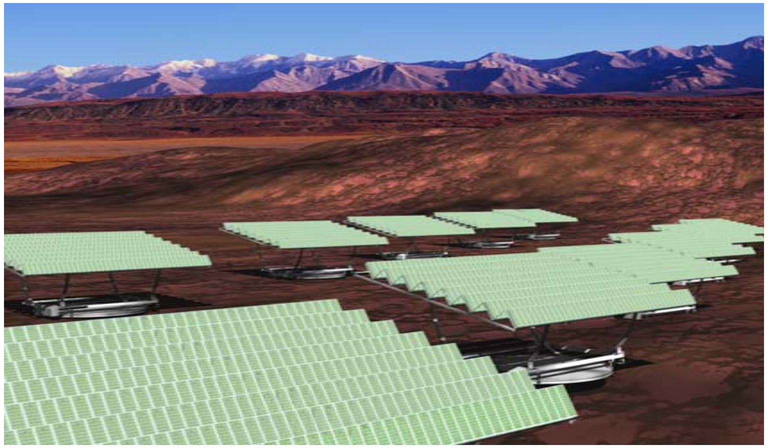


Concentrator PV: From Space to Earth

AZUR SPACE Solar Power

Klaus-Dieter Rasch

EEVF 2007

Rüschlikon, 18 September 2007

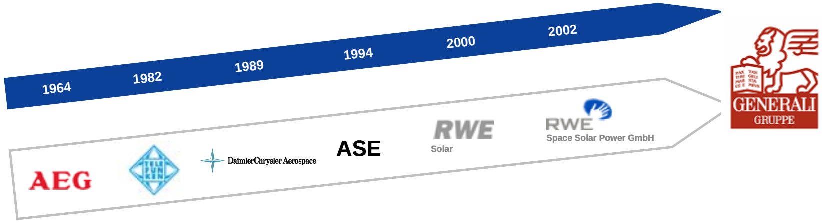
Topics

- A „new“ company with a long tradition
- Key milestones, heritage
- GaAs solar cells for space applications
- Terrestrial concentrator photovoltaic (CPV) systems
- GaAs cells for CPV applications
- CPV market potential

“Telefunkenpark” Heilbronn

Historic development

Founded in 2002,
AZUR SPACE Solar Power GmbH …



… has 40 years space flight heritage

Key Milestones

1964	**Silicon space solar cell 8 % AMO (10 % AM 1.5)**
1974	**First multicrystalline Si solar cell 10 cm x 10 cm 10 % AM 1.5 (cooperation Wacker Chemitronic – Telefunken)**
1983	**First fully automated terrestrial production line in screen printing technology**
1986	**High efficiency Si solar cell 18 % AMO (20 % AM 1.5) in production**
1990	**Ultrathin (5 µm) GaAs solar cell 20 % AMO (22 % AM 1.5)**
2001	**First European triple junction (TJ) GaAs space solar 25 % AMO**
2006	**First TJ GaAs solar cell 8 cm x 8 cm 28.5 % AMO (30 % AM 1.5)**

