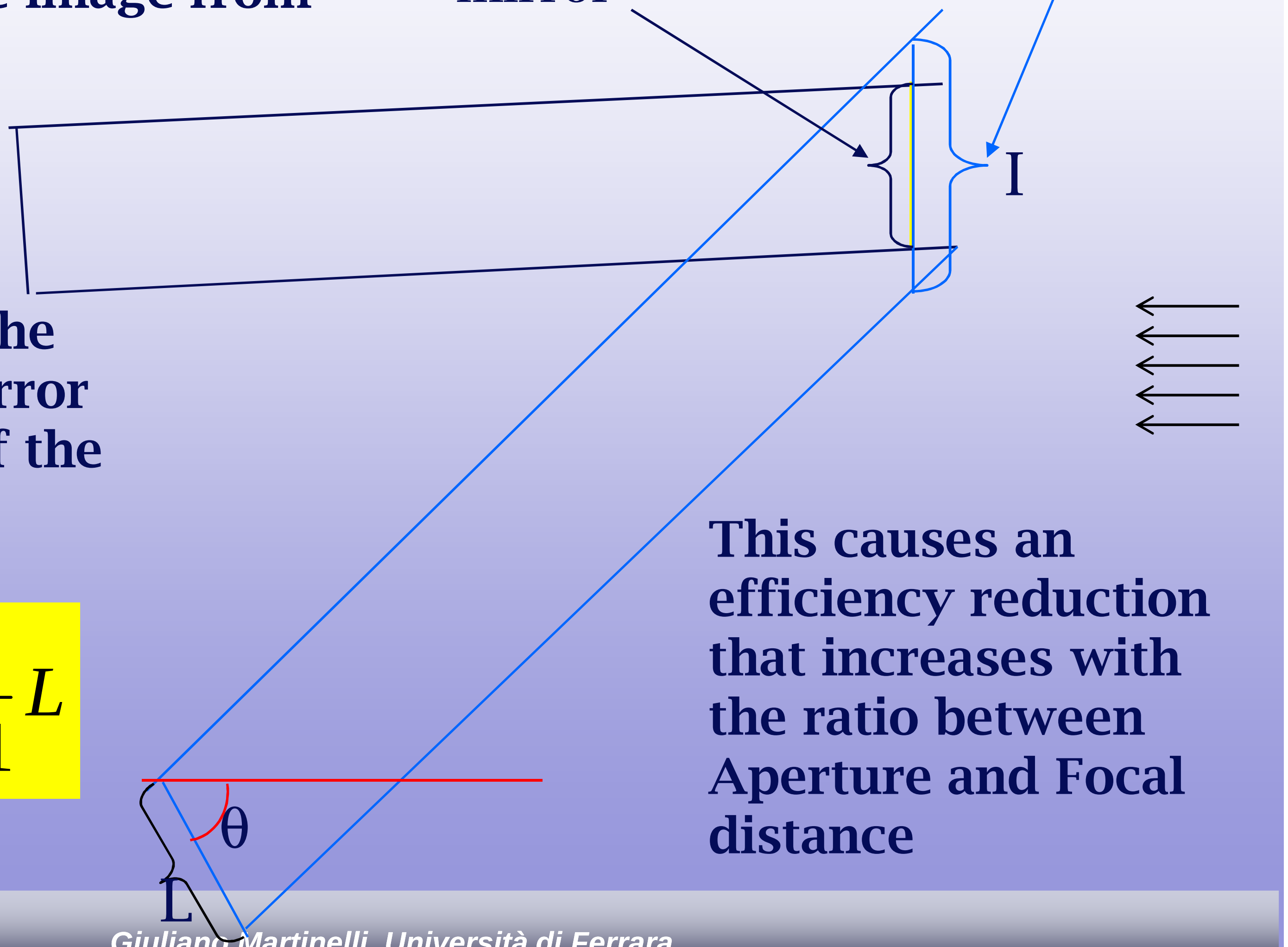


Image from central mirror

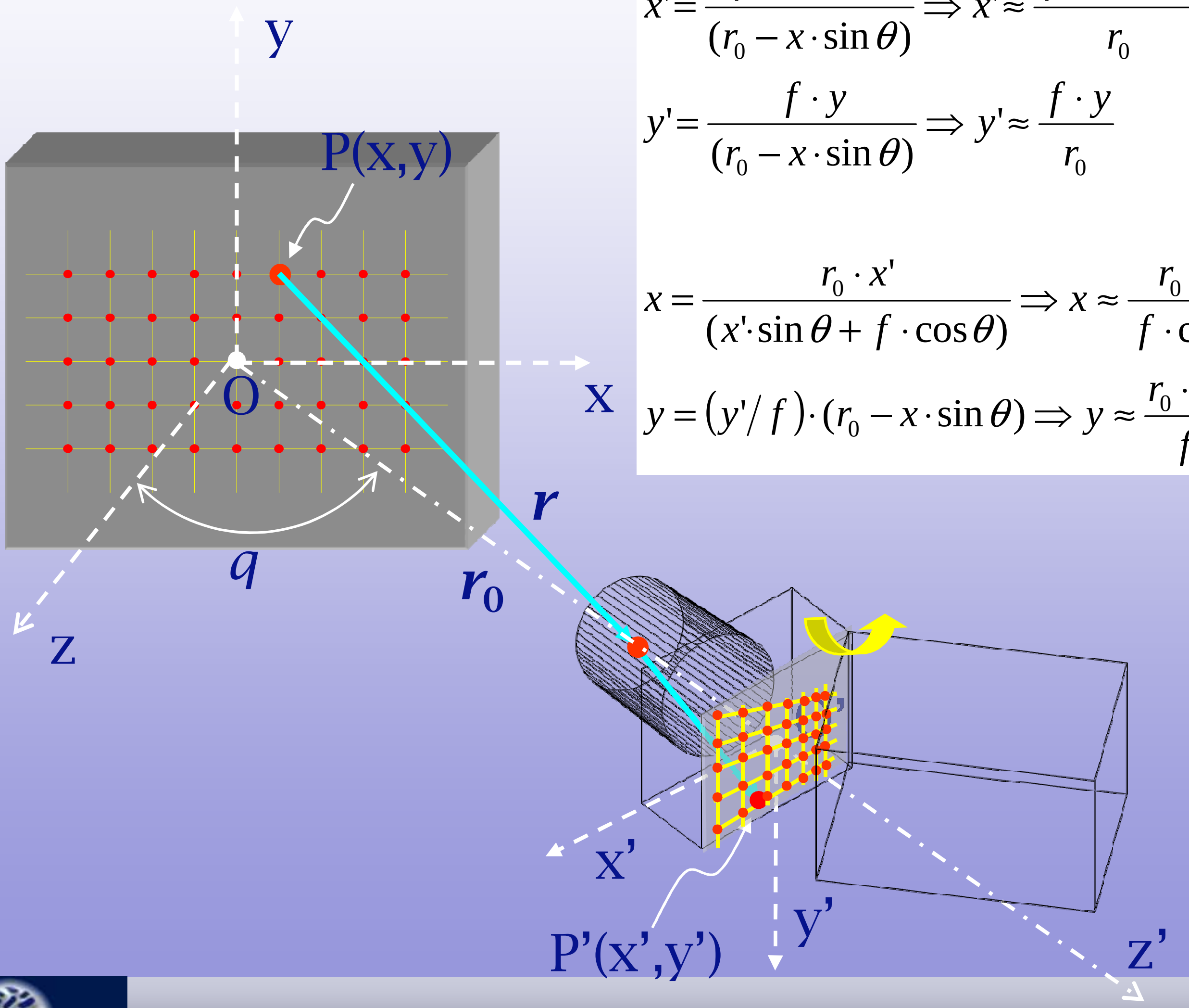
Image from peripherical mirror

The per-mirror loss is related to the angle between mirror and optical axis of the system

$$I = \frac{\sin(\vartheta)}{2\cdot\sin^2(\vartheta)-1}L$$

This causes an efficiency reduction that increases with the ratio between Aperture and Focal distance

Irradiance profile simulation measurements



$$x' = \frac{f\cdot x\cdot\cos\theta}{(r_0 - x\cdot\sin\theta)} \Rightarrow x' \approx \frac{f\cdot x\cdot\cos\theta}{r_0}$$

$$y' = \frac{f\cdot y}{(r_0 - x\cdot\sin\theta)} \Rightarrow y' \approx \frac{f\cdot y}{r_0}$$

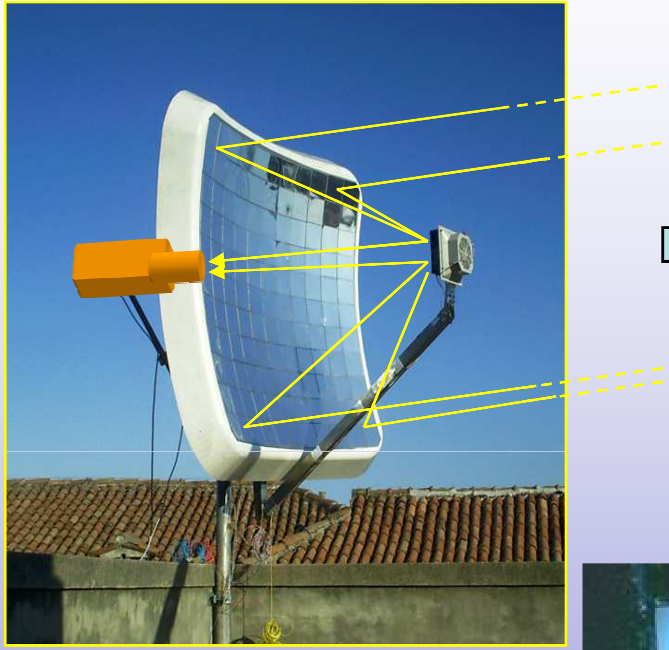
$$x = \frac{r_0\cdot x'}{(x'\cdot\sin\theta + f\cdot\cos\theta)} \Rightarrow x \approx \frac{r_0\cdot x'}{f\cdot\cos\theta}$$

$$y = \left(y'/f\right)\cdot(r_0 - x\cdot\sin\theta) \Rightarrow y \approx \frac{r_0\cdot y'}{f}$$

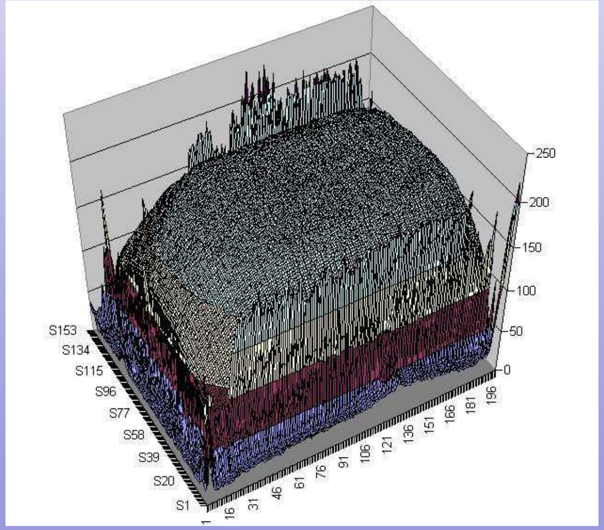
CCD camera and a custom software for the correction of perspective effects

