

硅太阳能电池

--助推碳达峰碳中和的主力军

中科院上海微系统与信息技术研究所 研究员

通威太阳能 光伏研究院 院长

上海科技大学 兼职教授

刘正新

2022.11.01



提纲

- 一、碳达峰、碳中和国家战略
- 二、新能源对碳达峰碳中和的贡献
- 三、太阳能电池的基本原理和发展
- 四、太阳能电池的种类和特点
- 五、晶体硅太阳能电池的基本制作：电池-组件-系统
- 六、太阳能电池的应用
- 七、太阳能电池的未来发展趋势
- 八、Q&A

一、碳达峰、碳中和国家战略



2060



中国庄严承诺

2030

“中国将提高国家自主贡献力度，采取更加有力的政策和措施，二氧化碳排放力争于2030年前达到峰值，努力争取2060年前实现碳中和。”

习近平主席

在第75届联合国大会一般性辩论上
庄严承诺

习近平主席在系列会议宣示碳达峰碳中和相关目标



- 中国将提高国家自主贡献力度，采取更加有力的政策和措施，二氧化碳排放力争2030年前达到峰值，努力争取2060年前实现碳中和
- 力争2030年前二氧化碳排放达到峰值
- 单位国内生产总值二氧化碳排放比2005年下降65%以上
- 非化石能源占一次能源消费比重达到25%左右
- 森林蓄积量比2005年增加60亿立方米左右
- 风电、太阳能发电总装机容量达到12亿千瓦以上

碳中和已成为全球共识

截至到2021年4月底，有明确碳中和目标和进展的国家

Energy & Climate Intelligence Unit 的净零排放跟踪表统计：
目前超过**130个国家和地区**提出了“零碳”或“碳中和”的气候目标**包括：已实现碳中和的2个国家，已立法的6个国家，处于立法中状态的包括欧盟（作为整体）和其他5个国家。**另外，有20个国家（包括欧盟国家）发布了正式的政策宣示。提出目标但尚处于讨论过程中的国家和地区近100个。

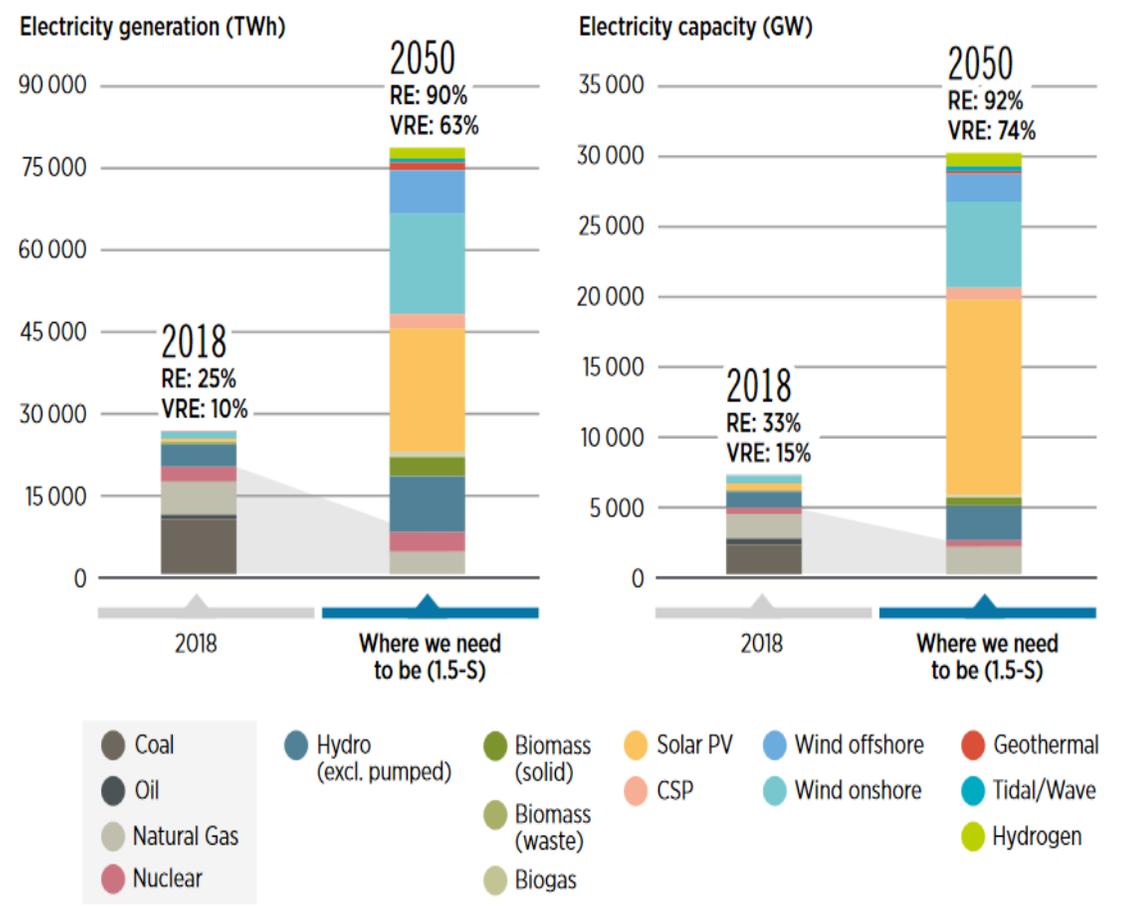
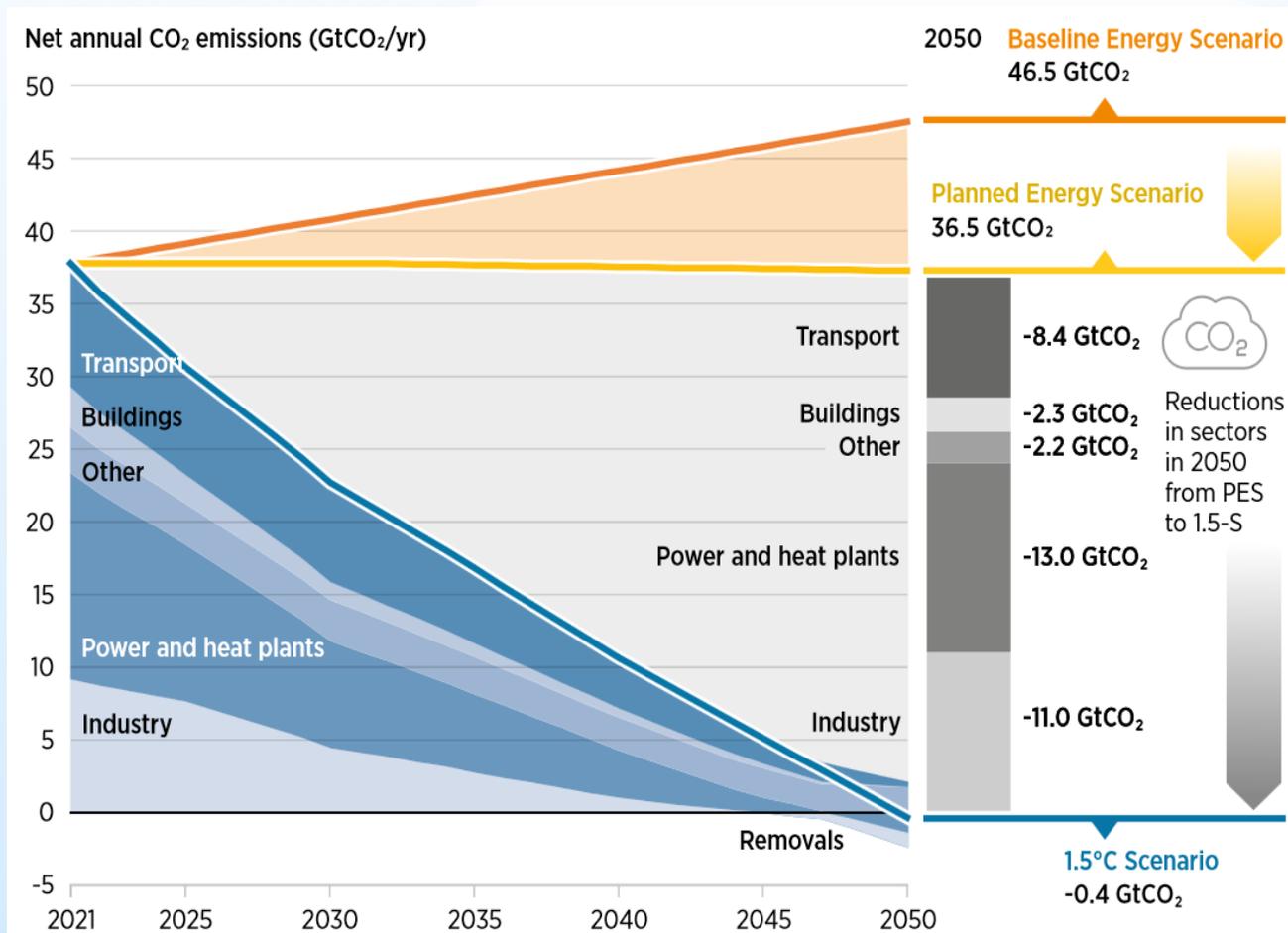
进展情况	国家和地区（承诺年）
已实现	苏里南共和国、不丹
已立法	瑞典（2045）英国（2050）、法国（2050）、丹麦（2050）、新西兰（2050）、匈牙利（2050）
立法中	欧盟（2050）、加拿大（2050）、韩国（2050）、西班牙（2050）、智利（2050）、斐济（2050）
政策宣示	芬兰（2035）、奥地利（2040）、冰岛（2040）、美国（2050）、日本（2050）、南非（2050）、德国（2050）、巴西（2050）、瑞士（2050）、挪威（2050）、爱尔兰（2050）、葡萄牙（2050）、巴拿马（2050）、哥斯达黎加（2050）、斯洛文尼亚（2050）、安道尔（2050）、梵蒂冈城（2050）、马绍尔群岛（2050）、中国（2060）、哈萨克斯坦（2050）