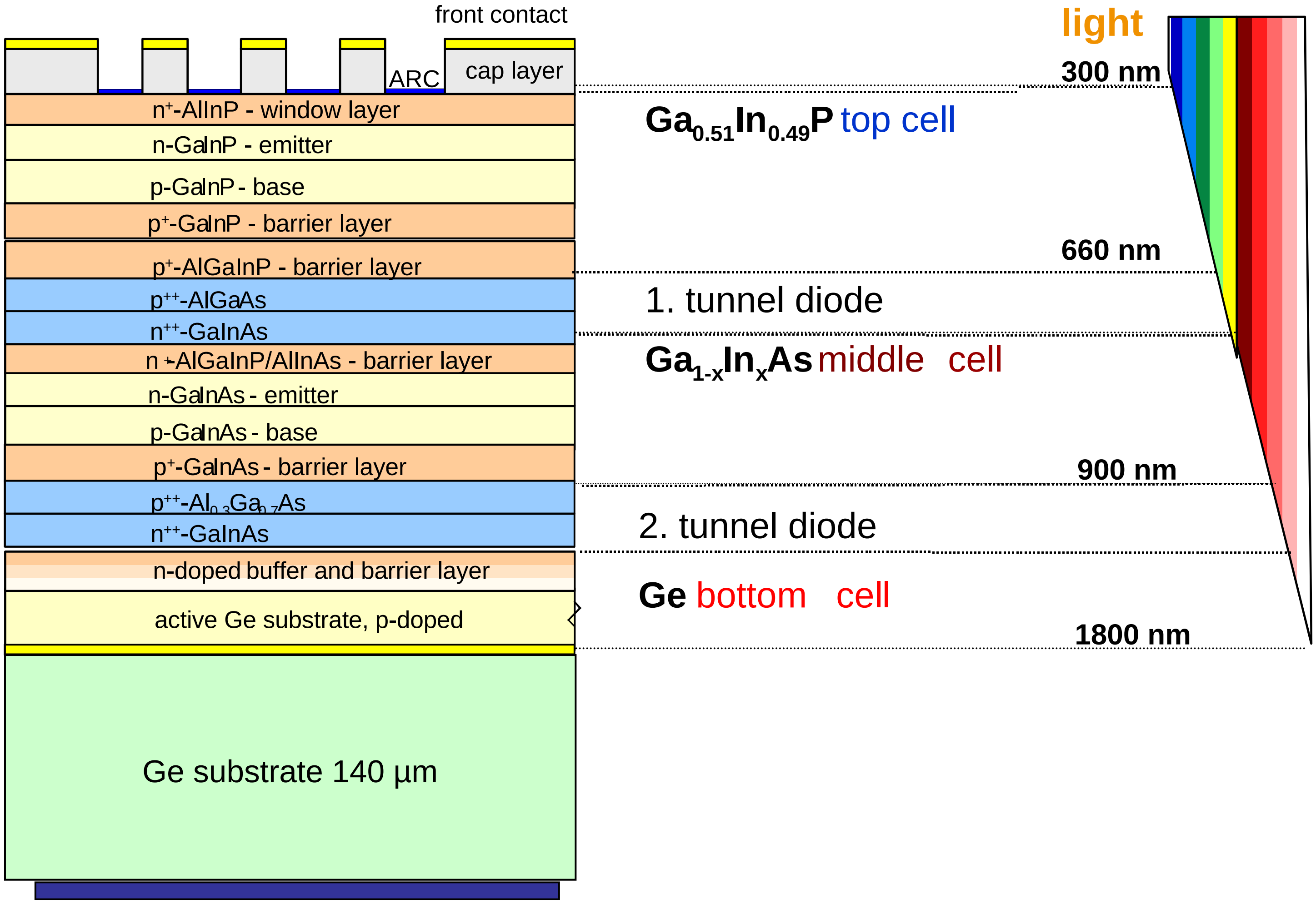
AZUR SPACE Solar Power in Space

AZUR (1) 1968/69
INTELSAT 4 (2) 1970/71
ESRO 4 (2) 1971/72
CTS / HERMES (2) 1973/74
HELIOS A (3) 1973/74
GEOS 1,2 (2) 1973/74
IUE (1) 1974/75
OTS 1,2 (2) 1974/75
ISEE-B (1) 1974/75
MAROTS (1) 1974/75
INTELSAT 5 (15) 1976/82
ECS (5) 1977/83
EXOSAT (1) 1978/79
HUBBLE SPACE TELESCOPE (1) 1978/90
MARECS (3) 1978/82
IRAS (1) 1978/79
OSCAR (3) 1980/81
TELECOM 1 (3) 1981/85
SPOT 1-4 (4) 1981/88
TDF (2) 1981/93
ARABSAT 1 (1) 1981/85
IRM-AMPTE (1) 1981/84
GIOTTO (1) 1981/85
TV-SAT (2) 1981/85
OLYMPUS (2) 1982/84
INTELSAT 6 (5) 1982/85
SKYNET 4 (3) 1982/85
IRS 1 (2) 1983/85
METEOSAT (4) 1983/88
DFS (3) 1983/88
TELE-X (1) 1984/85
HIPPARCOS (1) 1984/86
ROSAT (1) 1984/89
TDF (1) 1985/89
ERS (2) 1985/87
EURECA (1) 1985/88
SKYNET 4 (3) 1985/90
ASPERA (3) 1986/87
INSAT (2) 1986/89
EUTELSAT 2 (4) 1986/89
ISO (1) 1986/92
INTELSAT 7 (5) 1989/92
HELIOS (2) 1989/93
LOCSTAR (2) 1989/92
INSAT 2 (3) 1990/92
EUTELSAT 2 (1) 1990/92
BREMSAT (1) 1991/92
FREJA (1) 1991/92
TÜRKSAT 1 (3) 1991/92
SAX (1) 1991/93
ITALSAT 2 (1) 1991/93
IRS 1 (2) 1991/94
SOHO (1) 1991/94
POSAT (1) 1992/93
KITSAT (1) 1992/93
UOSAT (1) 1992/93
RADARSAT (1) 1992/94
CLUSTER (4) 1992/95
POLAR PLATFORM (1) 1992/96
IRS P2 (1) 1993
AMOS (1) 1993/94
TS 1 (1) 1993/94
INSAT (6) 1993/98
SROSS (1) 1993/94
ARTEMIS (1) 1994/95
ARABSAT (2) 1994/95
TÜRKSAT 2 (2) 1994/95
AGILA (2) 1994/95
THAICOM 3 (1) 1995/96
SPC (8) 1995/99
EQUATOR S (1) 1996/97
IRAD (6) 1996/97
EUTELSAT W24 (4) 1996/97
SIRIUS (4) 1996/97
NAHUEL 1 (1) 1996/97
HOTBIRD 4,5 (2) 1996/97
SKYNET (2) 1996/97
GLOBALSTAR (49) 1996/98
STENTOR (1) 1996/98
METEOSAT (3) 1996/99
SINOSAT (3) 1996/97
XMM (1) 1997
INTEGRAL (1) 1997/98
SBIRS (1) 1997/98
SINGASAT (1) 1997/98
ABRIXAS (1) 1997/98
ORION 2 (2) 1997/98
EOS (2) 1997/98
WORLDSTAR (4) 1997/98
ICOP (1) 1997/98
ASTRA (1) 1997/98
INTELSAT (1) 1997/98
ROCSAT (1) 1998
CHAMP (2) 1998
HISPASAT (2) 1998/99
SSL-AF (1) 1998/99
PROTEUS (1) 1998/99
ARABSAT (2) 1998/99
HES (3) 1998/99
METOP (3) 1998/99
SPOT 5 (2) 1998/99
HELIOS 2 (2) 1999
EUTELSAT W1R (1) 1999
GLOBALSTAR (10) 1999
ASTRA 2B (1) 1999
INTELSAT KTV (1) 1999
INSAT (1) 1999
Geolite (1) 1999
ATV (10) 2001/08
PROBA (1) 1999/00
ROSETTA (1) 2000
RADARSAT 2001
INTELSAT (2) 2001/02
INMARSAT 2001/02
ROCSAT 2001
W3A 2001
CAST 2001
SPC (10) 2002
HES 2 2002
AMAZONAS 2002
EROS B 2002
PROTEUS 2 2002
GOCE 2002
SARLUPE 2003
HERSCHEL 2003
PLANCK 2003
ANIK 2003
INSAT(2) 2004
ICOP FO 2004
ARABSAT(4) 2004
METEOSAT 2004
ASTRA 1 M 2004
HOTBIRD 2004
SKYNET 5A 2004
TALISAT 2004
ELECTRO L 2004
W3A 2004
TERRA SAR 2004
AEOLUS 2005
PLEIADES 2005
PROBA(2) 2005
THEOS 2005
VENUS EXPRESS 2005
ORBCOMM 2006
LISA PATHFINDER 2006
AEOLUS 2006
YAMAL 300 2006
PRISMA 2006