Reconstruction of the irradiance profile at the target surface

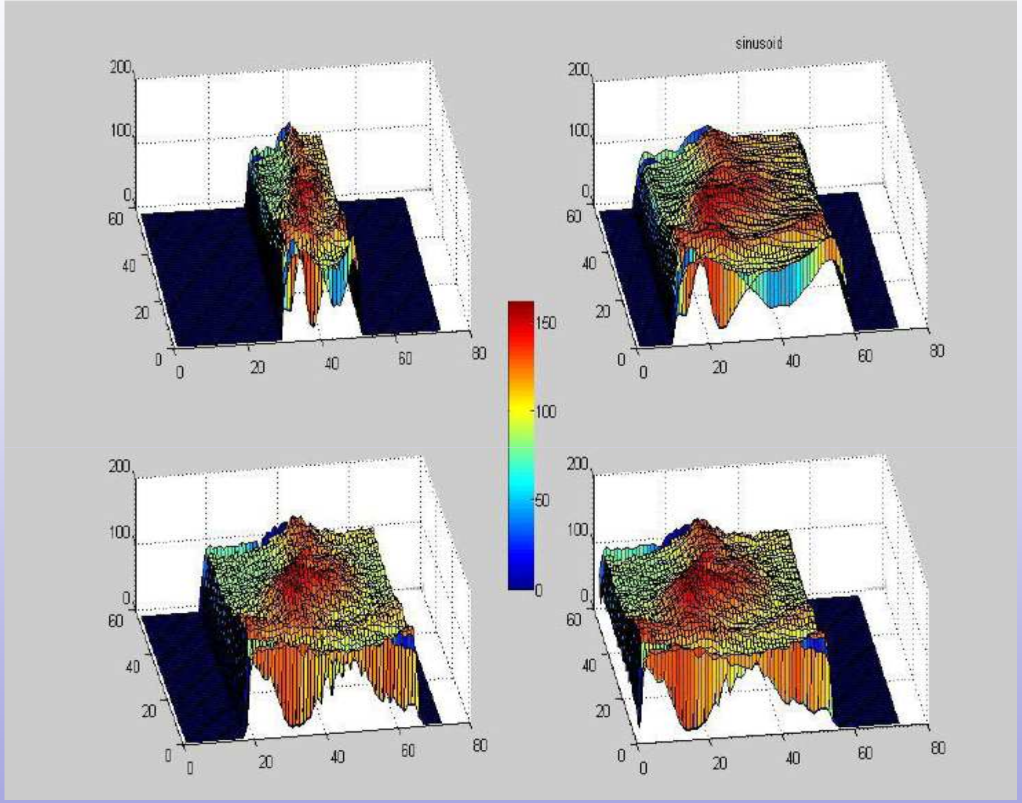
Irradiance profile simulation measurements

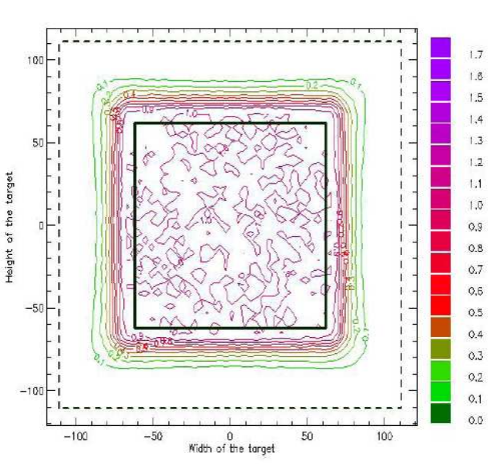


1. **Image acquisition**
2. **Software processing**
3. **Data analysis (irradiance profile)**



Irradiance profile simulation measurements



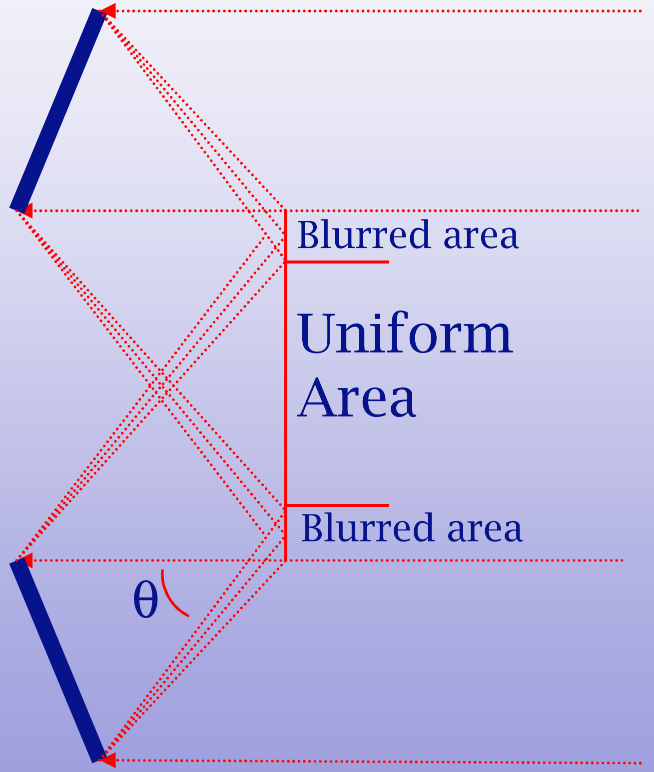


Irradiance profile retrieved from camera measurements

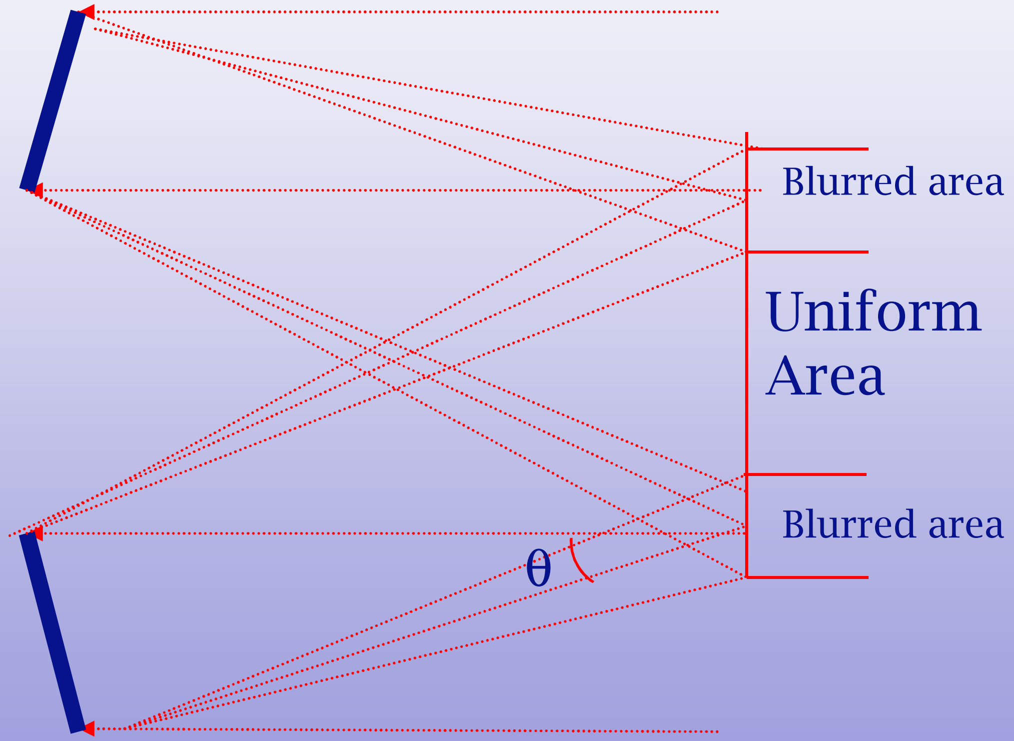
The optimal of focal distance

Sun–ray divergence (0.26°) tends to blur the uniform illumination area and this effect increases with system focal length.

A short focal length implies large impingement angles of light on the receiver (that may not be desirable on PV cells)

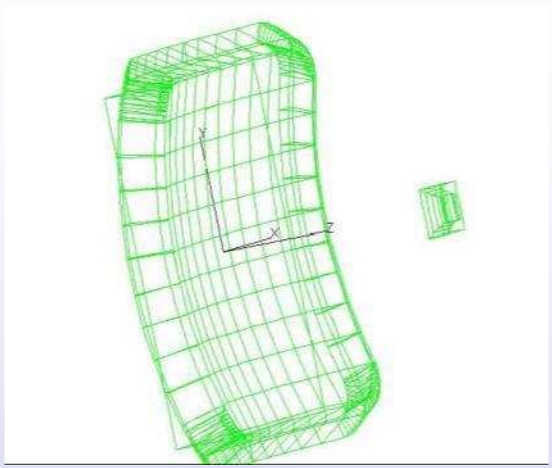


Low Focal to opening ratio
Larger uniform area
Larger θ on the receiver



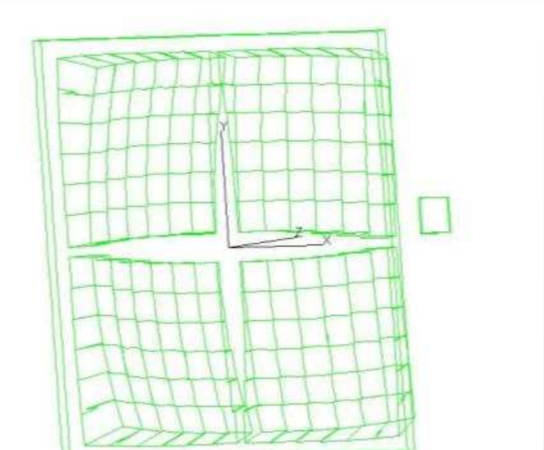
High Focal to opening ratio
Smaller uniform area
Smaller θ on the receiver

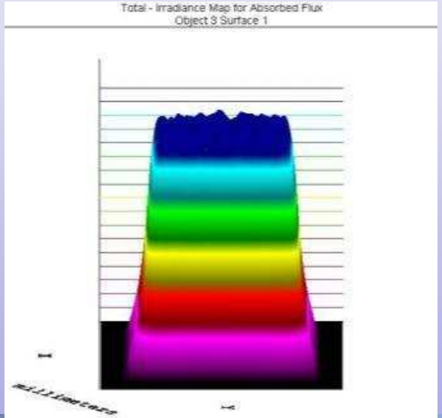
The prototipes: second and third generation



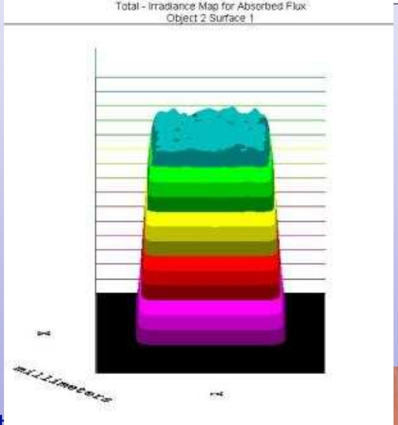
Flat faceted reflective surface

Aim → get uniform illumination on a defined target using a beam with soalr divergence as source