 风能专委会CWEA
<https://eciu.net/netzerotracker>

全球碳中和目标要求2050年净零碳能源系统

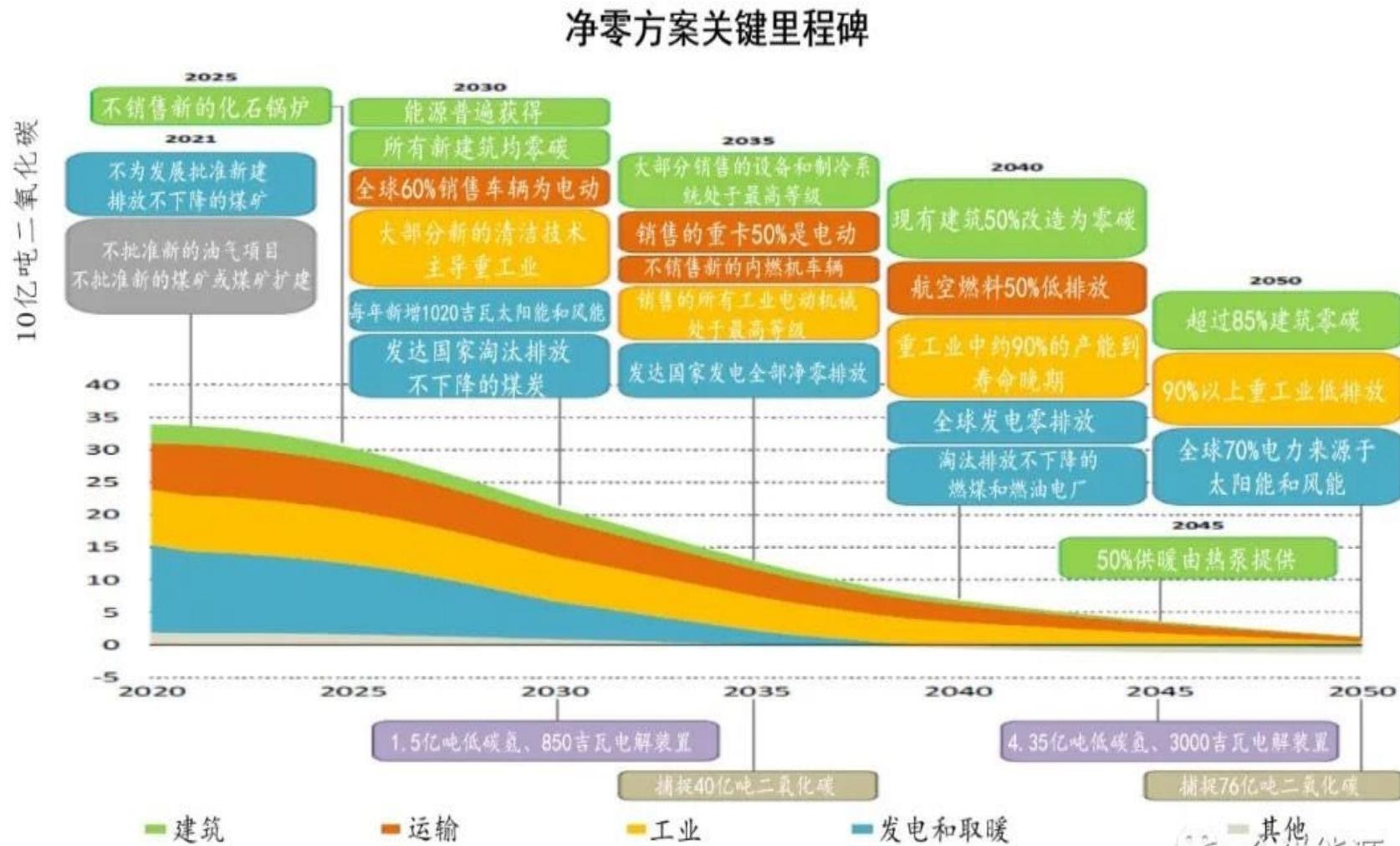
IRENA 的1.5度情景

2050年可再生能源发电量占比90%（风光占比63%）



IEA 《2050年净零排放：全球能源行业路线图》

- 从今天开始不再投资任何新的化石燃料供应项目，也不再投资新建燃煤电厂。
- 2035年，不再销售新的内燃机乘用车（新能源汽车代替传统油车等），
- 2040年，全球电力部门排放量达到净零。
- 到2030年，全球净零排放中大部分二氧化碳减排量都来自于当今可用的技术（现有技术）。但是到2050年，将近一半的减排量，将来自目前仍处于演示或原型阶段的技术（未来技术）



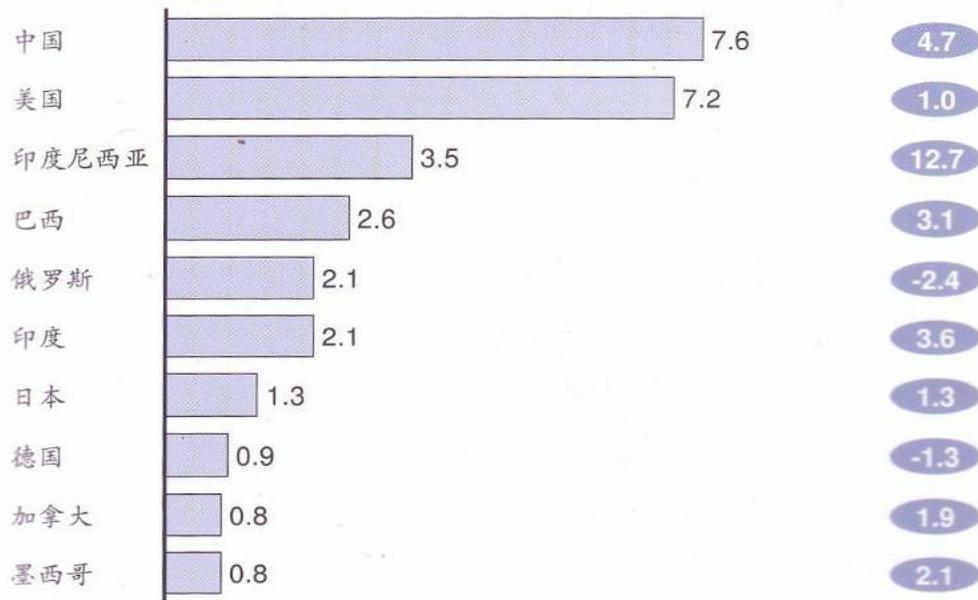
资料来源：IEA, Net Zero by 2050 -- A Roadmap for the Global Energy Sector, p20.