Since 1964
AZUR SPACE Solar Power has powered ...

... more than 300 satellites.

Structure of TJ – GaAs Solar Cell



front contact

ARC

cap layer

n^+-AlInP - window layer

n-GaInP - emitter

p-GaInP - base

p^+-GaInP - barrier layer

p^+-AlGaInP - barrier layer

p^{++}-AlGaAs

n^{++}-GaInAs

n^+-AlGaInP/AlInAs - barrier layer

n-GaInAs - emitter

p-GaInAs - base

p^+-GaInAs - barrier layer

p^{++}-$Al_{0.3}Ga_{0.7}As$

n^{++}-GaInAs

n-doped buffer and barrier layer

active Ge substrate, p-doped

Ge substrate 140 µm

light

300 nm

$Ga_{0.51}In_{0.49}P$ top cell

660 nm

1. tunnel diode

$Ga_{1-x}In_xAs$ middle cell

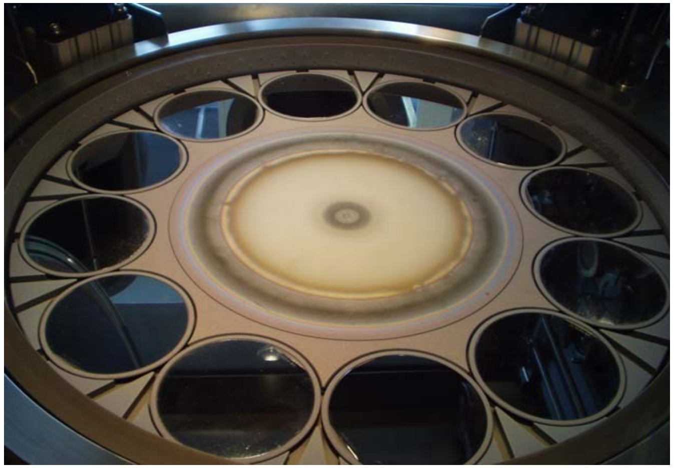
900 nm

2. tunnel diode

Ge bottom cell

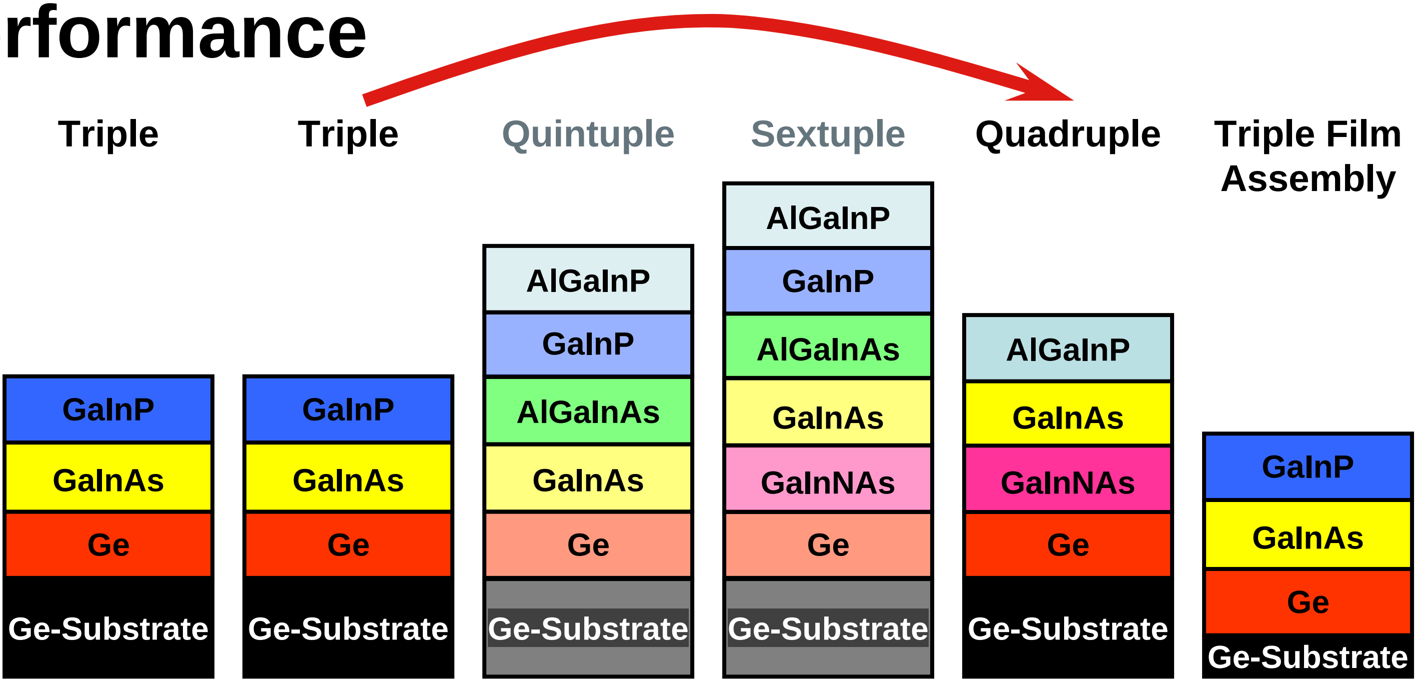
1800 nm

Epitaxial Reactors



Future Cells

- **Performance**