←Approach 1: squared mirrors
Perspectives effects of the more external mirrors



Approach 2: →
Flat mirrors shaped to obtain an almost perfect illumination profile

← Realizations →

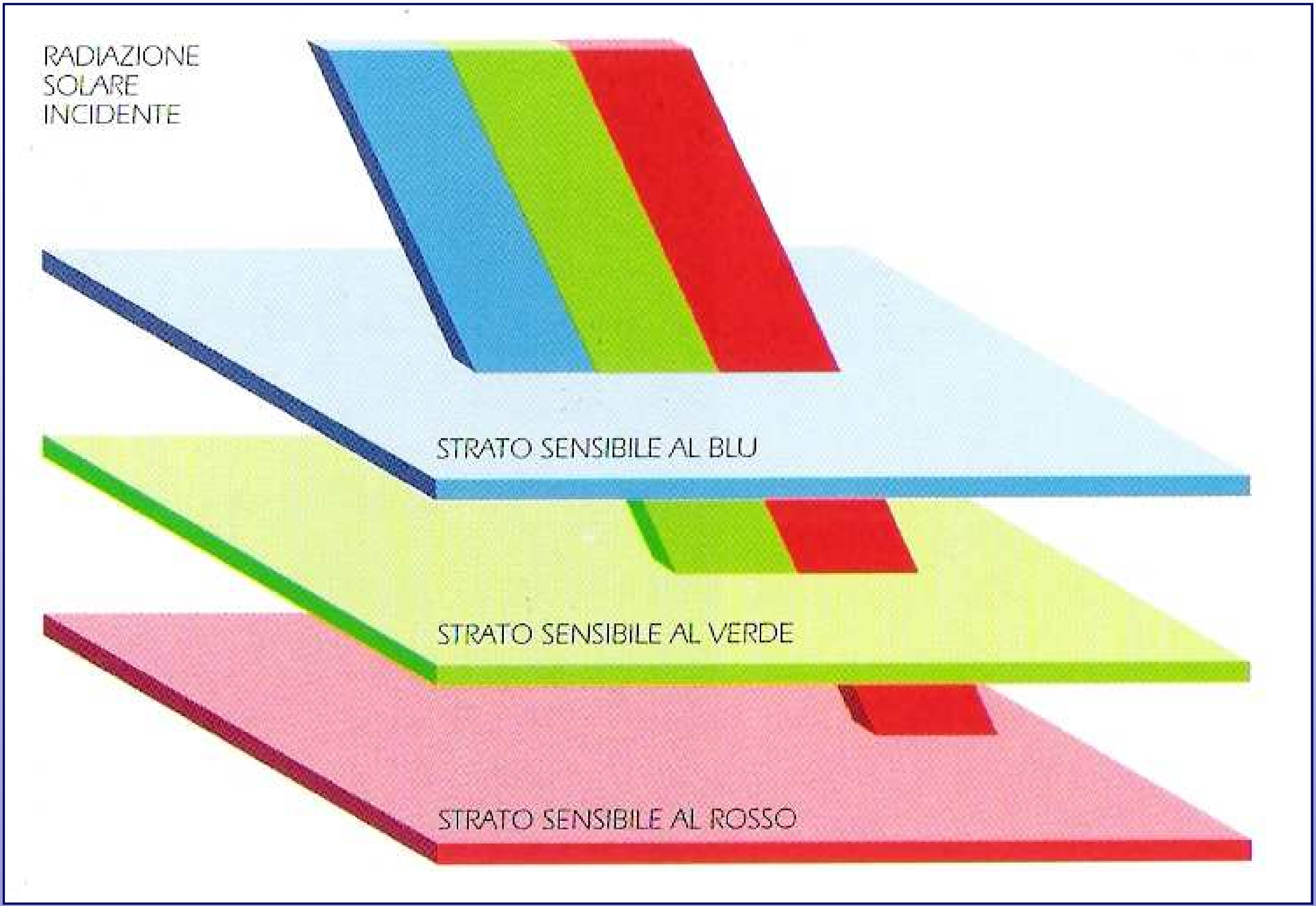
In concentration system the amount of Silicon is greatly reduced but the grid parity cannot be reached unless a higher efficiency is achieved.

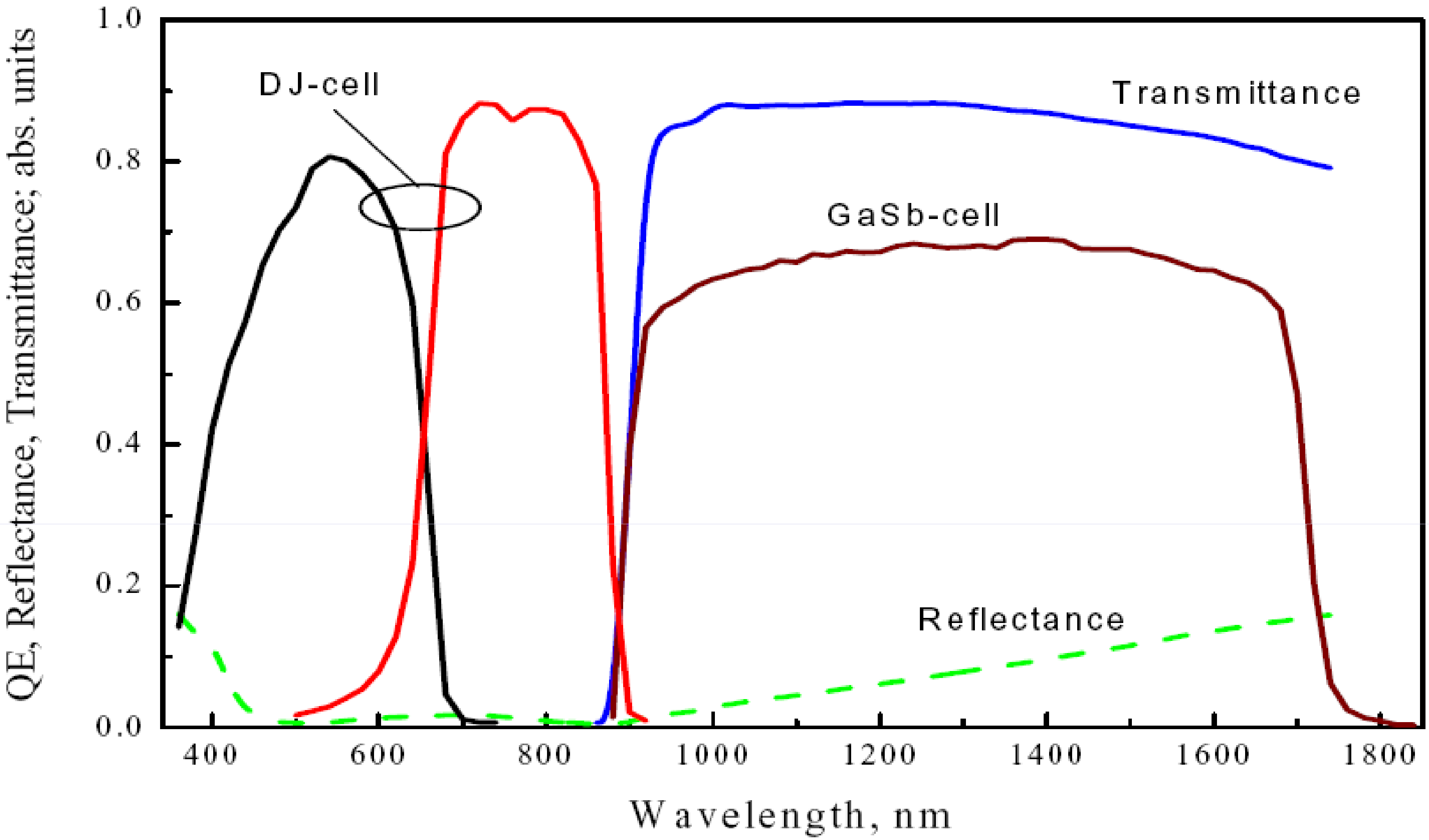
⬇

A possible way to exploit better the solar spectrum and to increase the conversion efficiency can be

Multijunction solar cells based on III-V compound semiconductors

3 different junction in series





QE/ transmittance/ reflectance data for DJ-GaInP/GaAs top cell and QE data for GaSb bottom cell situated behind DJ-cell.

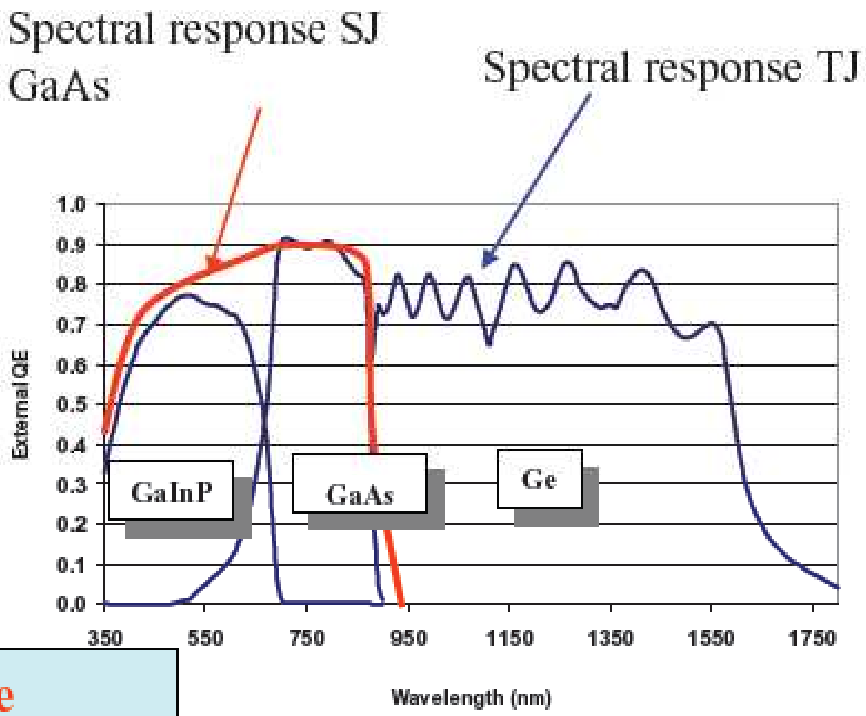
Electrical characteristics of MJ

Voltage :

Vtot = $V_1 + V_2 + V_3$

Current:

Itot=min(I_1,I_2,I_3)



Spectral response SJ GaAs

Spectral response TJ

In order to increase the efficiency the photocurrents shall be matched

The matching depends upon incident spectrum

Cell	Voc (V)	Jsc AM0(mA/cm2)
single	1 V	32 mA/cm^2
Triple	2.6 V	16 mA/cm^2

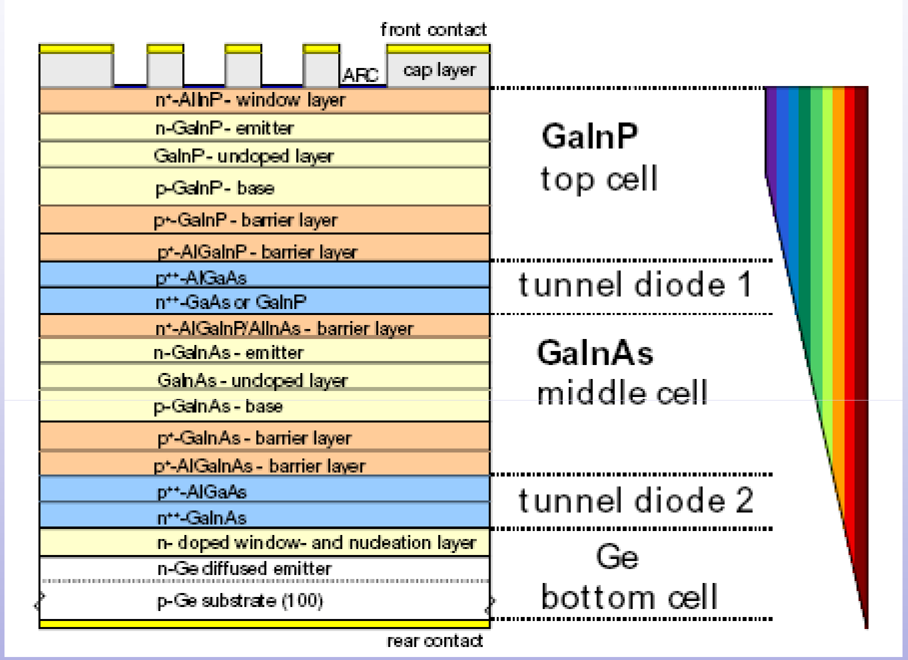
Limits of multijunction solar cells

Complex structure with many layers

A single defective layer induces the failure of the whole device.