中国的碳排放

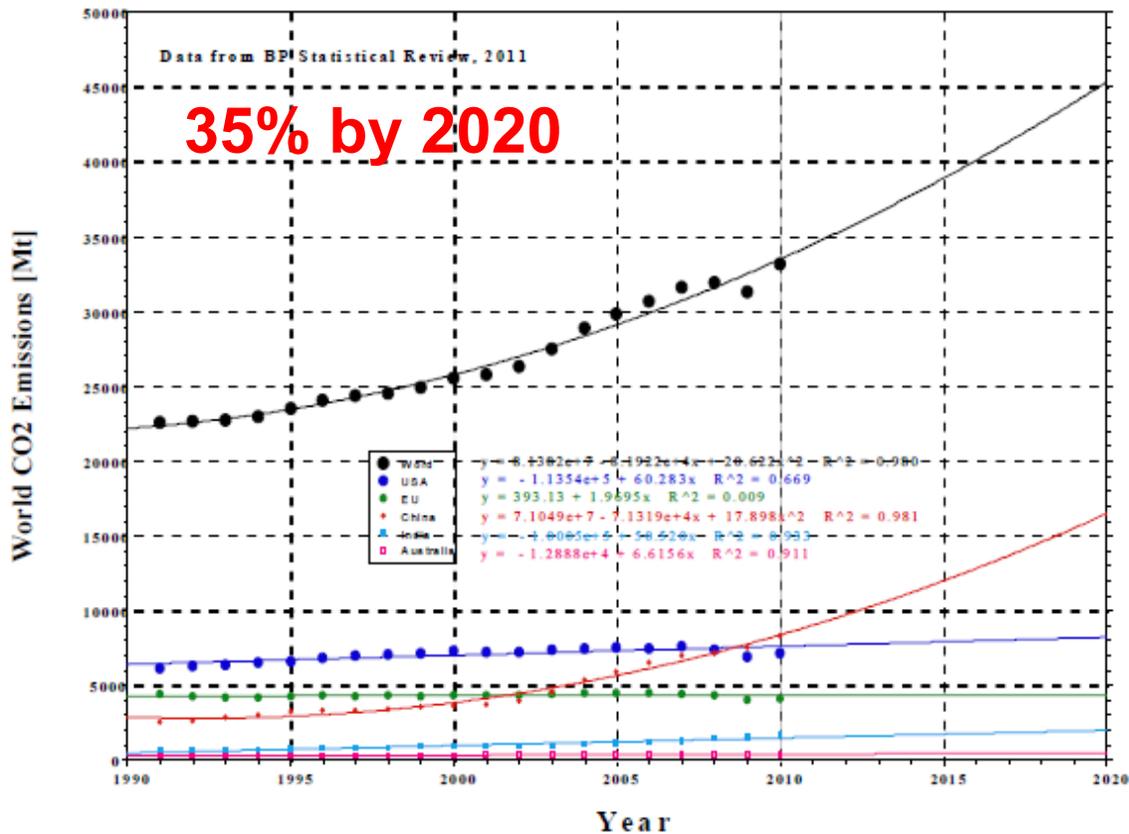
温室气体的主要排放国 - 2007

2007年温室气体排放量
十亿吨CO₂e

1990-2007年均增长率
百分比



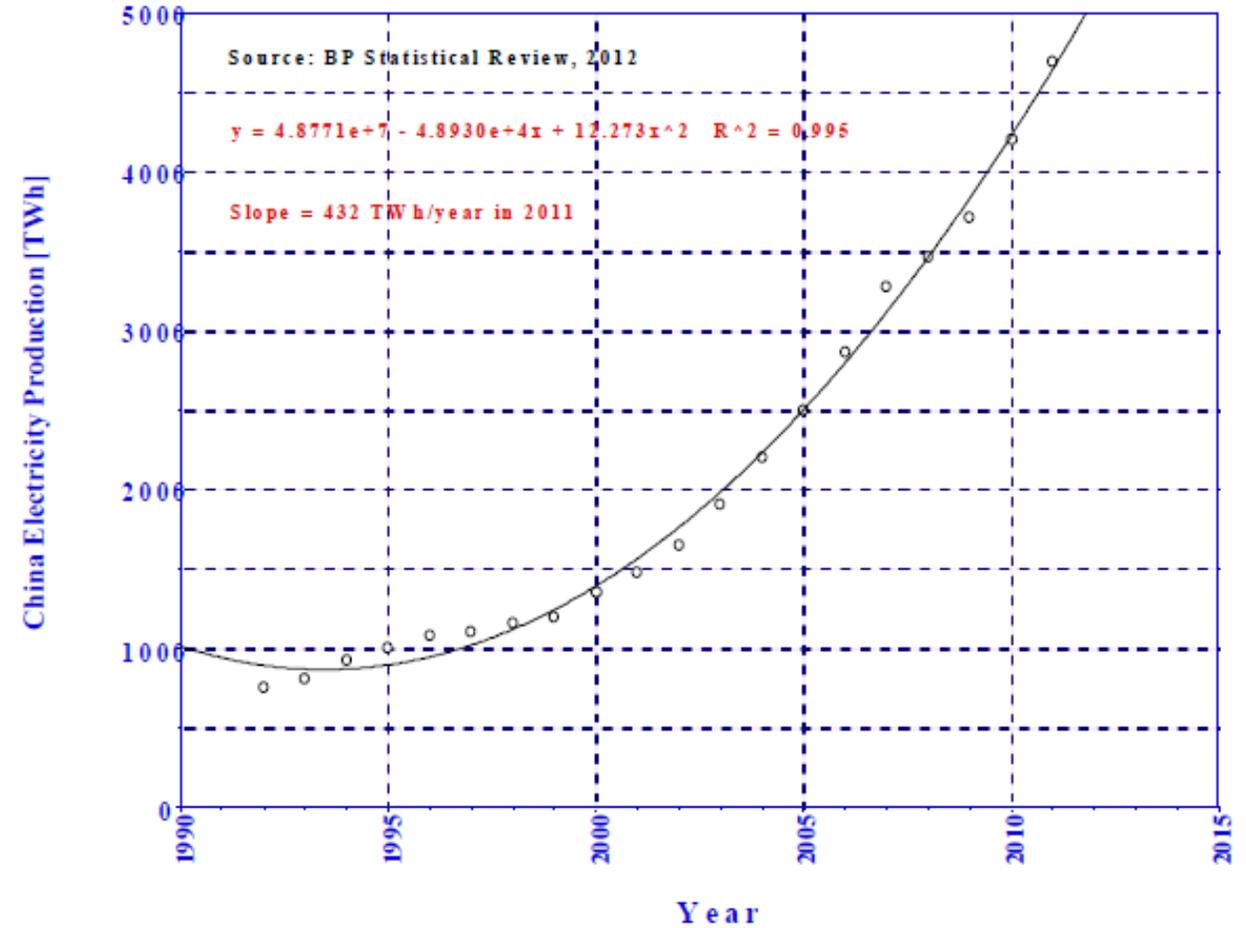
资料来源：国际能源署；美国环境保护署；世界资源研究所；联合国气候变化框架公约；麦肯锡分析



中国能源生产

China's electricity production:

Source: BP Statistical Review, 2012



Quadratically rising annual requirement!

2013-2018年中国能源生产和消费

能源生产

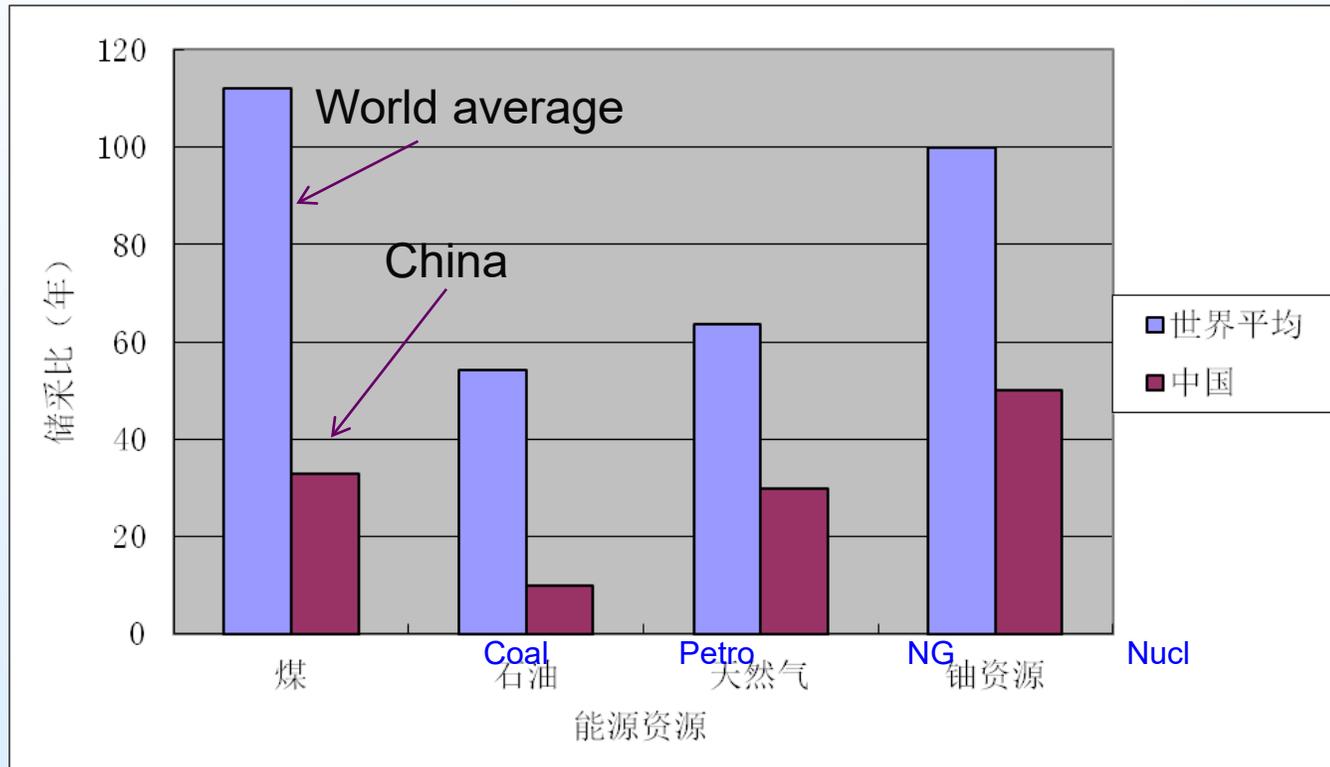


能源消费



中国能源资源的储藏量

储/采比: Storage/mining ratio



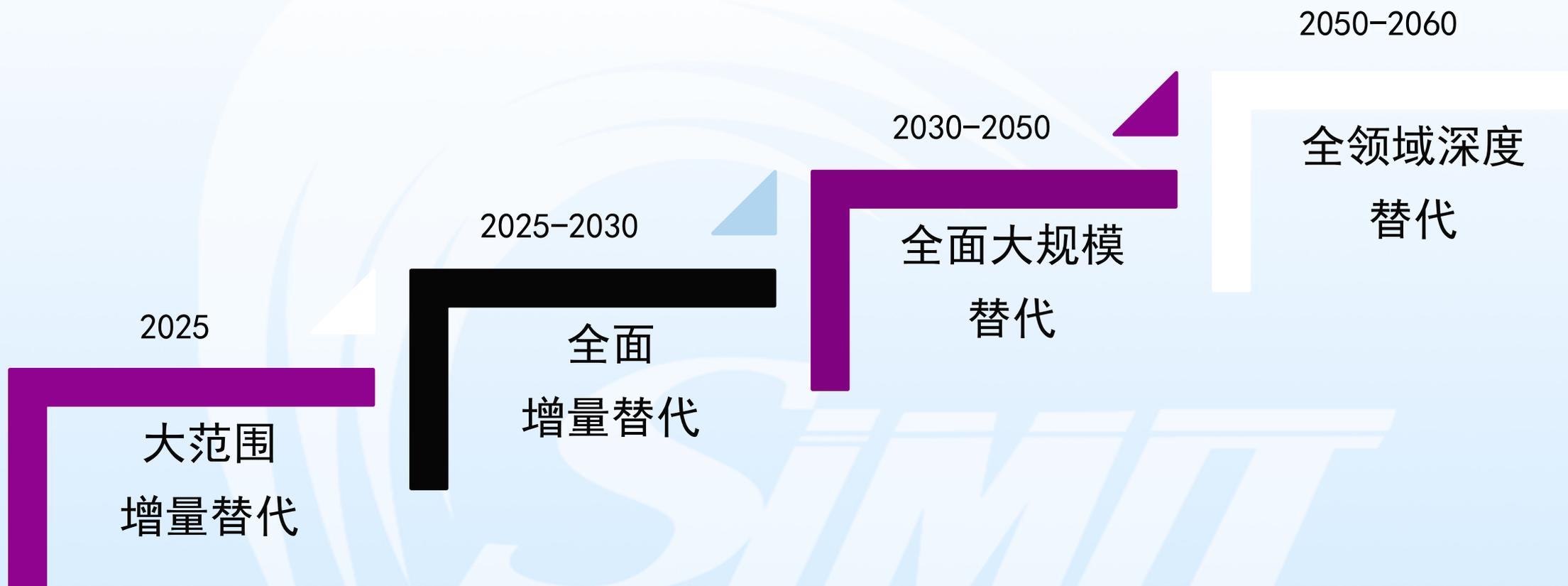
再过30年，中国将无煤可挖，无油可采，无气可开！

中国必须在今后20-30年内完成能源转型，发展光伏等可再生能源是中国能源和环境可持续发展的唯一出路！

Source: BP Statistical Review, 2012

Energy resources	Coal	Petroleum	NG	Nuclear
World average (year)	112	54.2	63.6	100
China (year)	33	9.9	29.8	50
%	29.46	18.27	46.86	50.00