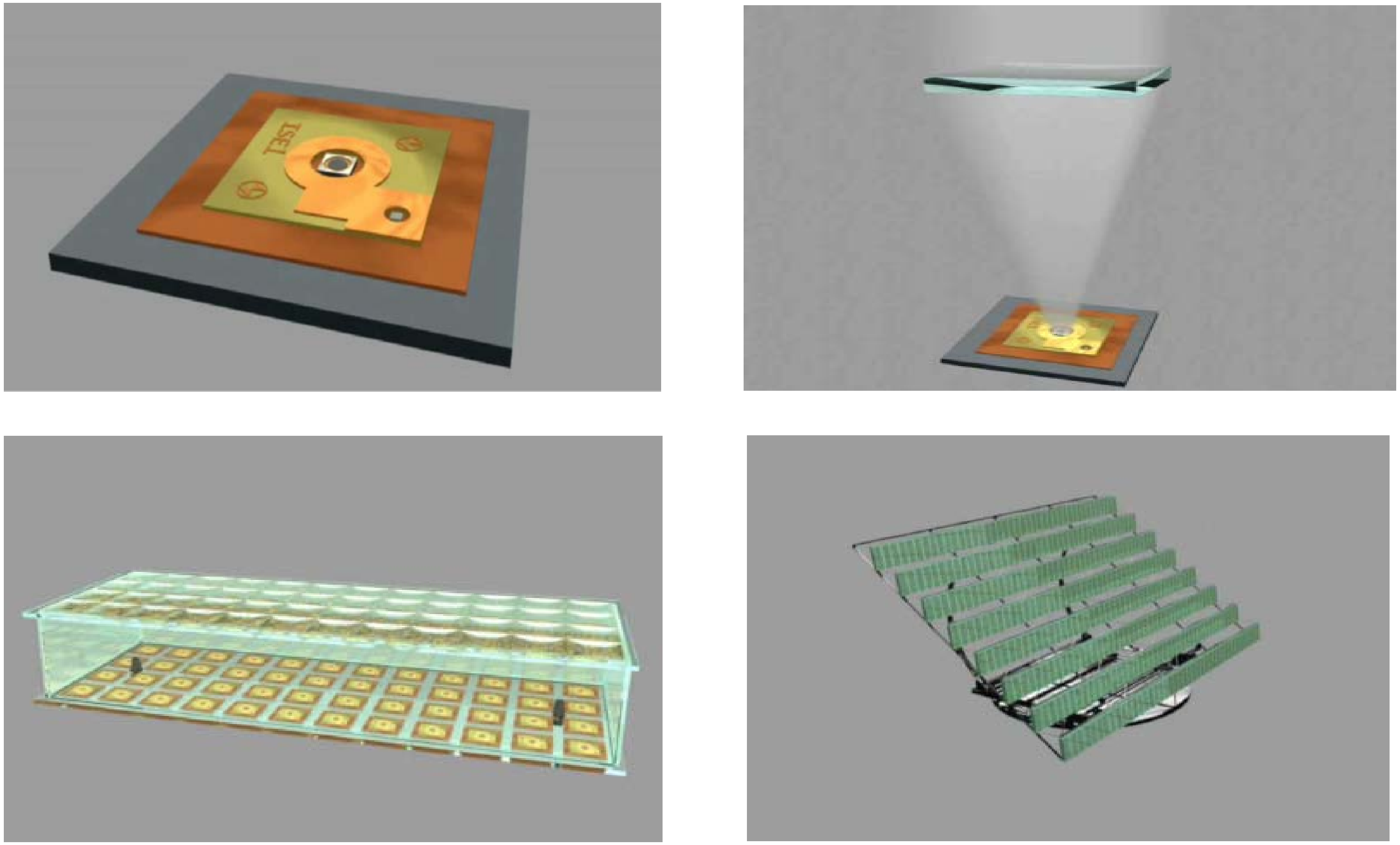
	Triple	Triple	Quintuple	Sextuple	Quadruple	Triple Film Assembly
	GaInP GaInAs Ge Ge-Substrate	GaInP GaInAs Ge Ge-Substrate	AlGaInP GaInP AlGaInAs GaInAs Ge Ge-Substrate	AlGaInP GaInP AlGaInAs GaInAs GaInNAs Ge Ge-Substrate	AlGaInP GaInAs GaInNAs Ge Ge-Substrate	GaInP GaInAs Ge Ge-Substrate
Year	2006	2008	2009	2010	2012	2015
Voltage	2.6 V	2.7 V	5.5 V	6.5 V	3.5 V	2.6 V
BOL eff.	28%	30%	29%	31%	33%	30%
EOL eff. (1E15 1MeV-e/cm²)	24%	25%	26%	27%	28%	26%

Terrestrial Concentrator PV Systems

GaAs compound cells have been used exclusively in satellite power applications, but the actual shortage of polysilicon material and the efficiency limits of silicon-based solar panels means that commercial terrestrial applications of CPV systems are now a real possibility.