High processing cost and high cost and limited availability of the monocrystal substrate (Ge e GaAs)

Cost effective just for very high concentration ratio



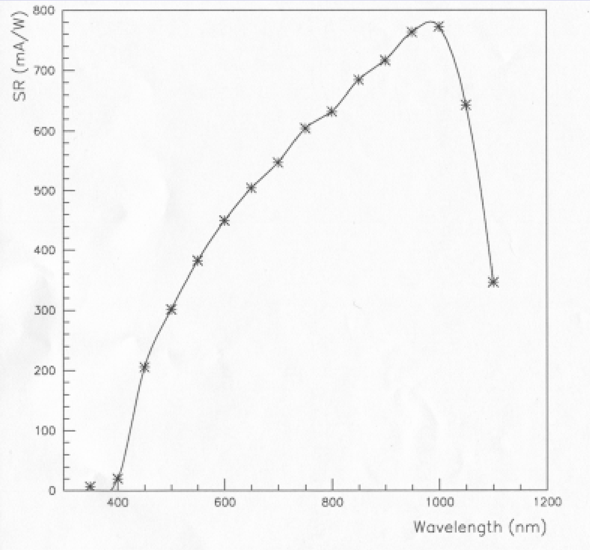
Complex cooling system to sink the excess heat concentrated onto the solar cell

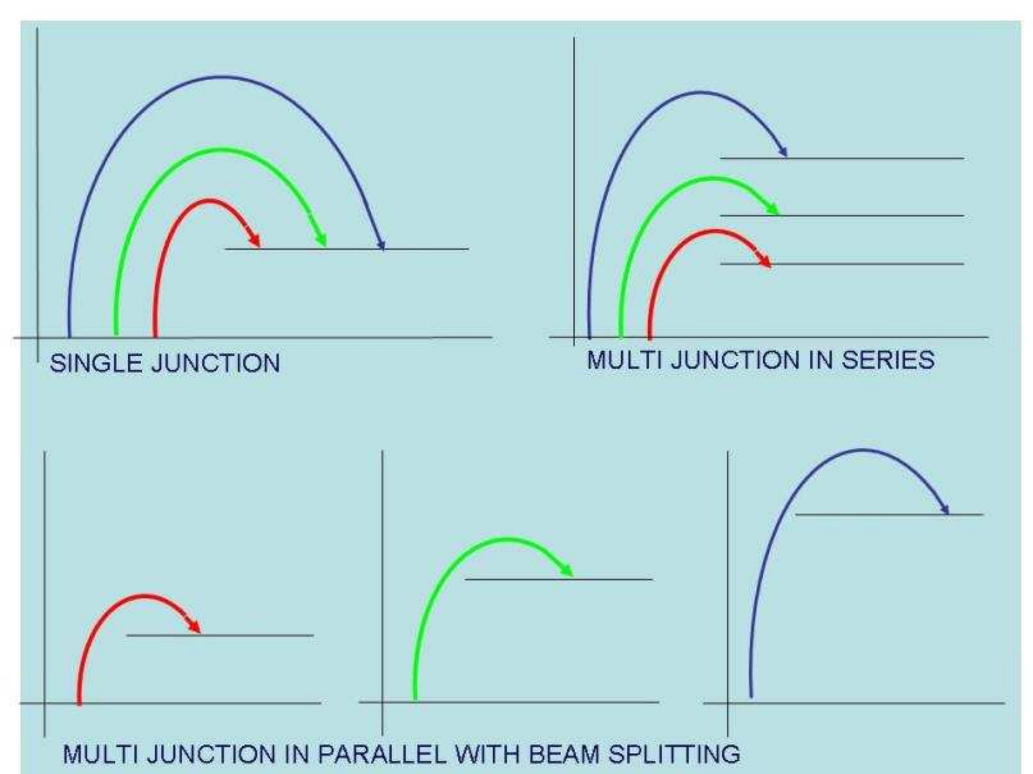
Many photon energies in just one ray

Ferrara University approach

Single junction in "parallel"

Spectral Response of a single junction Si cell

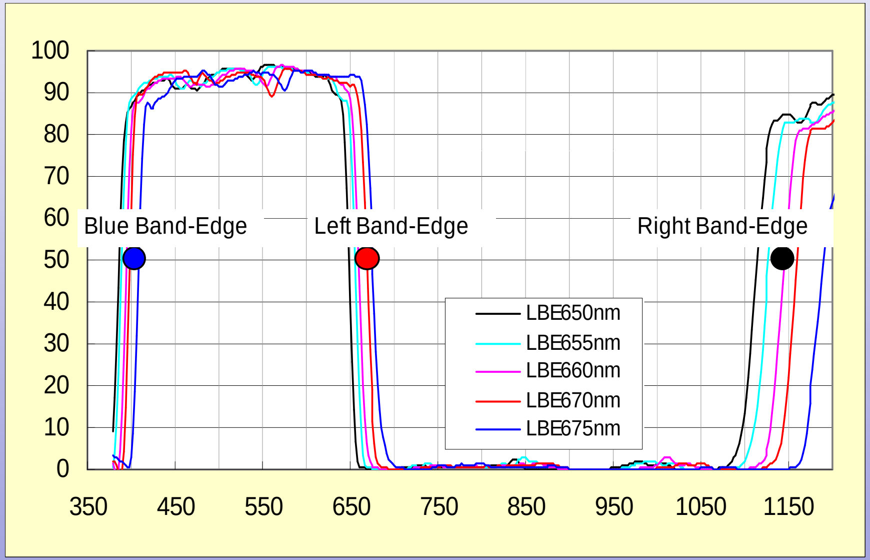




The solar collector split the solar radiation in three wavebands and concentrate them on 3 different PV receivers.

Dichroic filters to improve system efficiency.

Each kind of single junction photovoltaic cell has a specific bandgap. Radiation with energy much higher or lower than the bandgap itself is poorly converted (or not at all) and increases the thermal system load.



Dichroic mirrors can be used for this purpose.

A spatial separation of different light wavelength may allow to concentrate simultaneously on two or more different concentrators employing different kind of solar cells.

This may allow to substantially improve the system performances.

Dichroic filters to improve overall system efficiency.

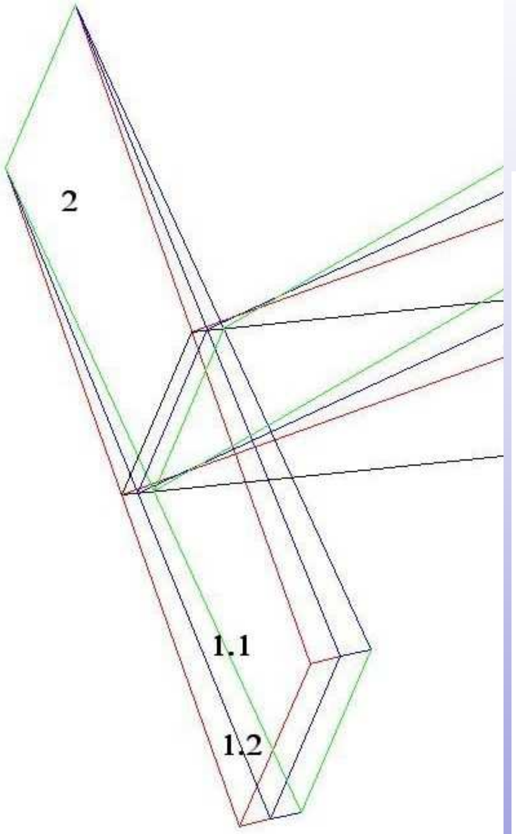
The problems are then:

a) How to obtain two concentration regions where each region is reached only by radiation in a specific wavelength region.

b) How to employ the different radiation components in the best way

Additional flat mirrors, tilted with respect to the primary collector can be coated with a dichroic filter to achieve the desired spatial beam separation.

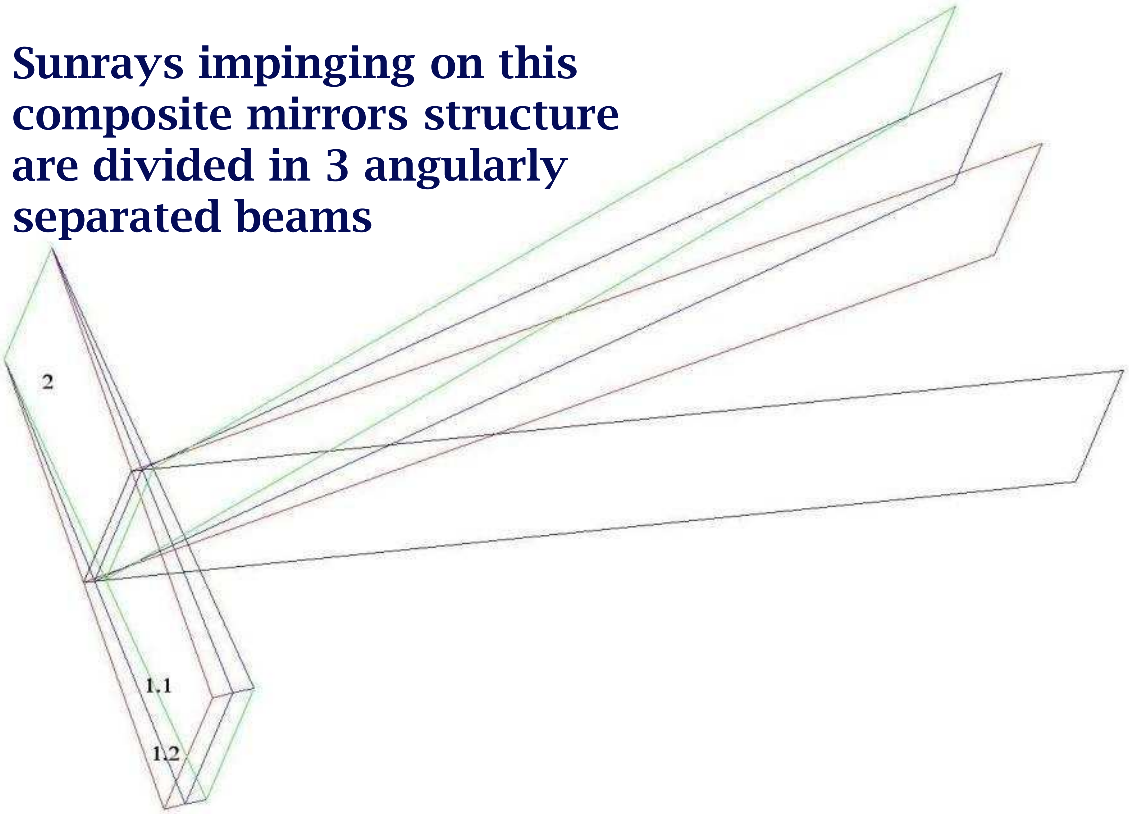
How to obtain two spatially separated areas.