可再生能源增加供应和替代化石能源路径



十四五：新阶段、关键期、窗口期

大规模

- 年均装机规模有大幅度的提升
- 可再生能源发电装机容量占电力总装机的比例将超过50%

高比例

- 在全社会用电量增量中的比重将达到三分之二
- 在一次能源消费增量中的比重将超过50%
- 在电力消费增量中：从补充变为主体

市场化

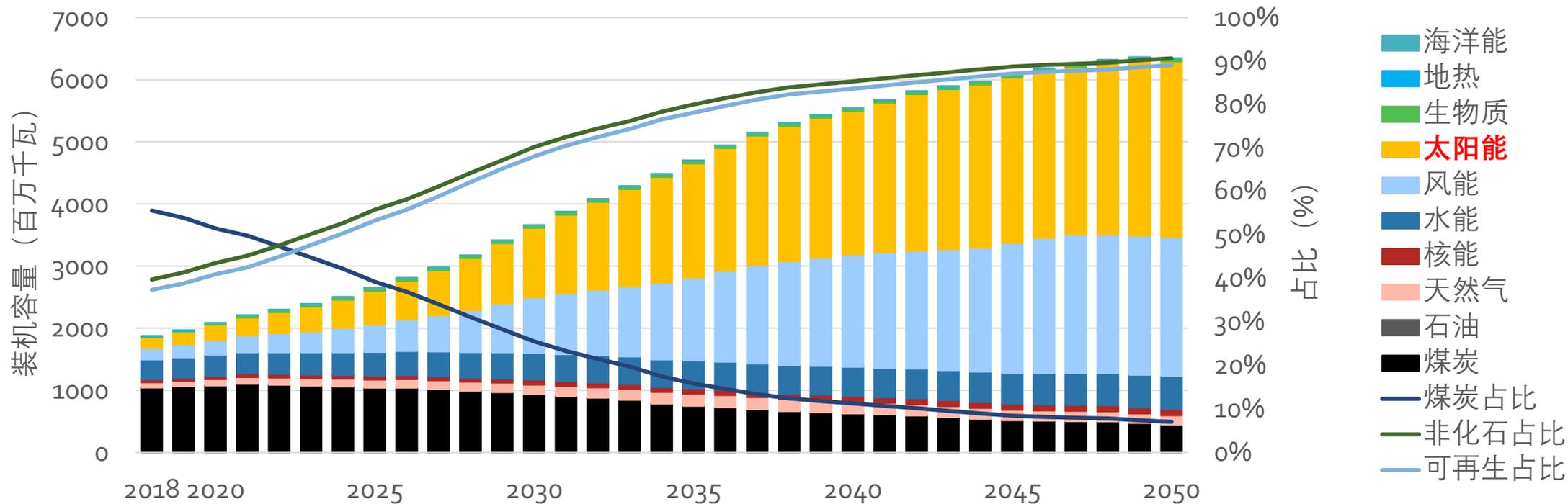
- 进一步发挥市场在可再生能源资源配置中的决定性作用
- 风电、光伏进入平价阶段
- 实现市场化发展、竞争化发展

高质量

- 加快构建以新能源为主体的新型电力系统
- 大规模开发、高水平消纳、电力可靠性

风电和光伏发电成为新增主力电源

- 更多驱动力：低成本、全民参与、电力市场、新型电力系统
- 未来3个五年逐步加速发展！？
- “十四五”：“平价”规模化发展，年均增加45GW风电和65GW光伏
- “十五五”：电力市场释放灵活性，年均增加100GW风电和150GW光伏
- “十六五”：新型电力系统初见成效，年均增加150GW以上的风电和光伏