The photovoltaics industry is looking therefore towards compound cells with its potential of 45% efficiency as a key technology for utility-scale, high-efficiency solar power, but also for residential houses or agriculture applications with cogeneration of electricity & heat.

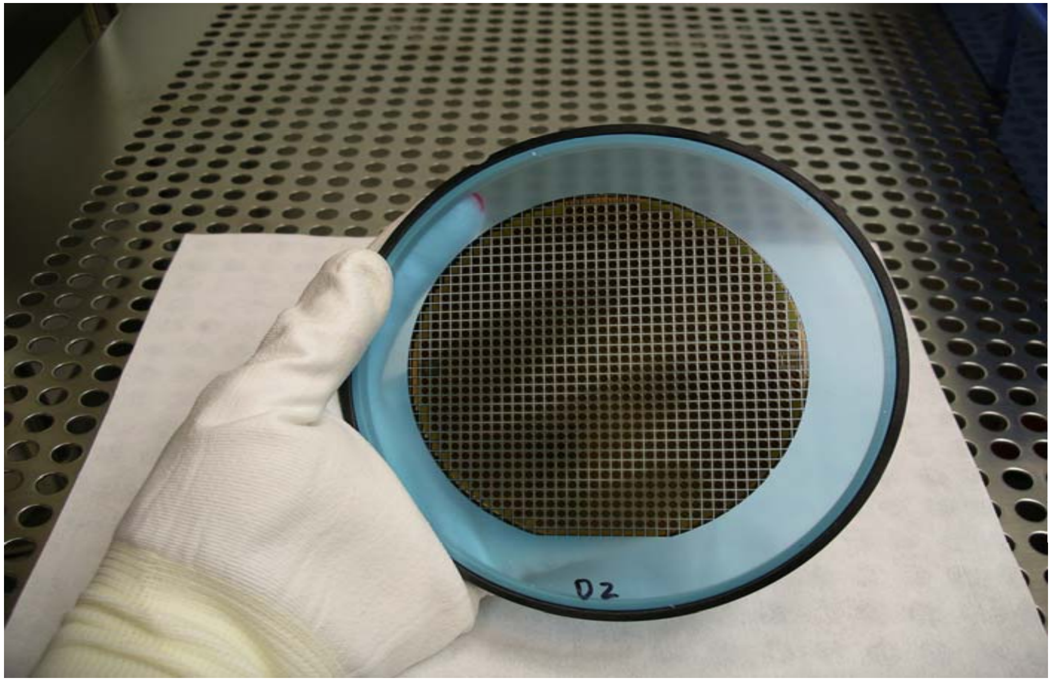
Design of a CPV Fresnel System

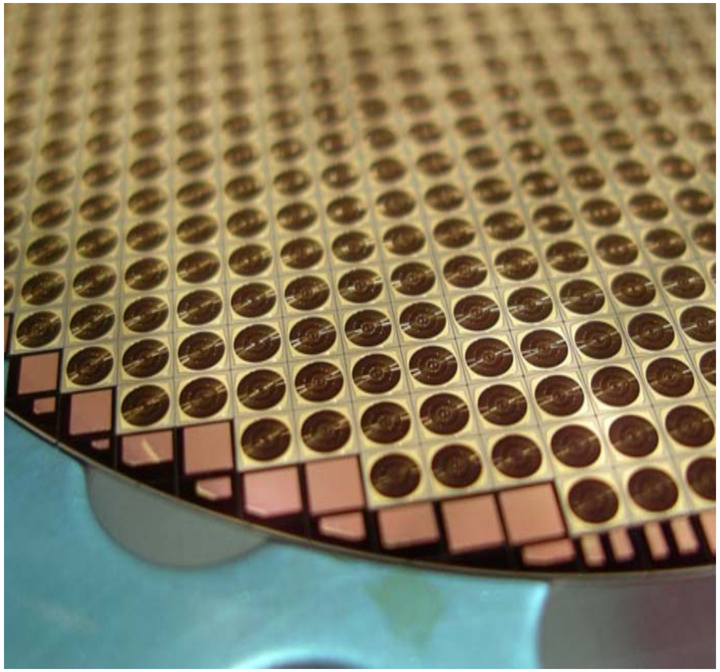


Strength of CPV Systems

- Efficiency improvement by concentrated sunlight
- Efficient use of solar cell material
- Optical concentration are inexpensive compared with large photovoltaic material
- The overall manufacturing process (besides the cell production) is lower-tech than for flat plate modules. The estimated investment cost are of a CPV manufacturing plant is only 20-30 % compared to crystalline silicon PV or Thin–film PV
- Cell efficiency is approaching 40 % for the benefit of bringing down the cost per watt installed and ultimately per kWh produced