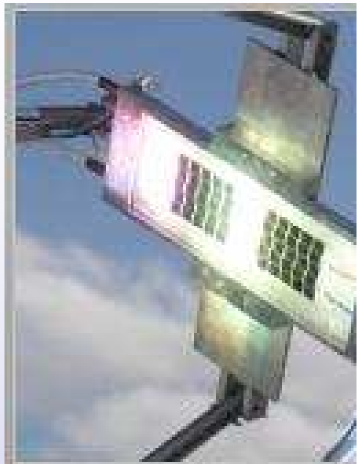


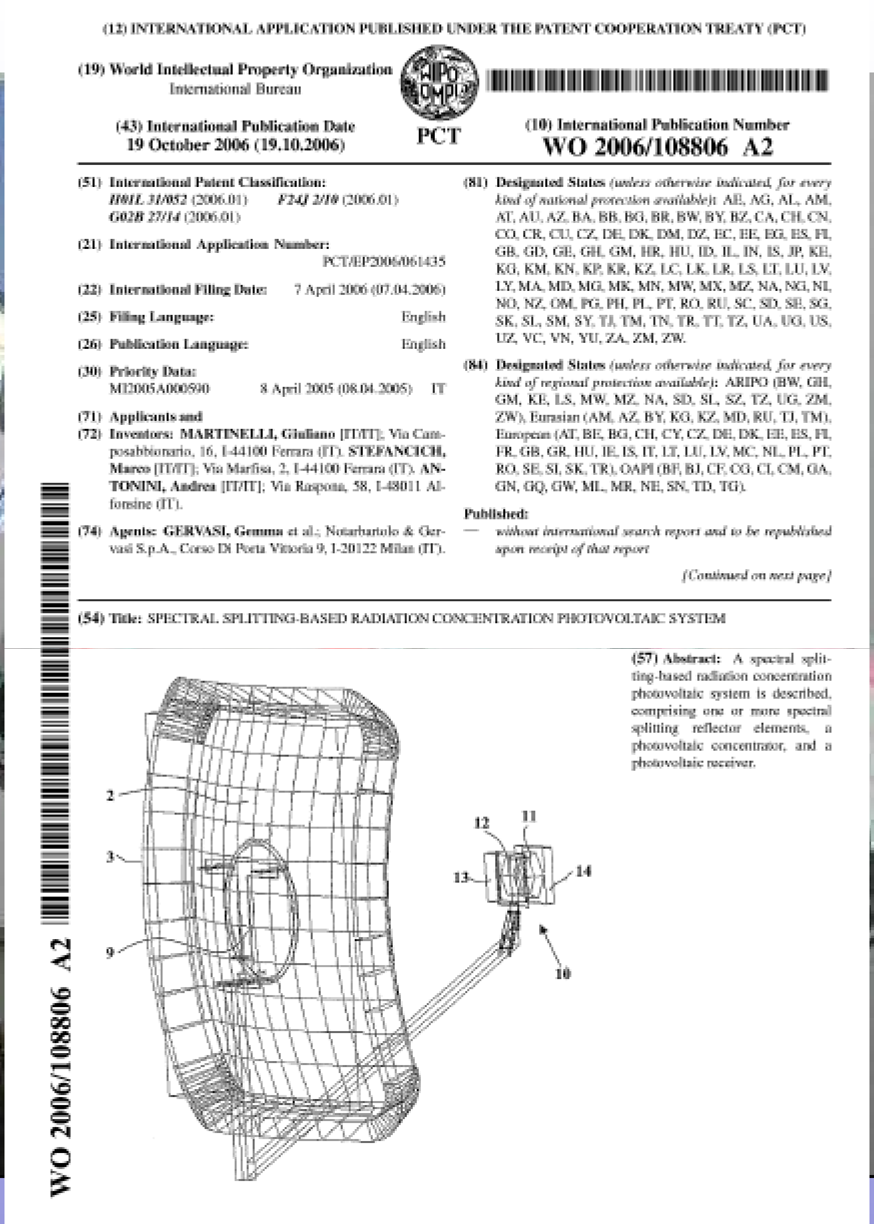
Some flat dicroich surfaces are placed at an angle with respect to the other reflective surface

The use of flat surfaces allows to find on the market dichroic mirrors suitable for the desired spectral separation

Sunrays impinging on this composite mirrors structure are divided in 3 angularly separated beams







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[Continued on next page]

(54) **Title:** SPECTRAL SPLITTING-BASED RADIATION CONCENTRATION PHOTOVOLTAIC SYSTEM

(57) **Abstract:** A spectral splitting-based radiation concentration photovoltaic system is described, comprising one or more spectral splitting reflector elements, a photovoltaic concentrator, and a photovoltaic receiver.

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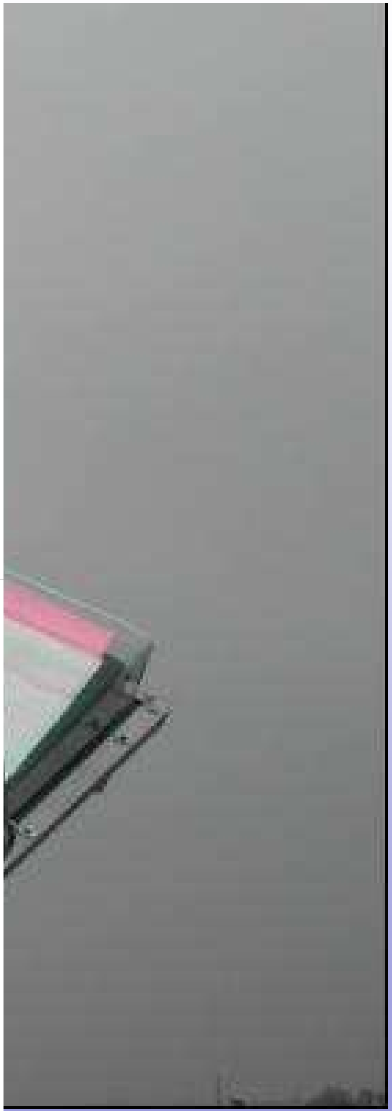
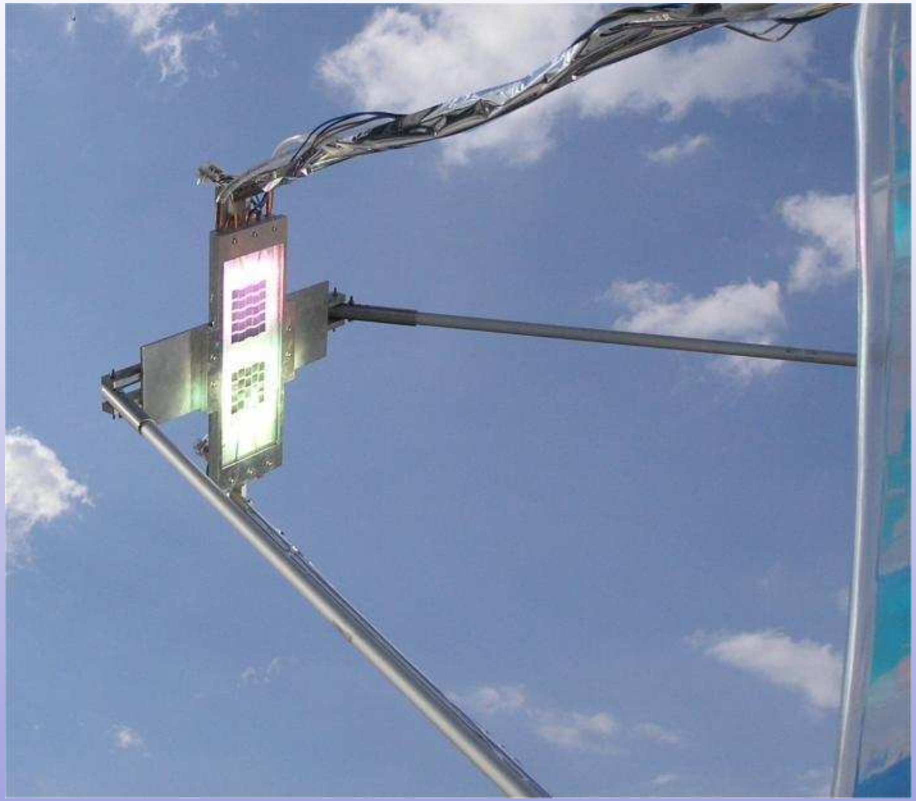
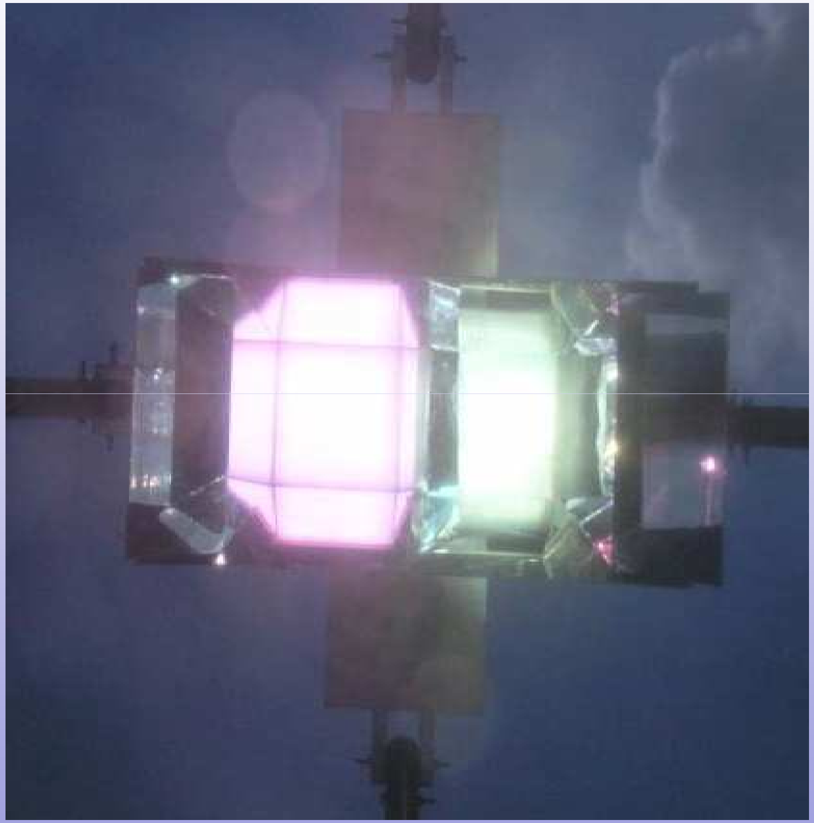
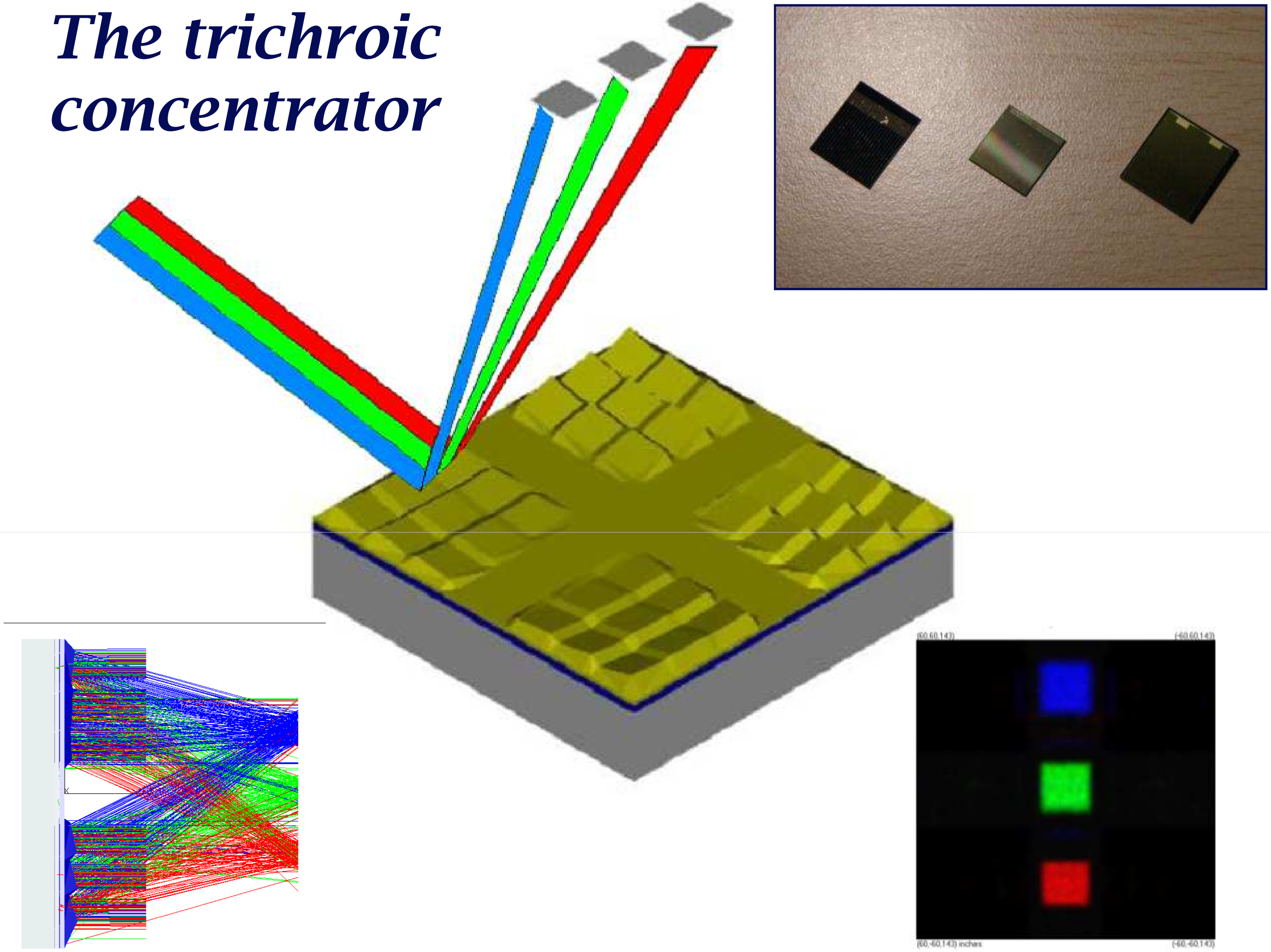