二、新能源对碳达峰碳中和的贡献



传统能源



煤



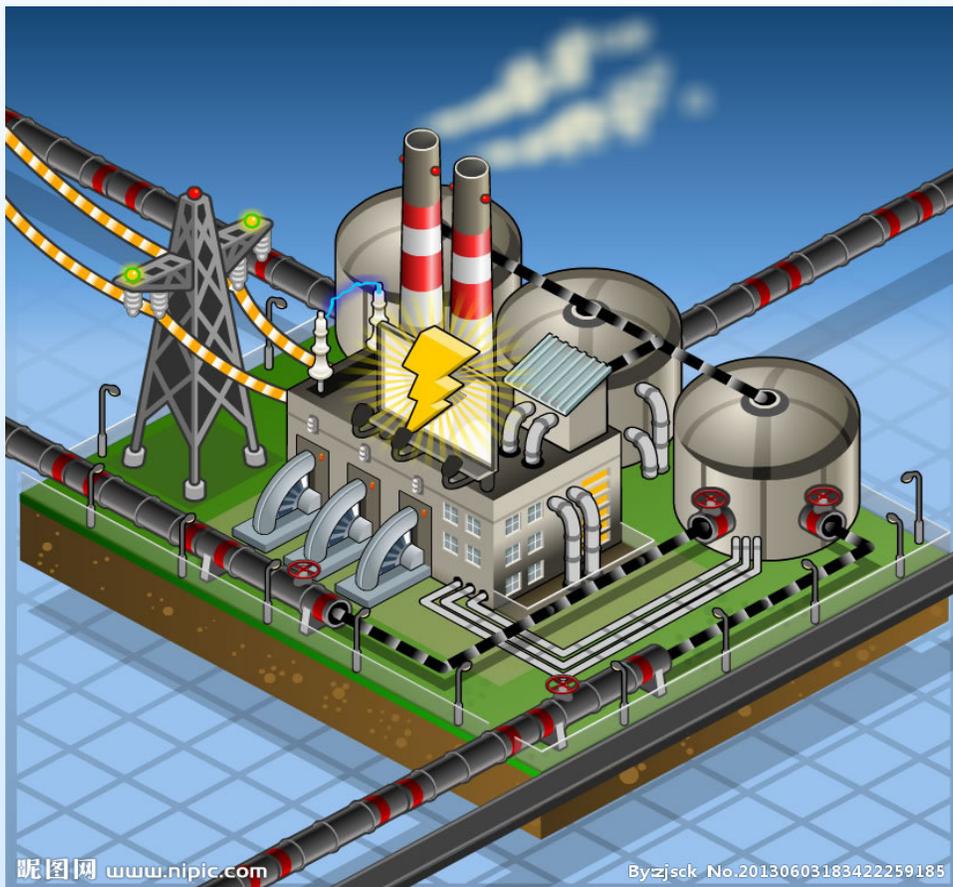
石油



汽油

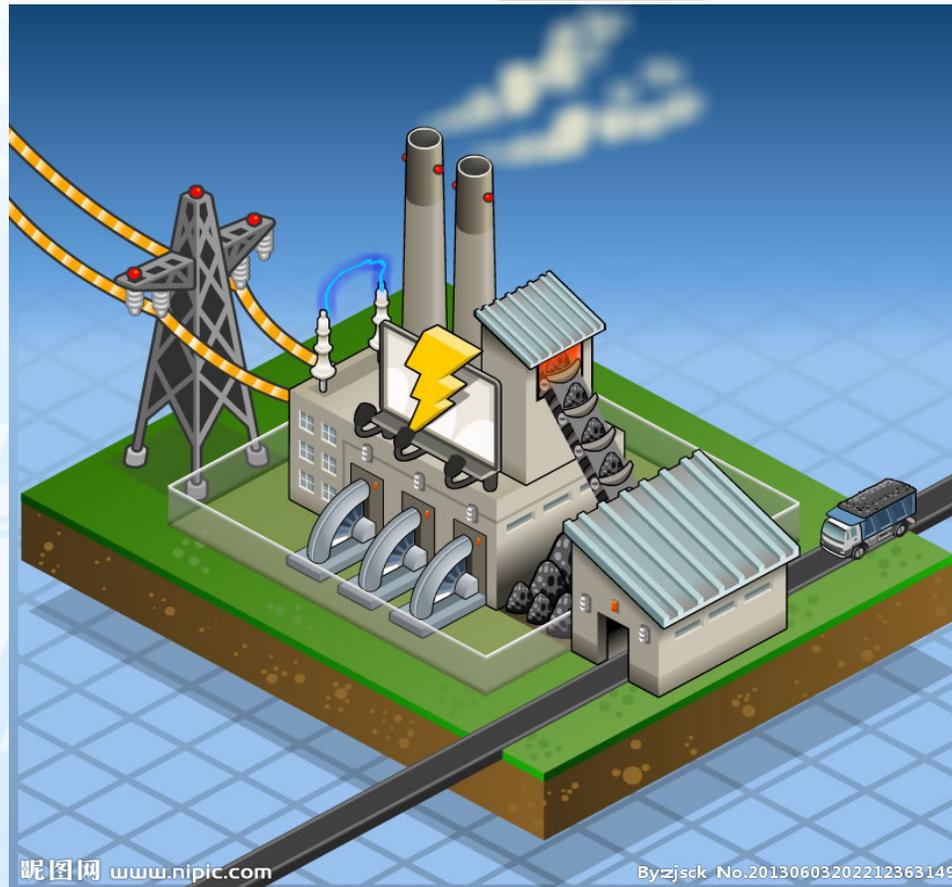


柴油



昵图网 www.nipic.com

Byzjsck No.20130603183422259185



昵图网 www.nipic.com

Byzjsck No.20130603202212363149

传统能源

天然气



核能（新能源？）



日本福岛311核事故



什么是新能源？



水电



- ❖ 受地域限制
- ❖ 对生态环境影响较大
- ❖ 我国水电资源已开发殆尽

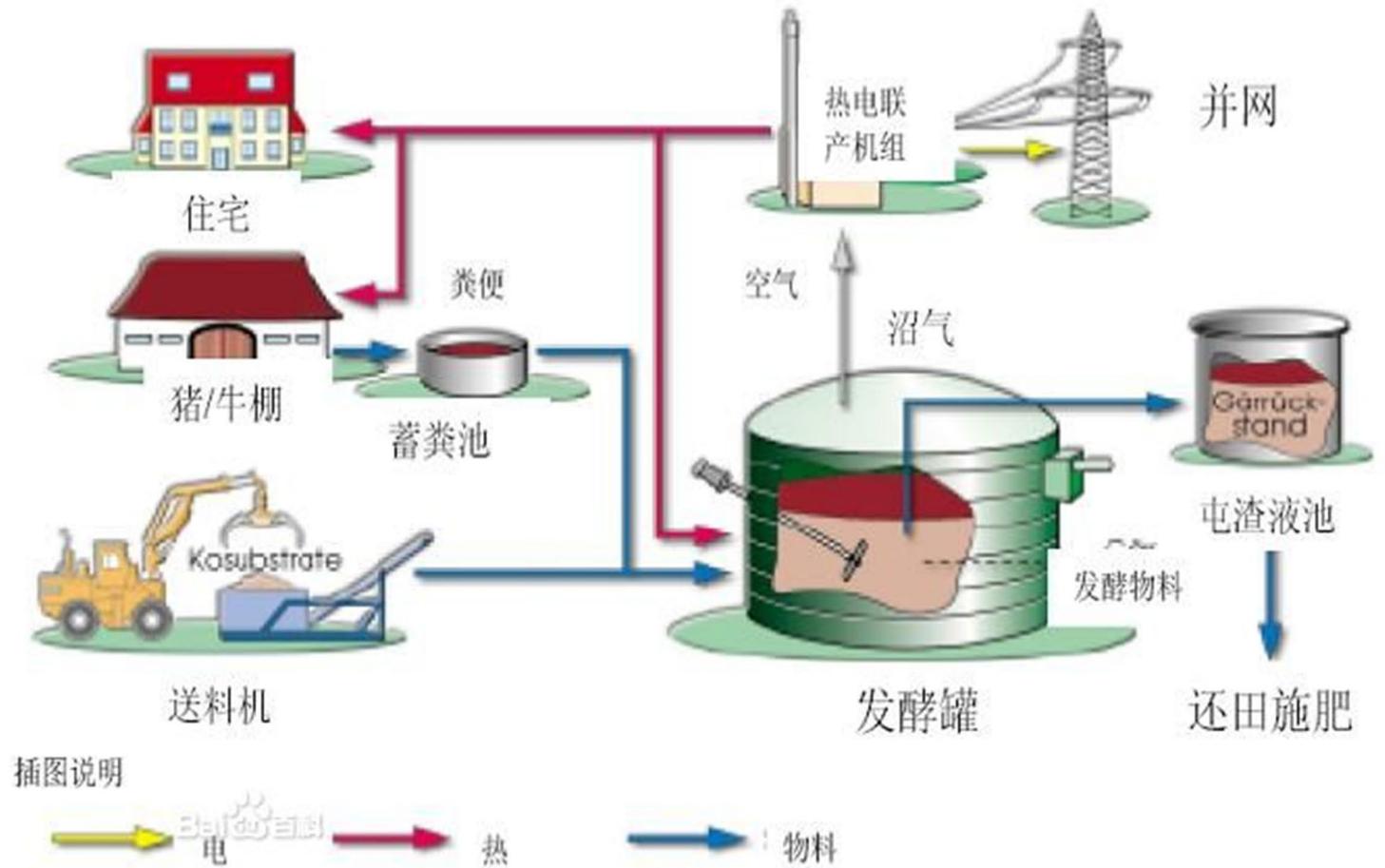


生物质发电

- ❖ 垃圾有效再利用
- ❖ 供电稳定
- ❖ 成本较高



禽畜粪便加农作物下料的沼气发电供热工程



风电



- 最有潜力的新能源之一
- 发电量波动大，难以控制，对电网造成大的波动
- 需要关注对生态的影响



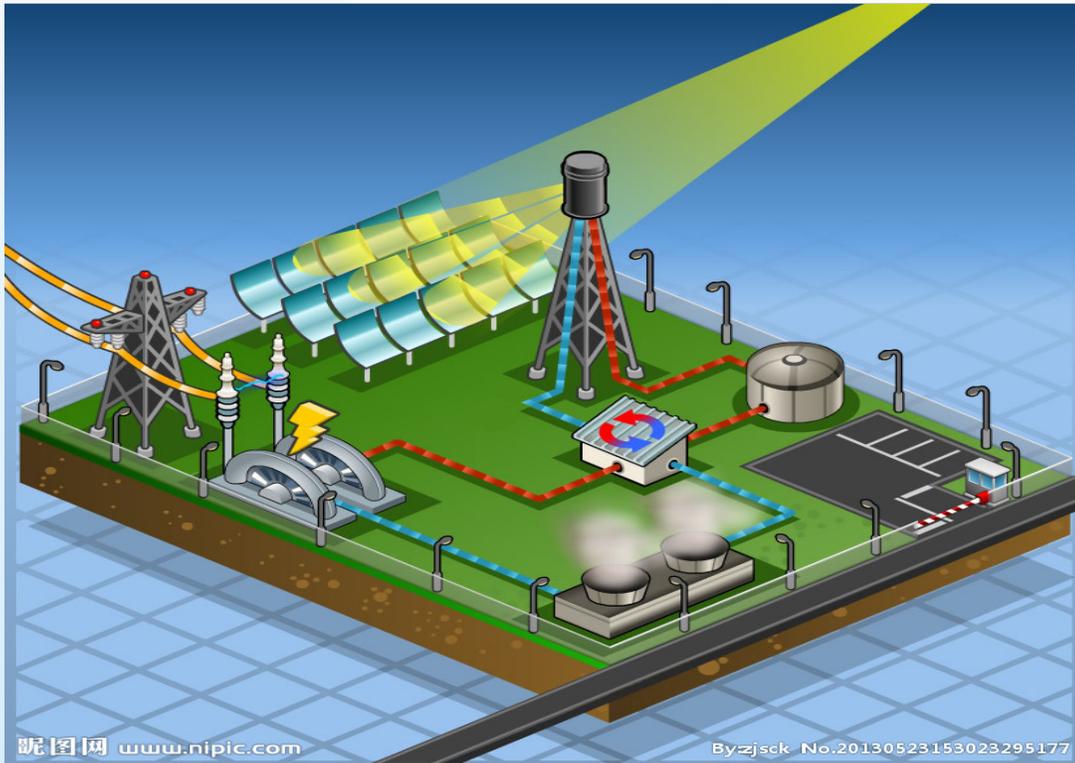
太阳能热利用：太阳能热水器

- ❖ 最有潜力的新能源之一
- ❖ 输出稳定，发电输出波动小，可作为储能用



太阳能光热发电

- ❖ 最有潜力的新能源之一
- ❖ 输出稳定，发电输出波动小，可作为储能用



太阳能光伏发电

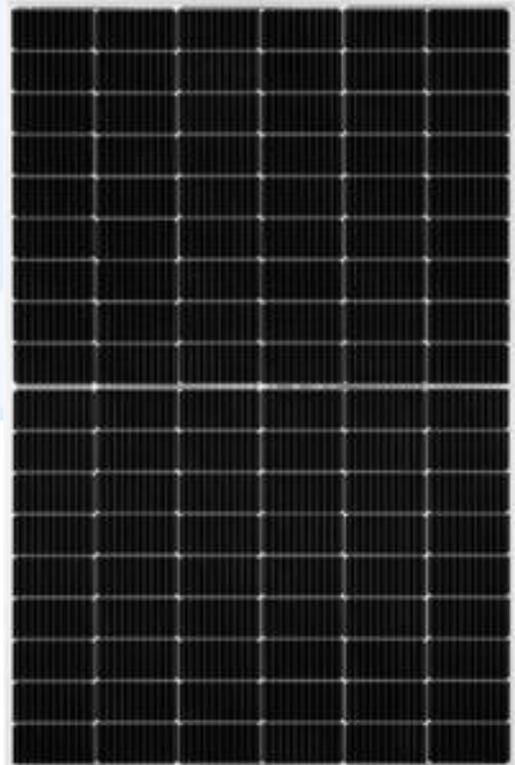
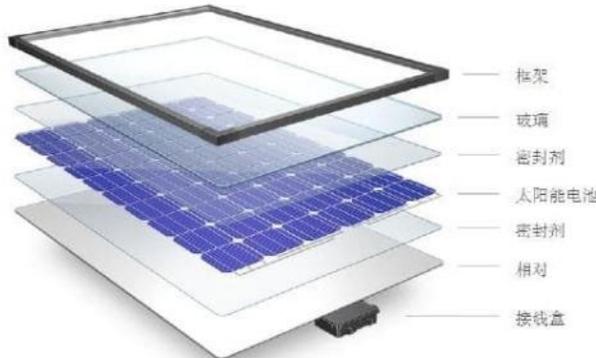
- ❖ 最有潜力的新能源之一，不受地域限制，任何地域都可以发电
- ❖ 无法蓄电，夜晚不能发电