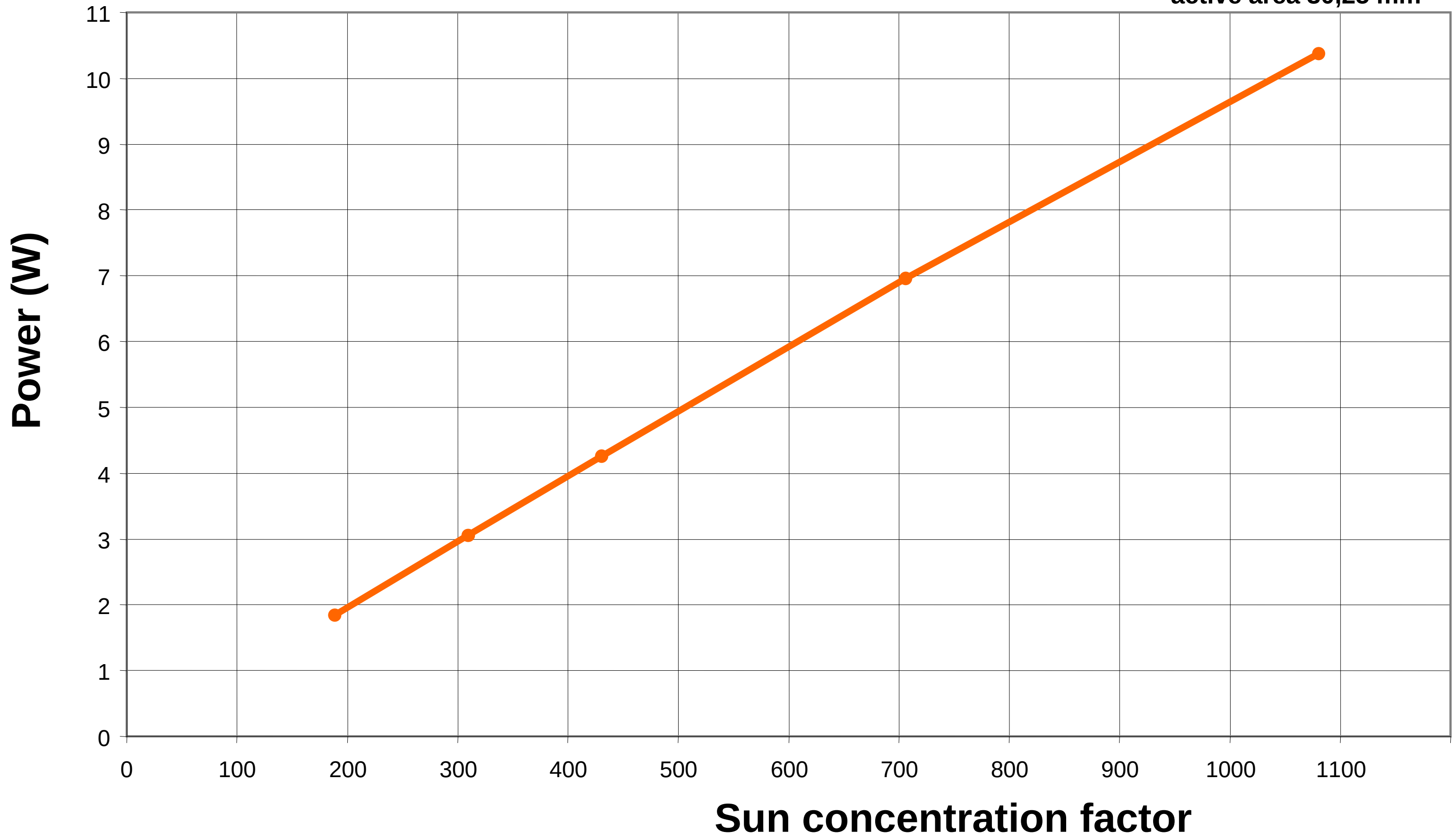
From a 2mm Chip to a MW Solar Plant





GaAs CPV Cells

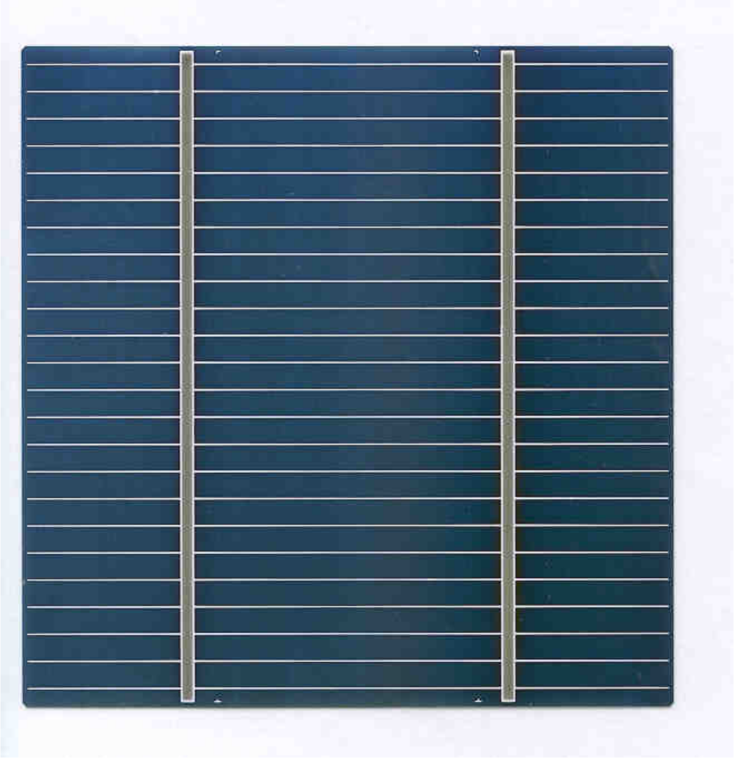
6mm x 6mm
active area 30,25 mm²



Comparison

Si Standard Cell   GaAs CPV Cell

100 mm x 100 mm

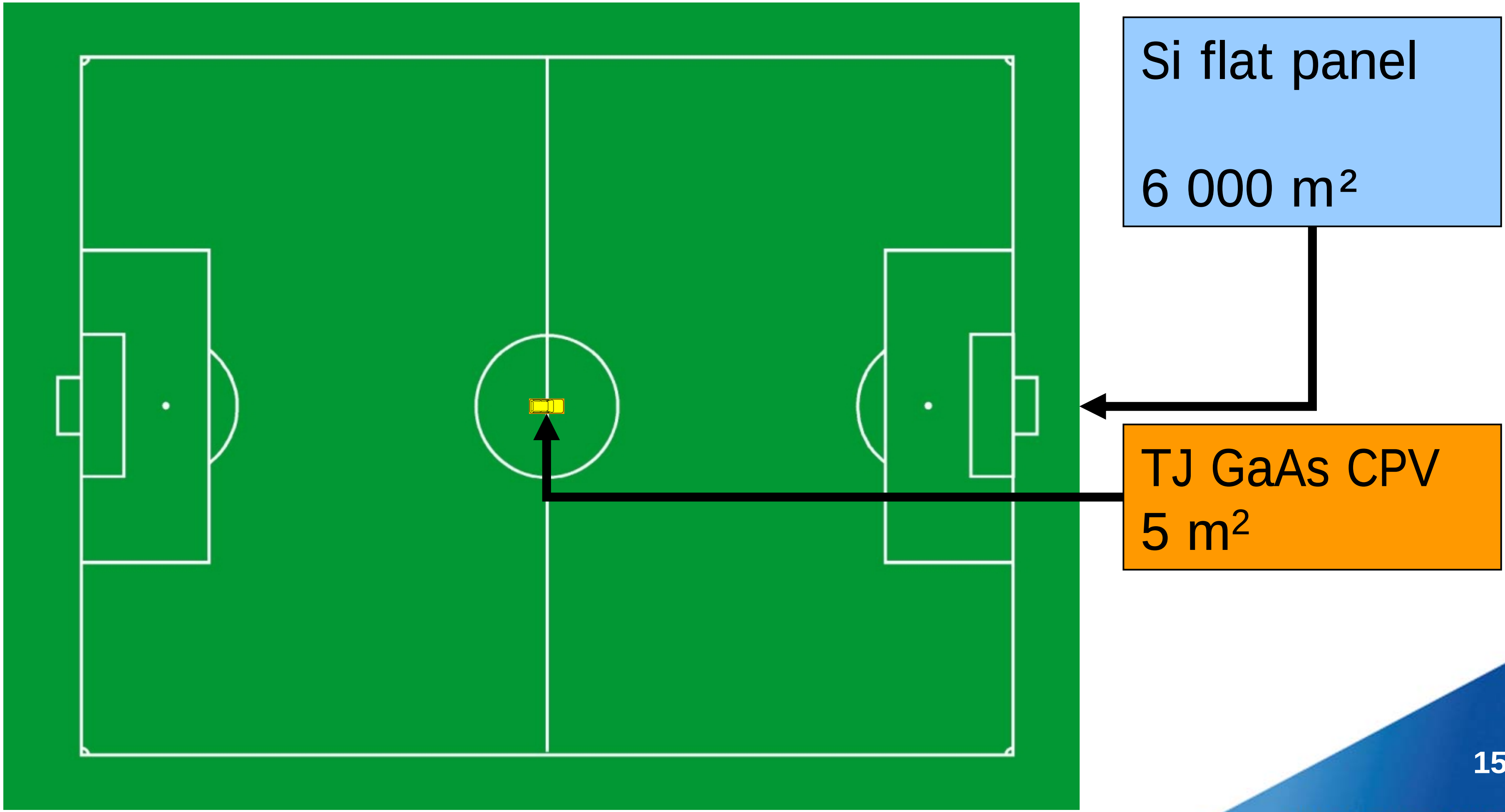


1,55 W @ AM1.5

2,5mm x 2,5mm

1,58 W @ 920X AM1.5

Semiconductor usage for a 1 MWp solar power plant



Si flat panel

6 000 m²

TJ GaAs CPV

5 m^2

Roadmap Multijunction GaAs Concentrator Cells

Year	**2001**	**2007**	**2009**	**2012**
Type	Triple Junction Gen 1	Triple Junction Gen 2	Triple Junction Gen 3	Multi Junction
Max Efficiency (World Record)	34.2 %	40.7 %	42.0 %	45.0 %
Year in Production	2006	2007	2010	2015
Average Efficiency	32.0 %	35.0 %	37.0 – 39.0 %	40.0 – 42.0 %