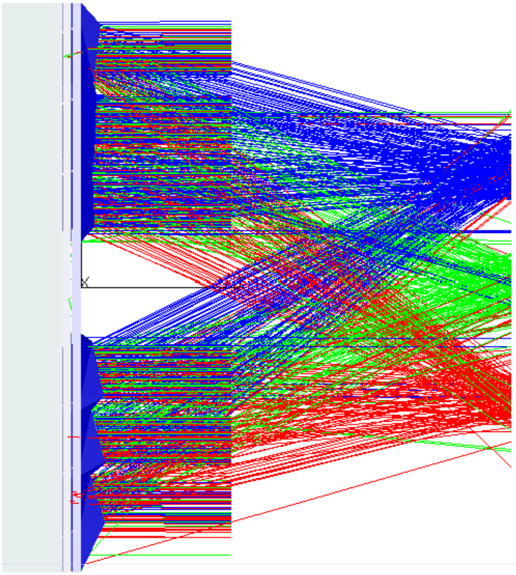
The two foci of the dichroic concentrator

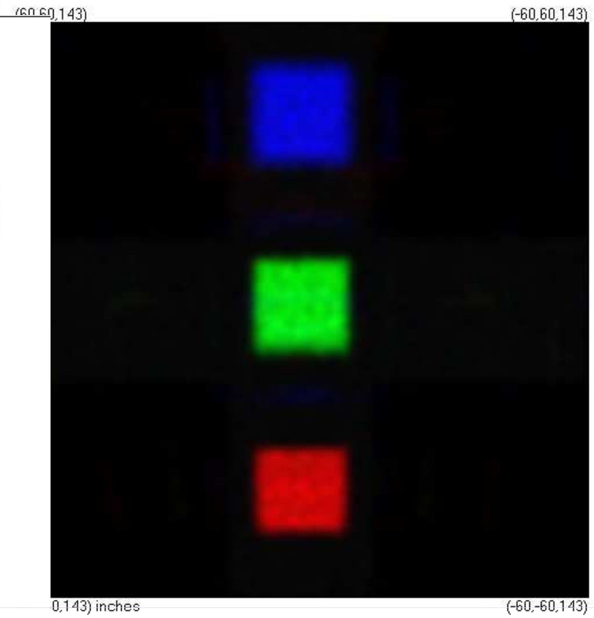




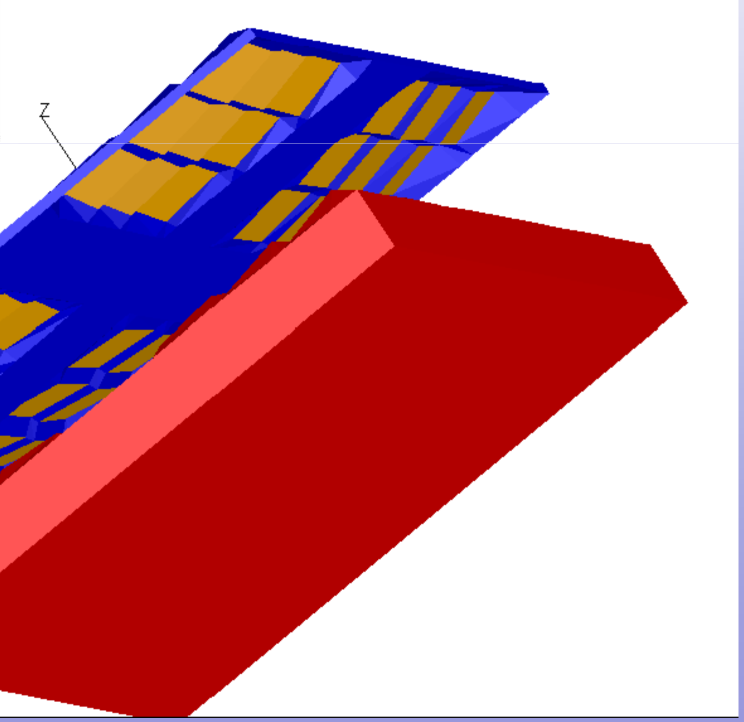
The trichroic concentrator





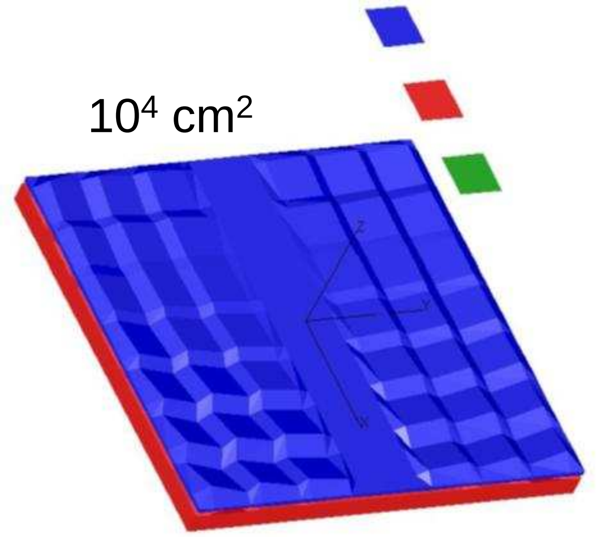


Modular concentrator with trichroic feature



3 dichroic layers (red, green, blue) concentrate different wavebands on 3 different receivers

Substrate III-V in SiGe/Si



857 W

Beam Split
Solar concentrator

Efficiency could be as high as 40%

150x
144 W

67 cm^2

Si

14.4 W (optical loss)

48 W (converted)

81.6 W (heat)

250x
250 W

40 cm^2

GaAs
/SiGe

25 W (optical loss)

120 W (converted)

105 W (heat)

250x
337 W

40 cm^2

InGaP
/SiGe

33.7 W (optical loss)

158 W (converted

145 W (heat)

With the trichroic approach it's possible to reach a conversion efficiency as high as that of multijunction solar cells, just separating the spectrum of the radiation