太阳电池组件

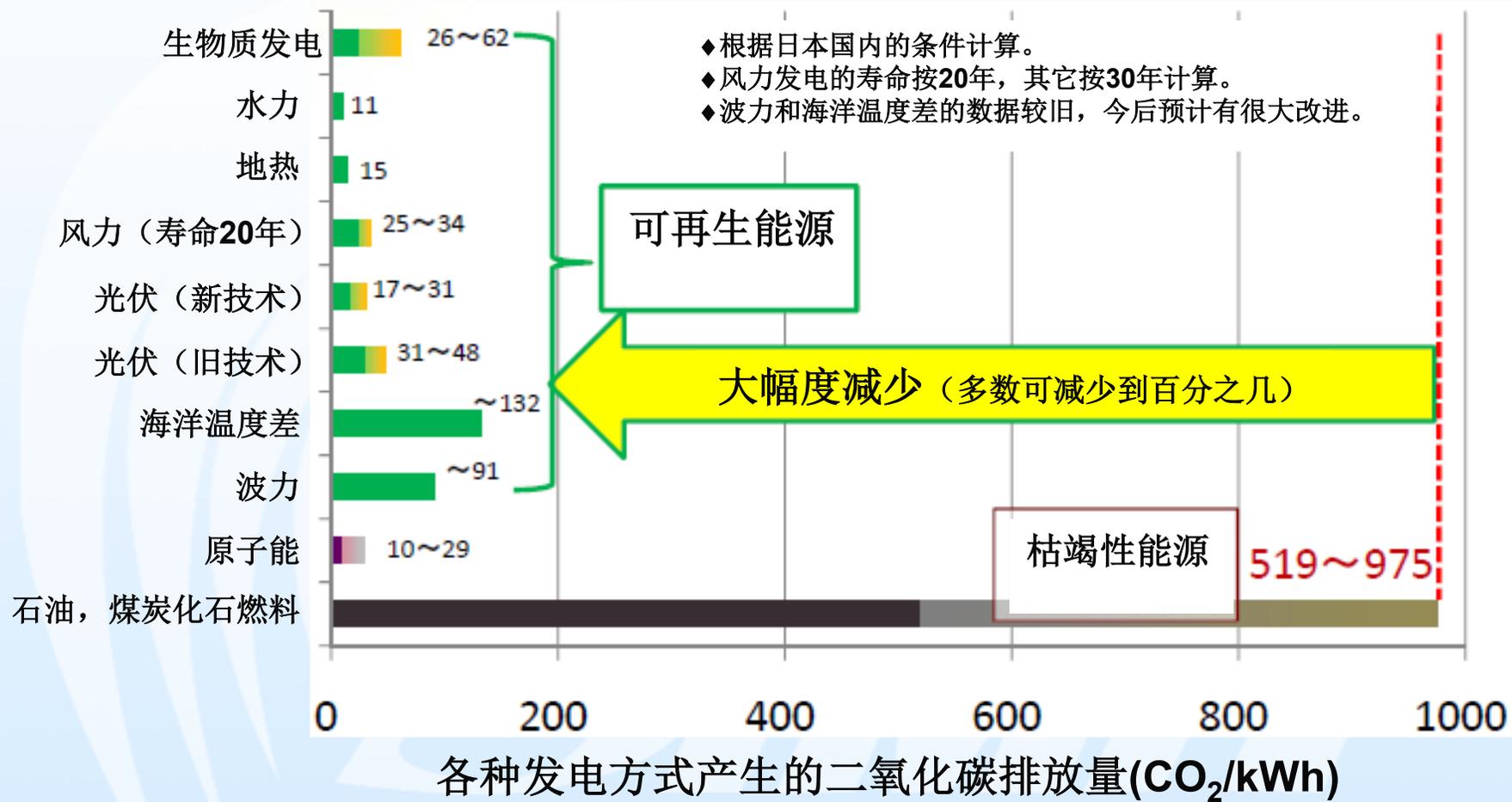


太阳电池片



光伏电站

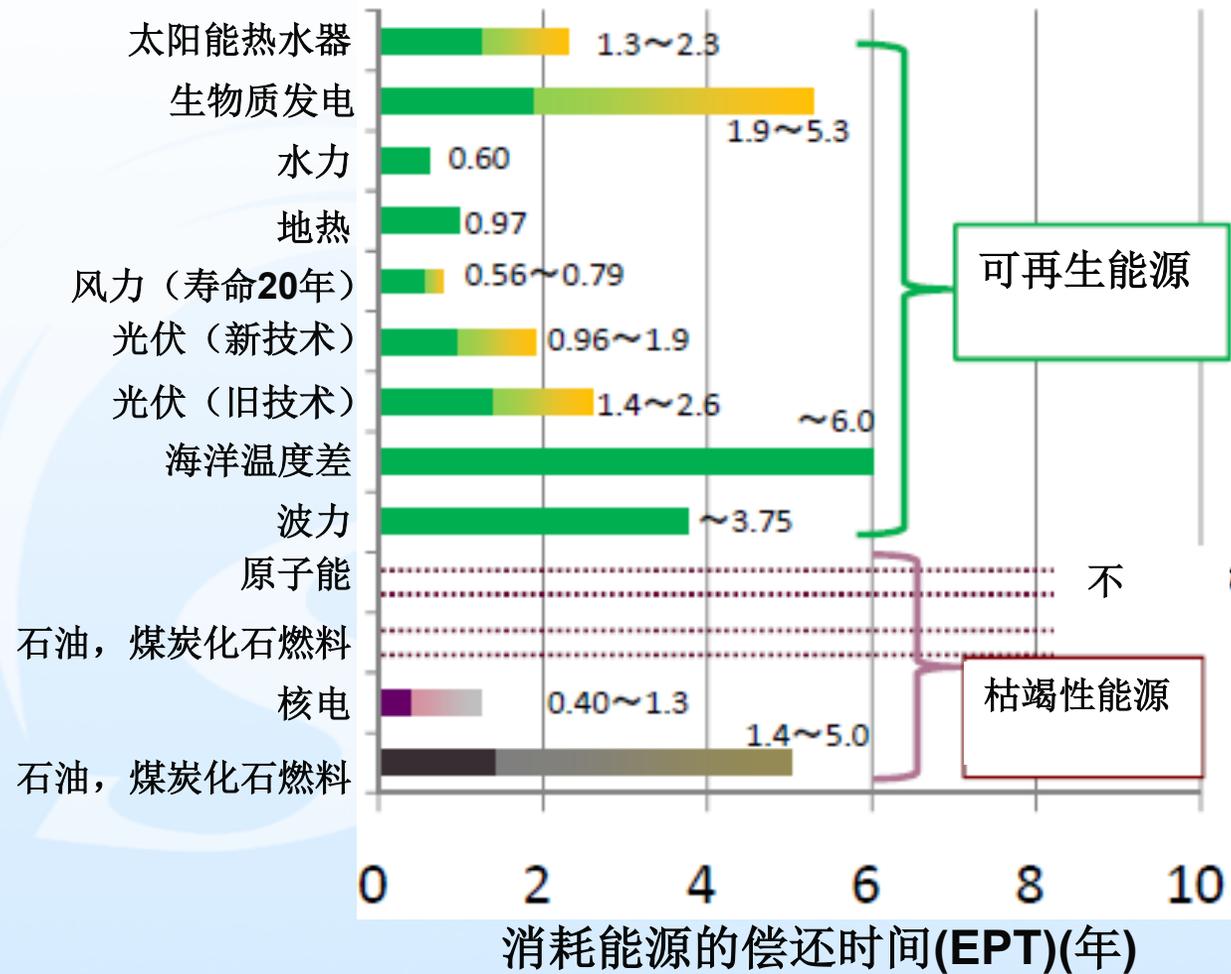
新能源的减排效果



使用新能源可以大幅度减少温室化气体排放量!

制造时消耗能源的偿还时间

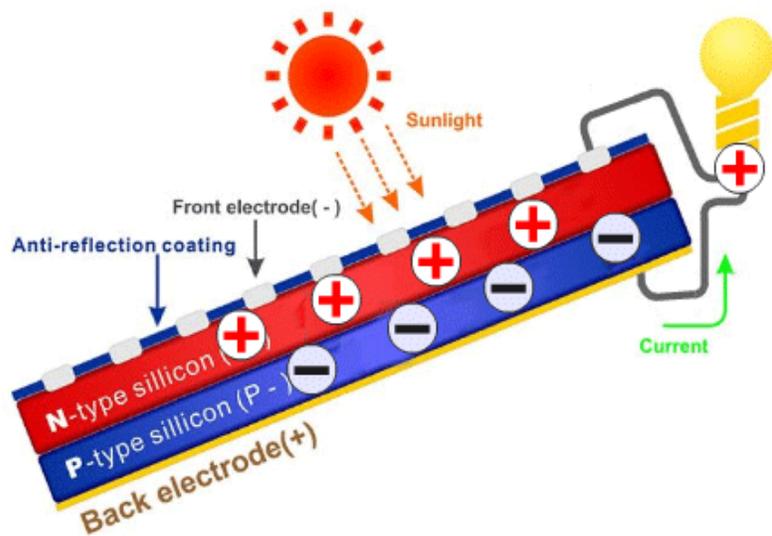
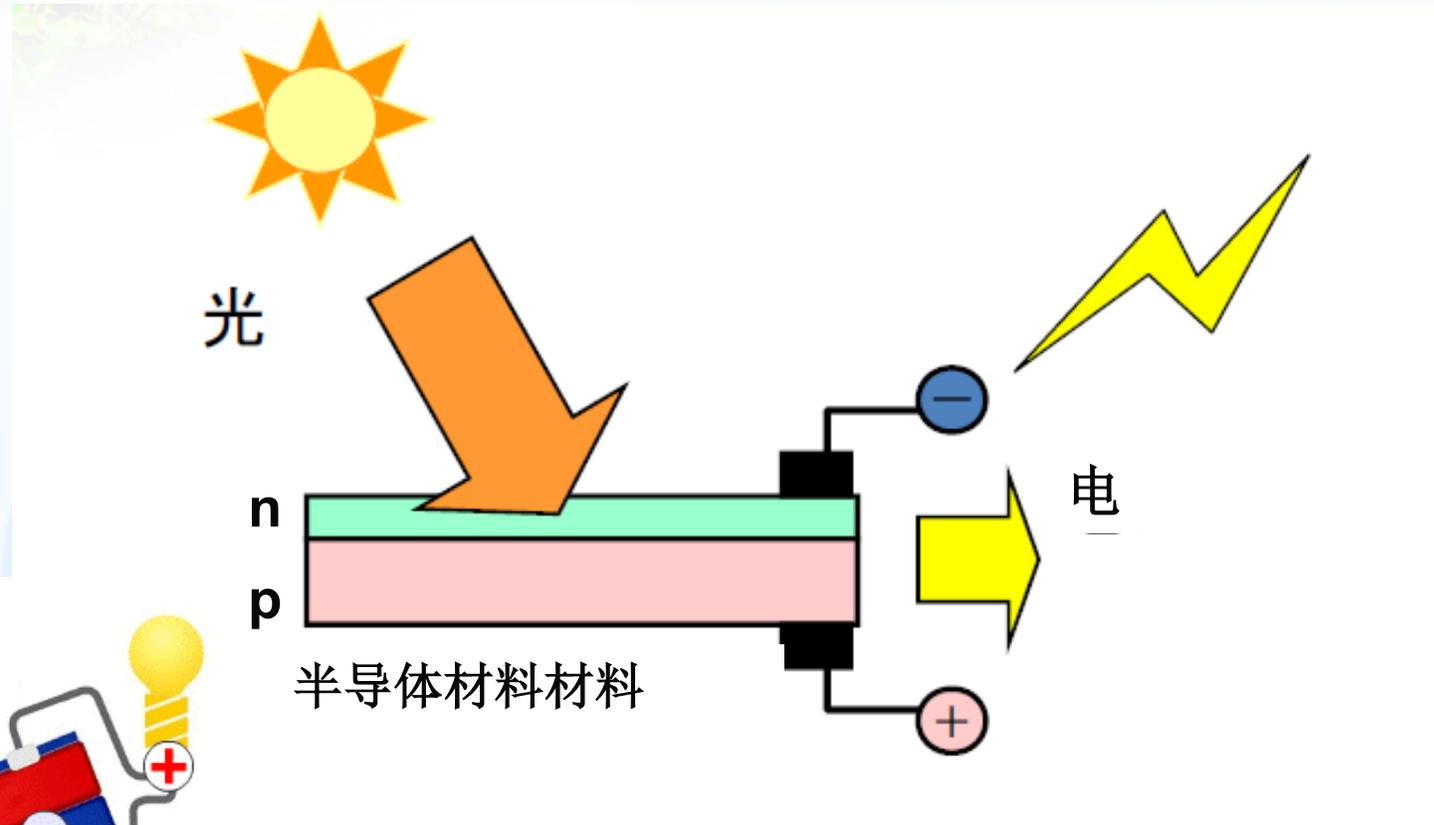
Energy pay-back time: EPT