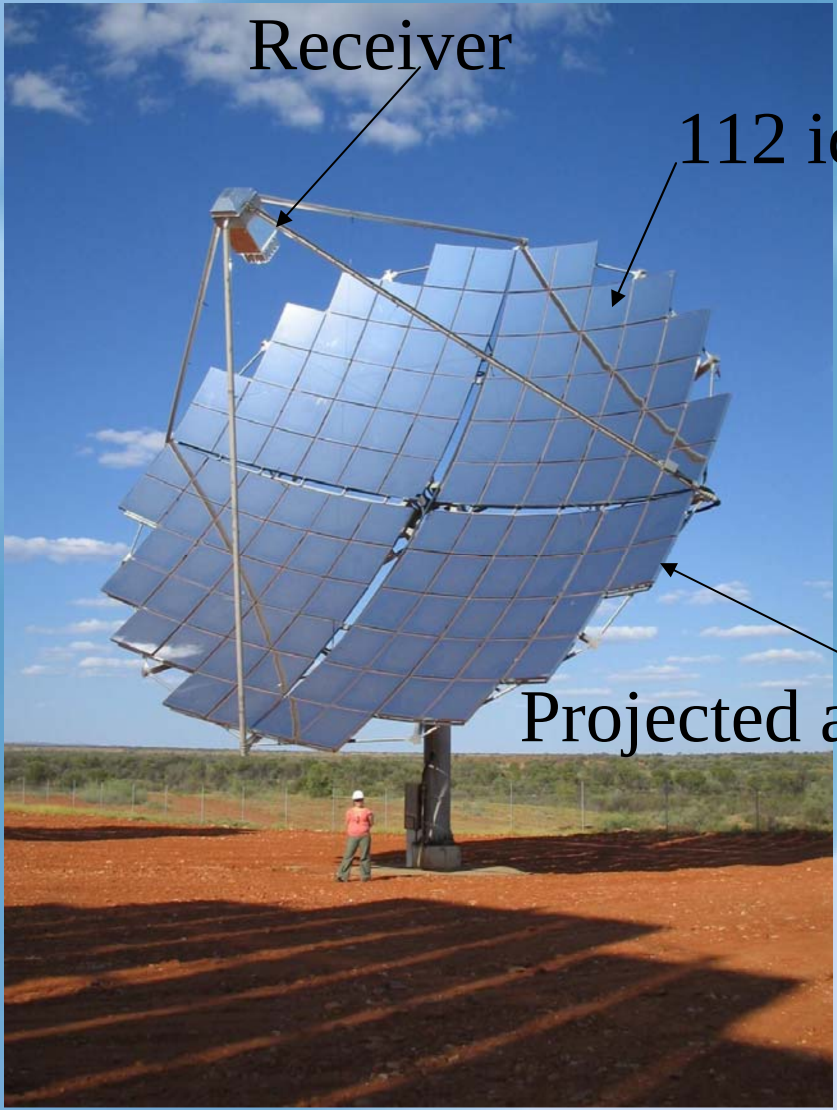
Concentrator PV Fresnel Units

Lorca, Spain

Concentrix 6kW / unit 31 m²

Concentrator PV Dish Unit

Optical efficiency 85%



Receiver

112 identical mirrors

Projected aperture 130 m^2

Concentration 500X

Relative Cost Index

	GaAs CPV	Fix mounted Si Flat Plate Module	Fix mounted High Eff Si Flat Plate	Tracked High Eff Si Flat Plate
Assumption				
cell efficiency 25 °C	35 %	14.5 %	19 %	19 %
cell efficiency operating conditions (incl. optical losses)	25 %	11.0 %	14 %	14 %
Generator level	100	112	127	130
Utility level	100	122	128	144
Climate level break even > 55%*)	100	107	113	100
sun belt	100	131	138	117
desert	100	154	162	131

*) ratio direct to overall irradiation

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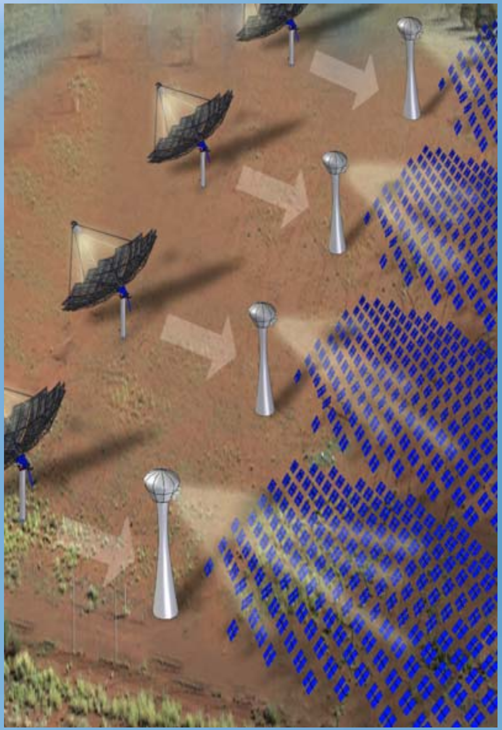
Key Cost Reduction Elements for CPV Systems

	2007	2010	2015
Cell Efficiency in Production	35 %	39 %	42 %
Wafer Size	100 mm dia	150 mm dia	150 mm dia
Optical Efficiency	70 – 80 %	80 %	85 %
Concentrator Factor	300 – 500	500 – 1000	1000 – 6000
AC System Efficiency	19 – 23 %	24 – 26 %	30 %

Roadmap for Terrestrial Concentrator Systems

STEP 1	CPV Systems for Solar Electricity
STEP 2	Combined Concentrator PV and Thermal System (CPVT)
STEP 3	24h Solar Electricity Systems by combined CPVT System and Hydrogen Fuel Cell System



✓In sun belt regions CPV is already competitive with conventional PV

✓Heliostat CPV will bring the cost down to the level of “clean” fossil fuel generation by 2020

Solar Systems

Conclusions

CPV is already competive with Flat-Plate PV in sun belt regions.

Only CPV systems have the potential of low-cost, solar-generated electricity at a cost that is competitive with mainstream electric generation systems.

Key component is a “super” GaAs CPV cell working at high concentration.

The economics can be improved further by cogeneration of electricity, heat and hydrogen.