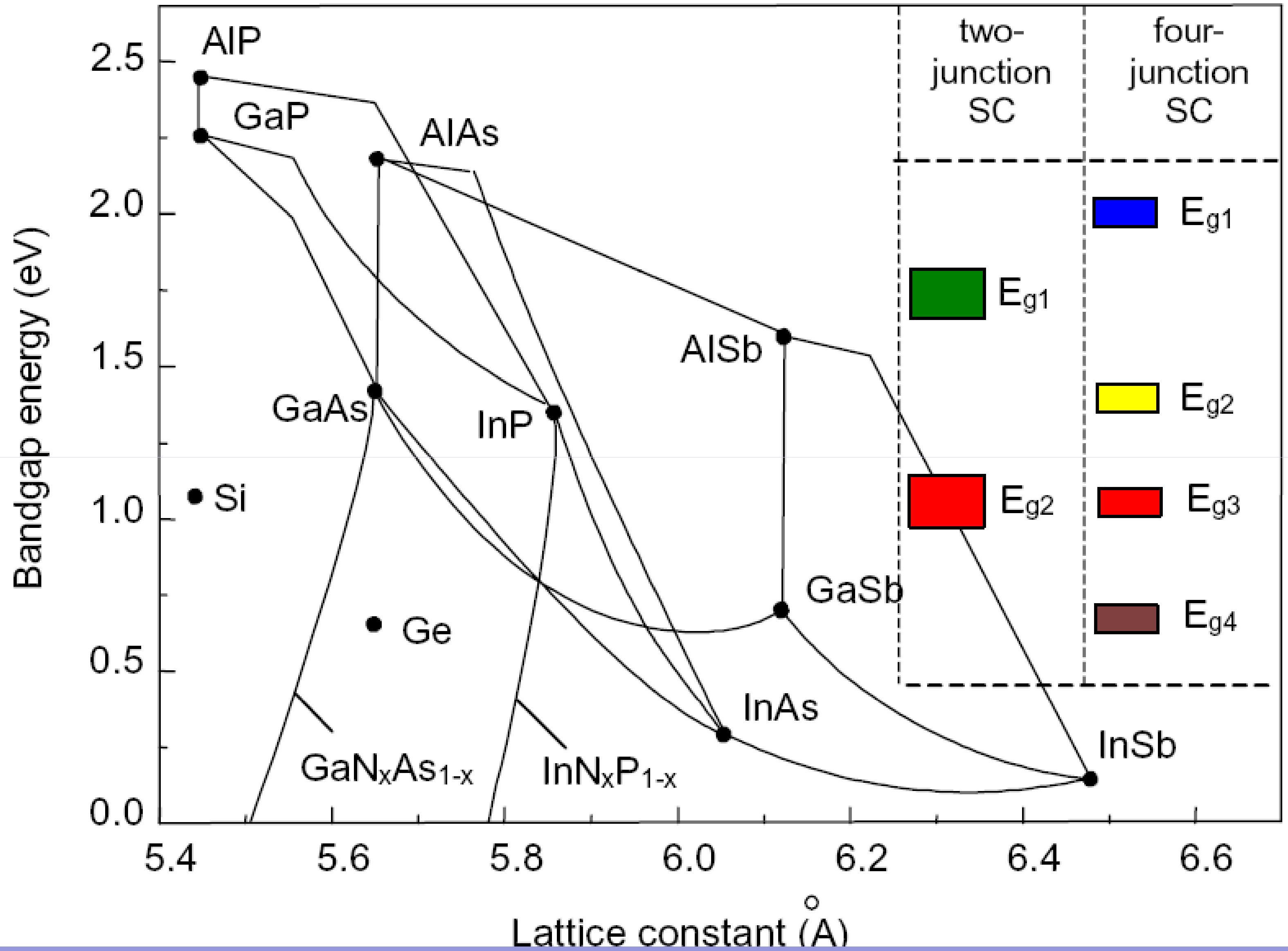
This approach already demonstrated an excellent potential

Active cooling of the received is not needed anymore

A new epitaxial deposition technique ***(LEPECVD)*** *allows to manufacture low-cost substrates with a lattice parameter compatible with most III-V semiconductors*

"Virtual Substrates" *overcome the problem of* ***high cost and shortage of Ge and GaAs monocrystal*** *(precently exploited as substrates for multijunction solar cells)*

Semiconductors and lattice parameters

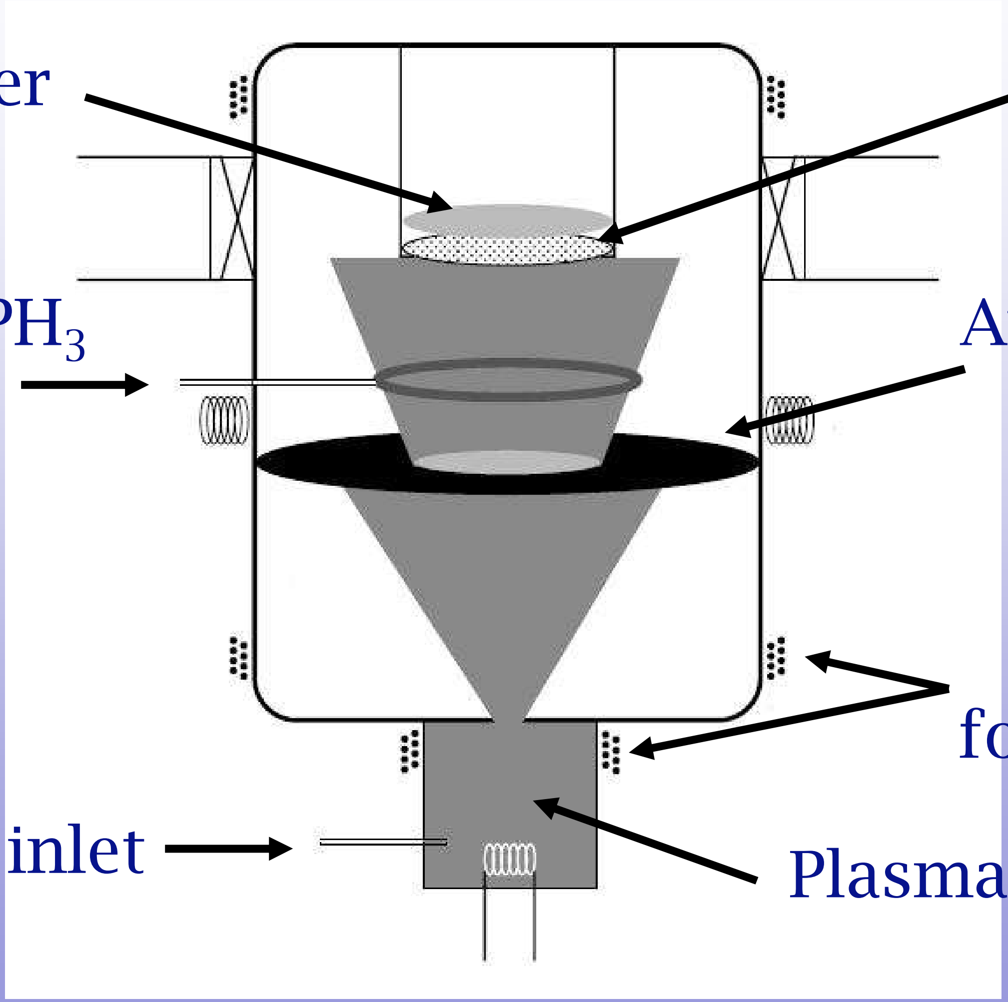


Our approach: Ge “virtual” substrates

From:

to:

LEPECVD reactor



Heater

Substrate

SiH_4, GeH_4, PH_3 inlet

Auxiliary anode

Plasma focusing coils

Ar inlet

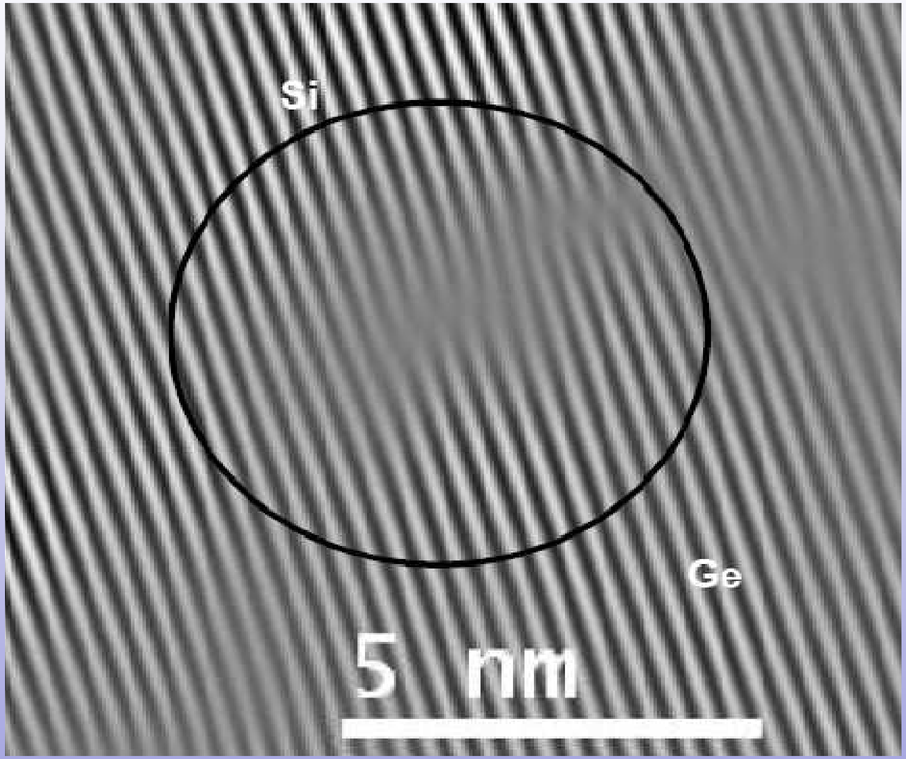
Plasma source

LEPECVD reactor (Unife e Dichroic Cell)

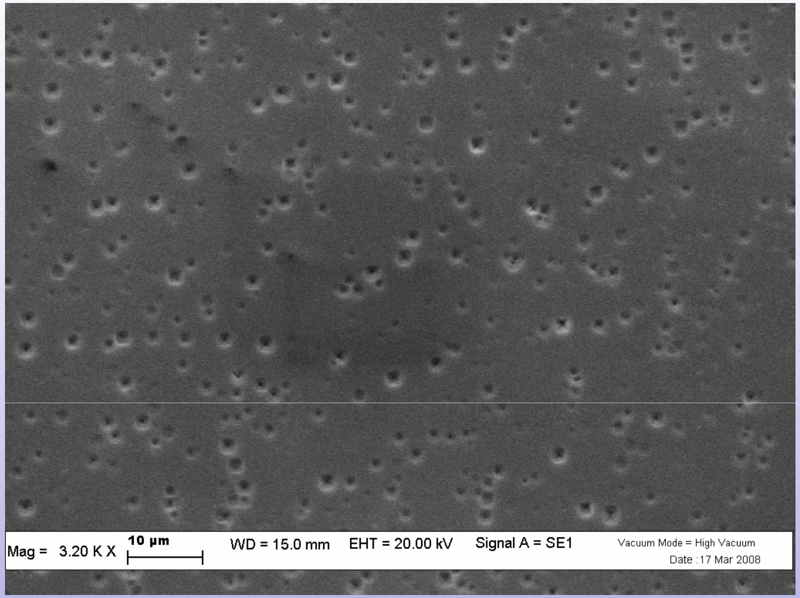
Plasma Reactor for epitaxial heteroepitaxy of SiGe alloy on Si

- High deposition rate (**up to 10 nm/s**)
- Substrate temperature can be tuned to **control surface depectivity** without affecting growth rate