三、太阳电池的基本原理和发展

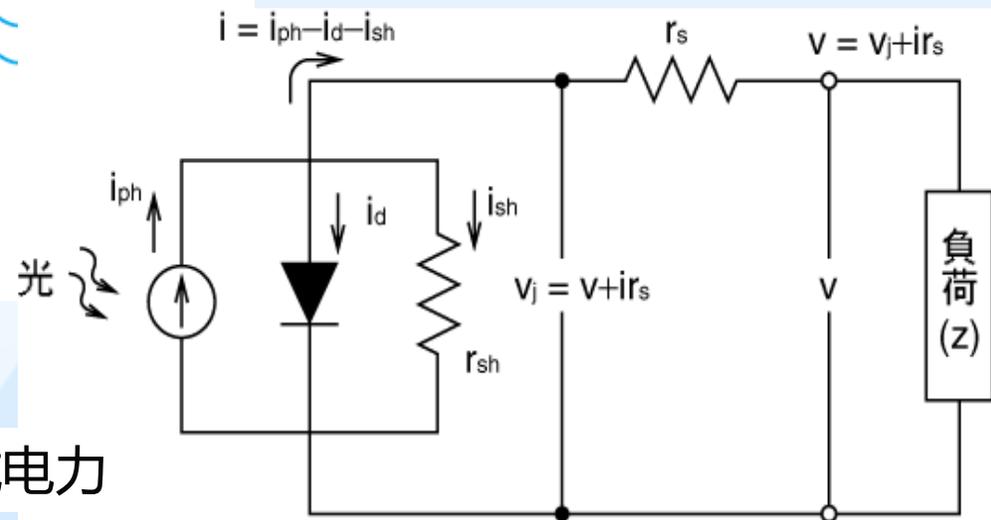
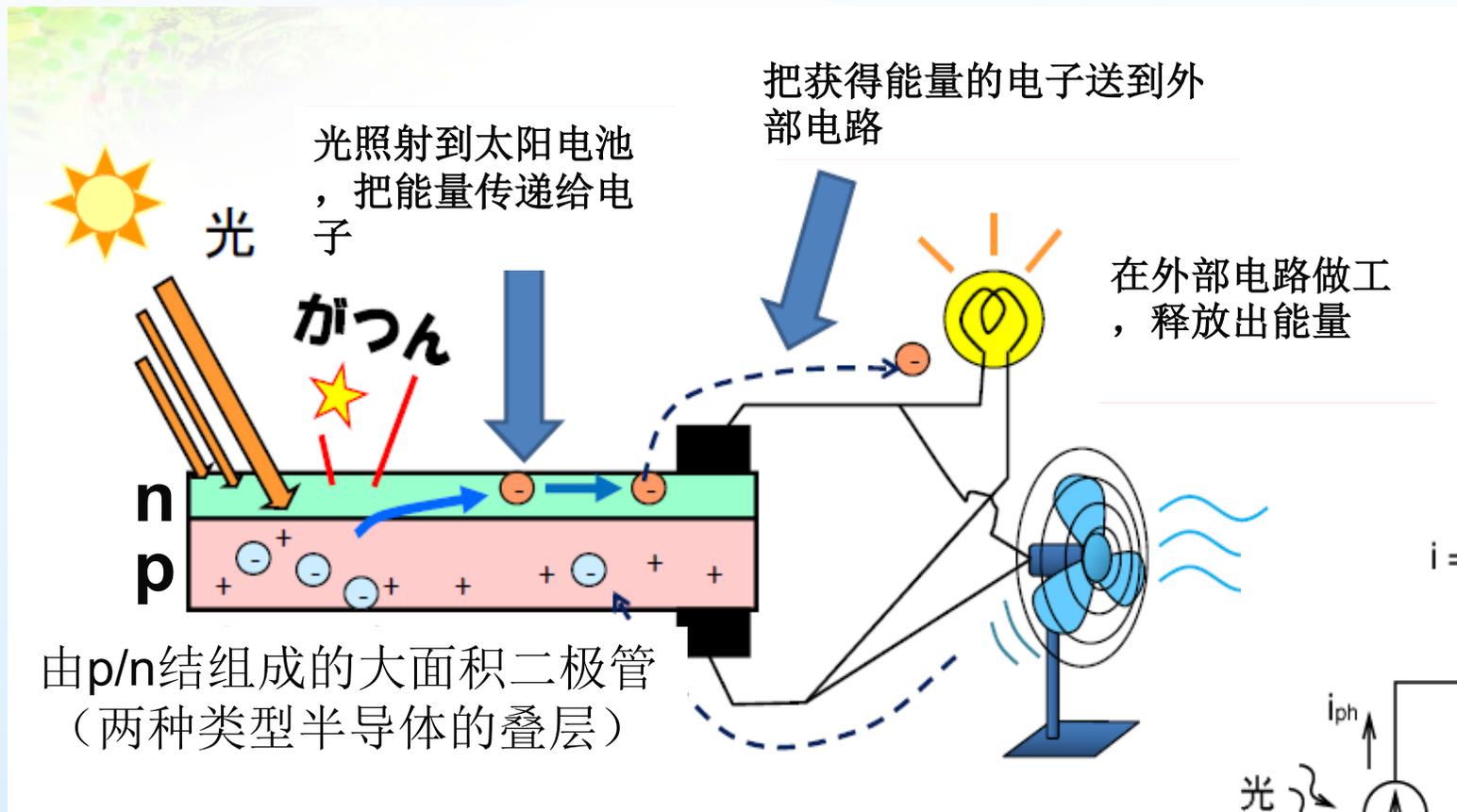


什么是太阳电池?



把**太阳光的能量**直接换成**电能**的**光电转换器件**

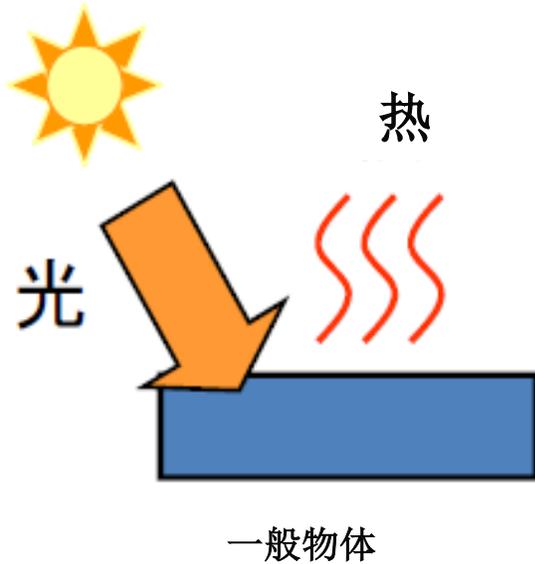
太阳电池为什么能发电?