Structural characterization: defect density at the interface and surface

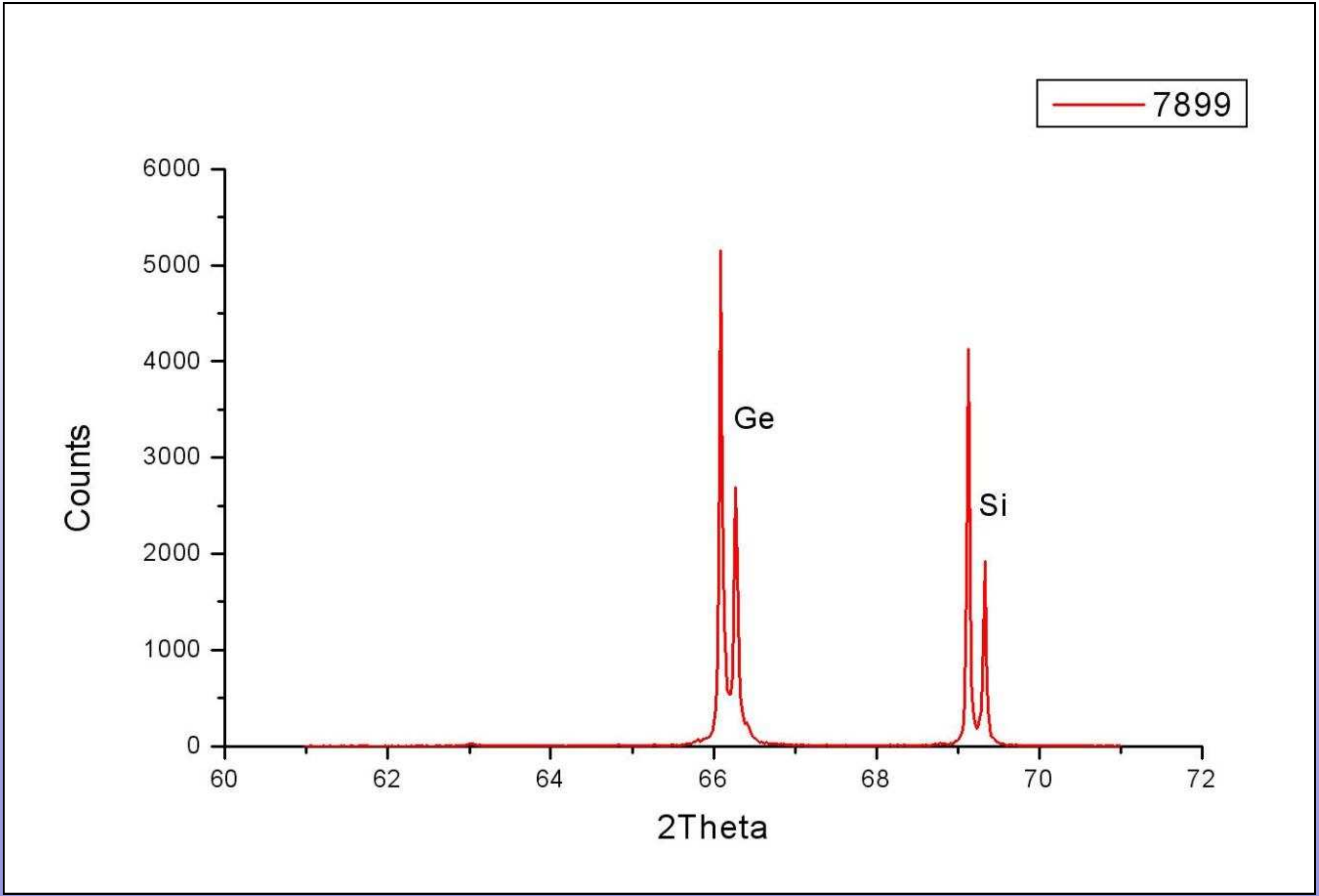


HR-TEM (in collaboration with ST Microelectronics)

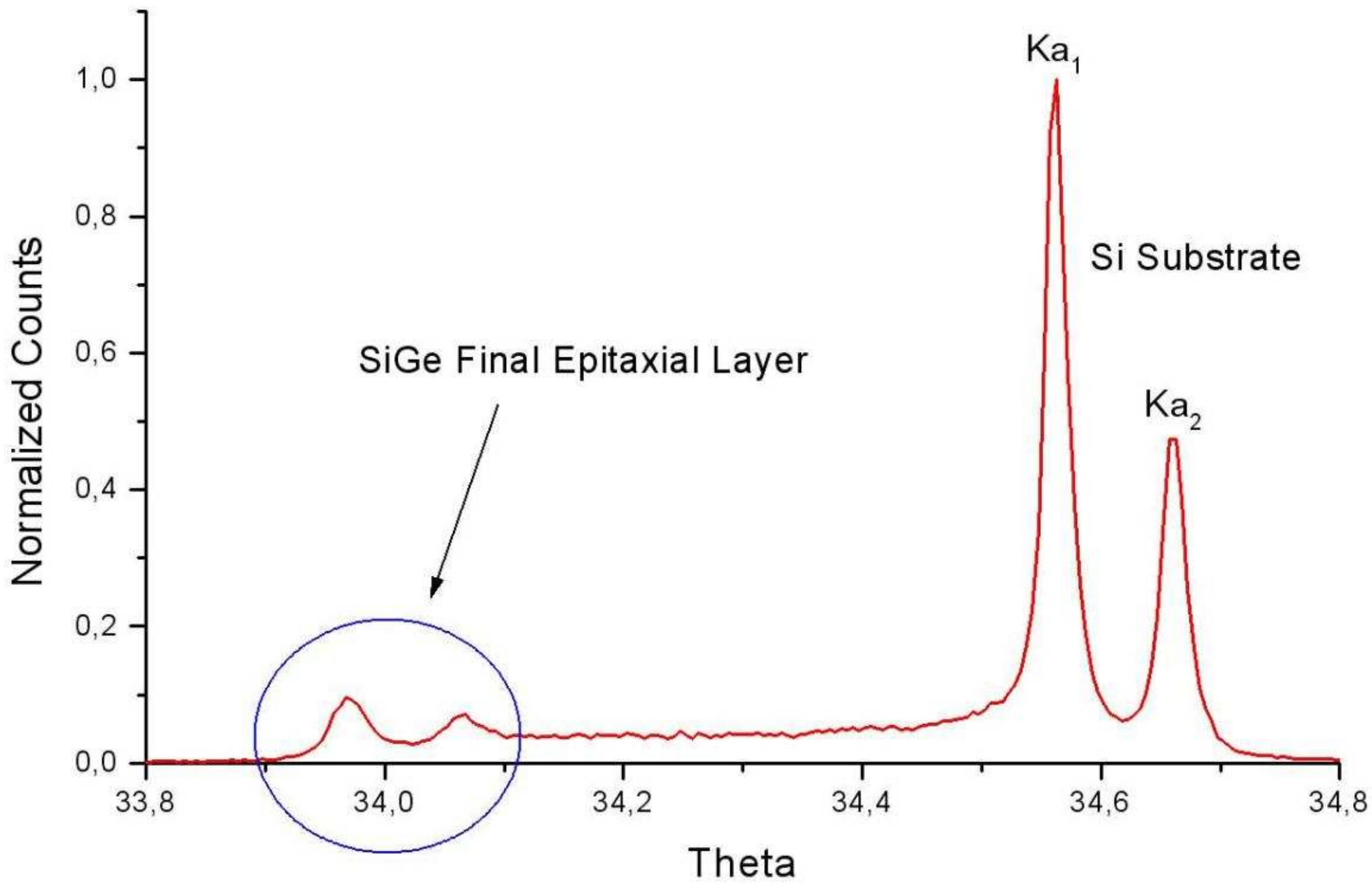


Etch Pit Density characterization (density of TD at surface 4.5x10^6 cm^{-2})

XRD characterization of EPI Ge on Si



XRD characterization of graded SiGe on Si

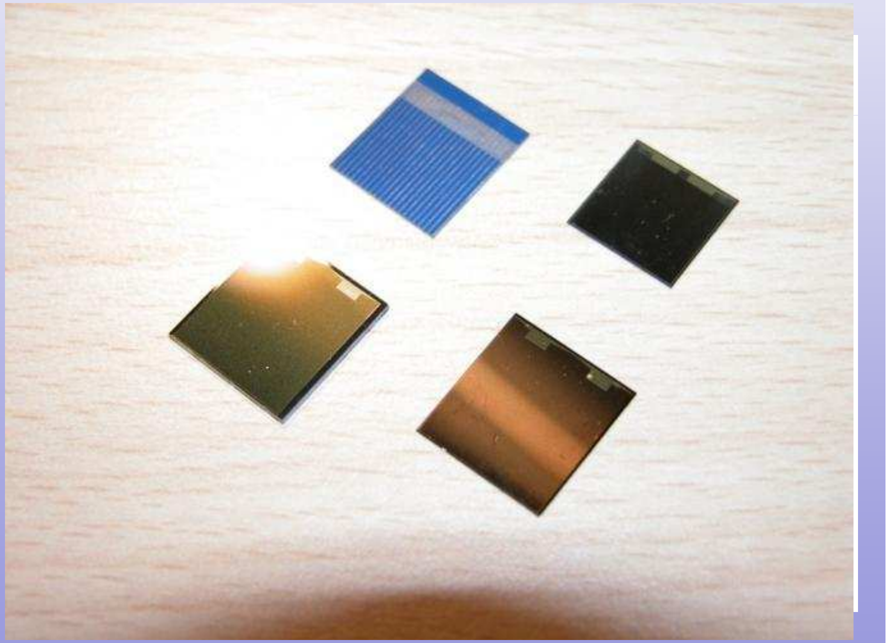


III-V solar cells on Virtual Substrates

C. Flores, CESI S.p.A.

Substrates: N–type, 4–inch Si wafers, covered by 1–3 μm of pure Ge, thermally annealed
Active layers: MOCVD using AIX 2600 and Veeco450 reactors
Epitaxial structures: SJ, DJ and TJ
Metals: Ti/Ag/Au metal evaporation
ARC: Double layer ARC Ta_2O_5/SiO_2
Cell size: 8 cm^2 down to 3 mm^2

III-V solar cells grown on SiGe virtual substrates demonstrated high efficiency, reduced cost and independence on the availability of Ge o GaAs



Consorzio “SUN to GRID”

Ha partecipato alla call per il Progetto di Innovazione Industriale sull’Efficienza Energetica nell’ambito del

Disegno di Legge INDUSTRIA 2015

Progetto del Ministero dello Sviluppo Economico

Il bando relativo a questa proposta è uscito il giorno 06/03/2008 (www.industria2015.ipi.it)

I Partner di SunToGrid

STMicroelectronics (coordinatore)

Università degli Studi di Ferrara

Università degli Studi di Catania

ENEL

ENI

ENEA

CESI Ricerca

CNR-IMM, CNR-ISOF, CNR-MATIS, CNR-ISMAC

System Group

Dichroic Cell

CPower

Silmar Energy

Elettronica Santerno

High Technology System (HTS)

Meta System

CIRPS

Sviluppi auspicati

E' auspicabile che la grande industria associ ai progetti di ricerca esistenti, un progetto industriale mirato a fornire con tecnologie innovative adeguate un contributo energetico significativo, dell'ordine del 10% del fabbisogno nazionale.

In tal caso, finalmente, una proposta scaturita dalla ricerca Universitaria e Industriale sarebbe ritenuta idonea per essere riversata in un progetto industriale. La ricaduta economica sarebbe dell'ordine di **7 miliardi di Euro** all'anno (30 milioni di MWh)

The “clean room” of the Sensor and Semiconductor Laboratory

Surface 115 mq
Yellow Room, ISO 6 Class
Air flow 20000 m^3/h
Bunker ADF

… and the roof of the Physics Department

Thank you for the attention