太阳电池接受太阳光，把光子能量转换成电子的能量，形成电力

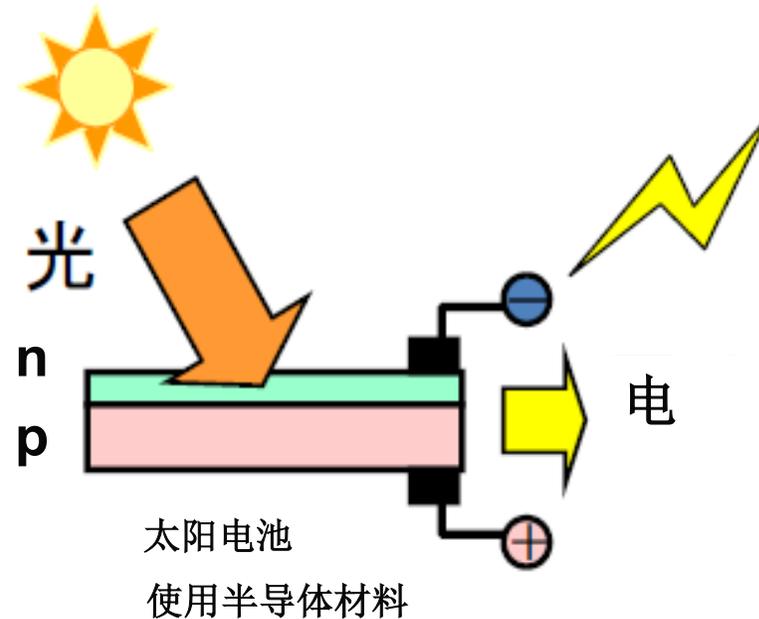
太阳能电池的特异性

一般物体



把太阳光的能量转换成热

太阳能电池

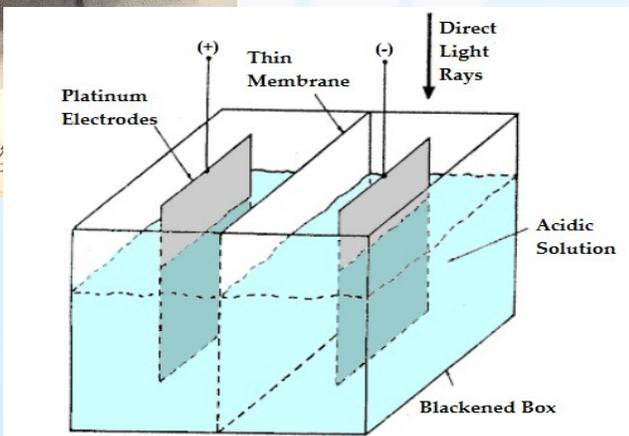


把太阳光的能量转换成电

太阳电池的发明和诞生



Edmond Becquerel,
French physicist

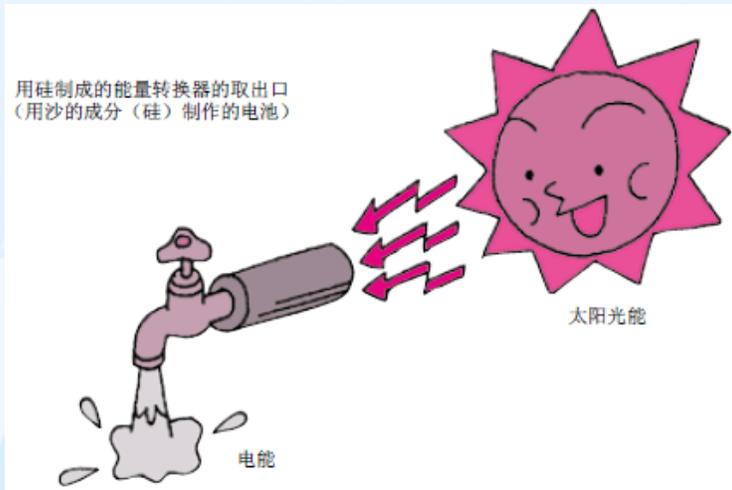


EDMOND BECQUEREL's First Photo
Electricity Generation Method



杰拉尔德·皮尔森，卡尔文富勒，达理查

1954年，美国贝尔实验室

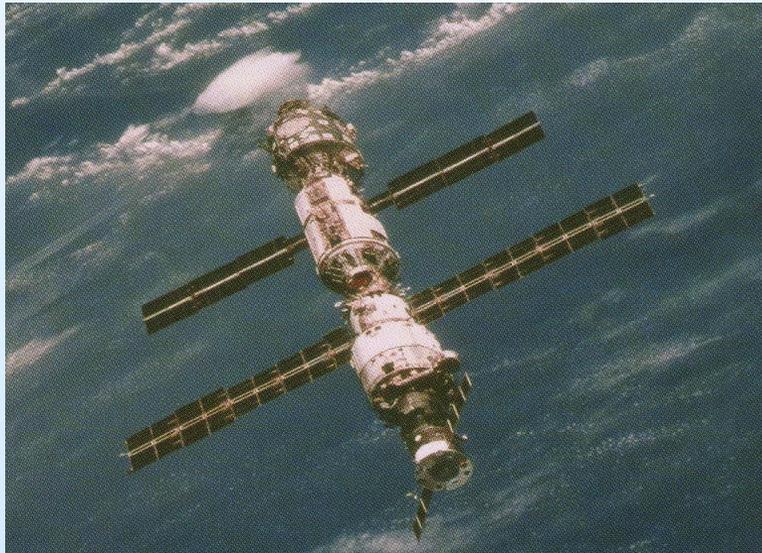
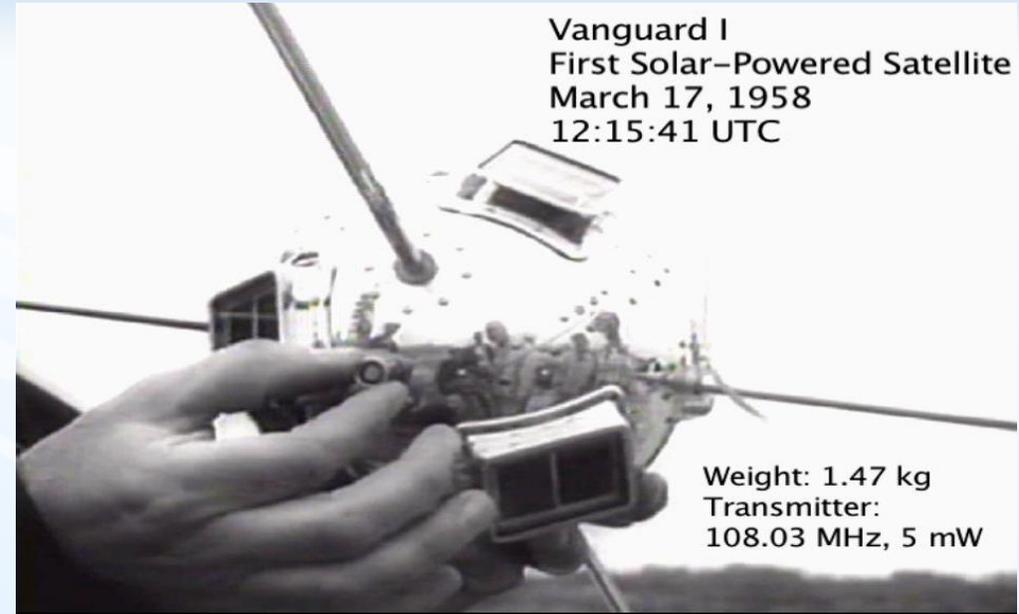


电能

PV effect-“Liquid electrolyte”
was discovered by in 1839

PV Memorabilia-Stage2_devices and development

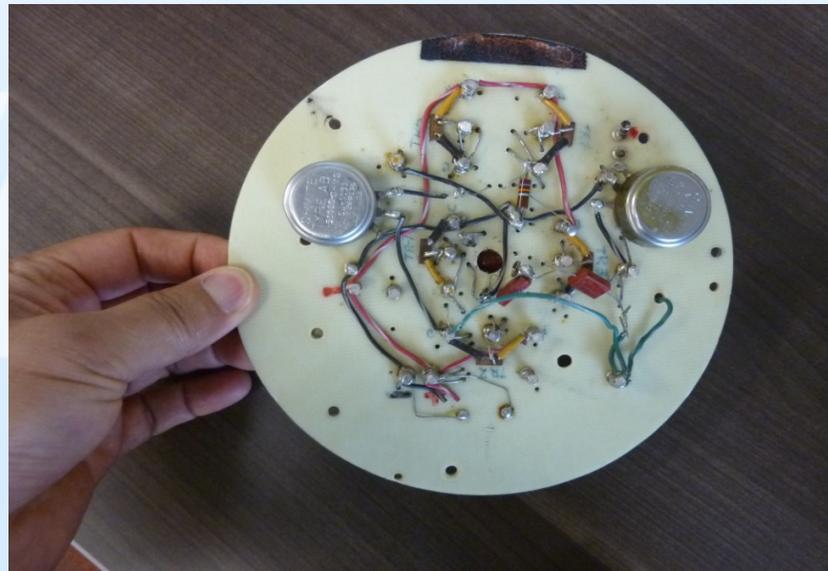
- ❖ In 1958, PV cells were used to power a small radio transmitter in the second US space satellite, **Vanguard I**.
- ❖ The use of PV as a power source for spacecraft has become almost universal.



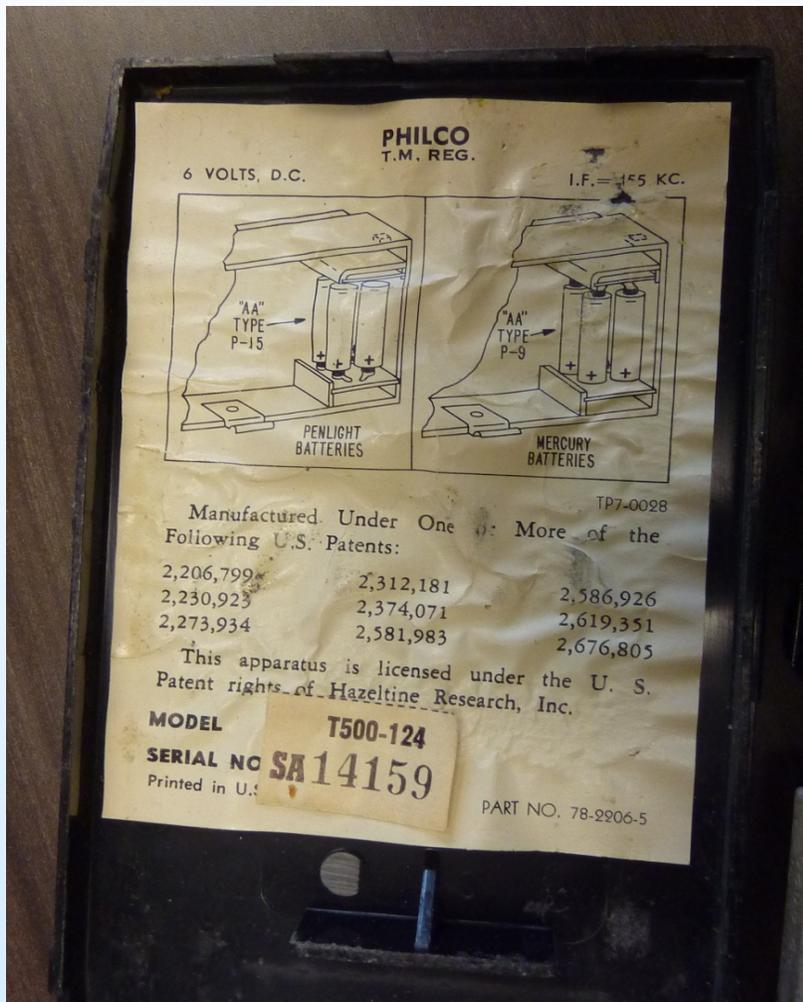
Hoffman mfg.

- 50 mW/module
- 6 modules
- \$12-15k/W
- **Lasted 7 years**
(Battery 2 weeks)

Vanguard I



The first solar powered radio in US in 1958



Radio: \$4-5

PV \$150, 30-40 times

太阳能电池--光伏

太阳能电池： Solar cell

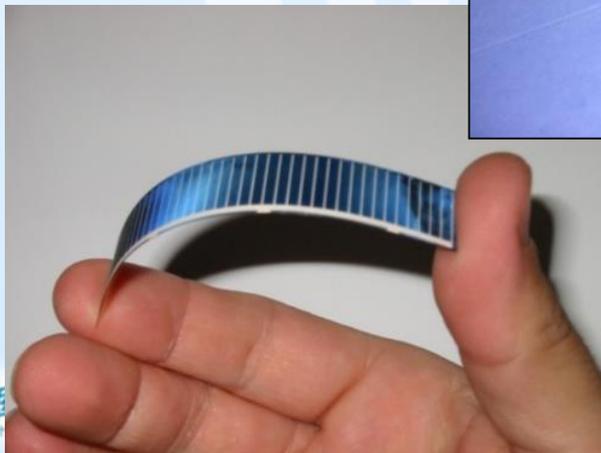
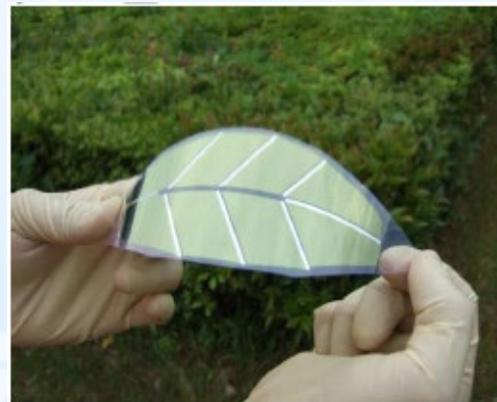
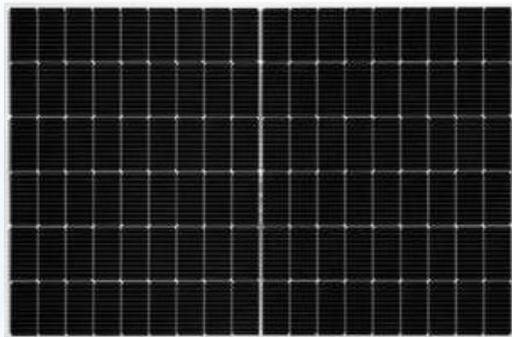
太阳能电池

光伏： Photovoltaics

光伏电池： Photovoltaic cell

太阳能光伏： Solar photovoltaic

太阳能电池是什么样？



身边的太阳电池



航天和卫星



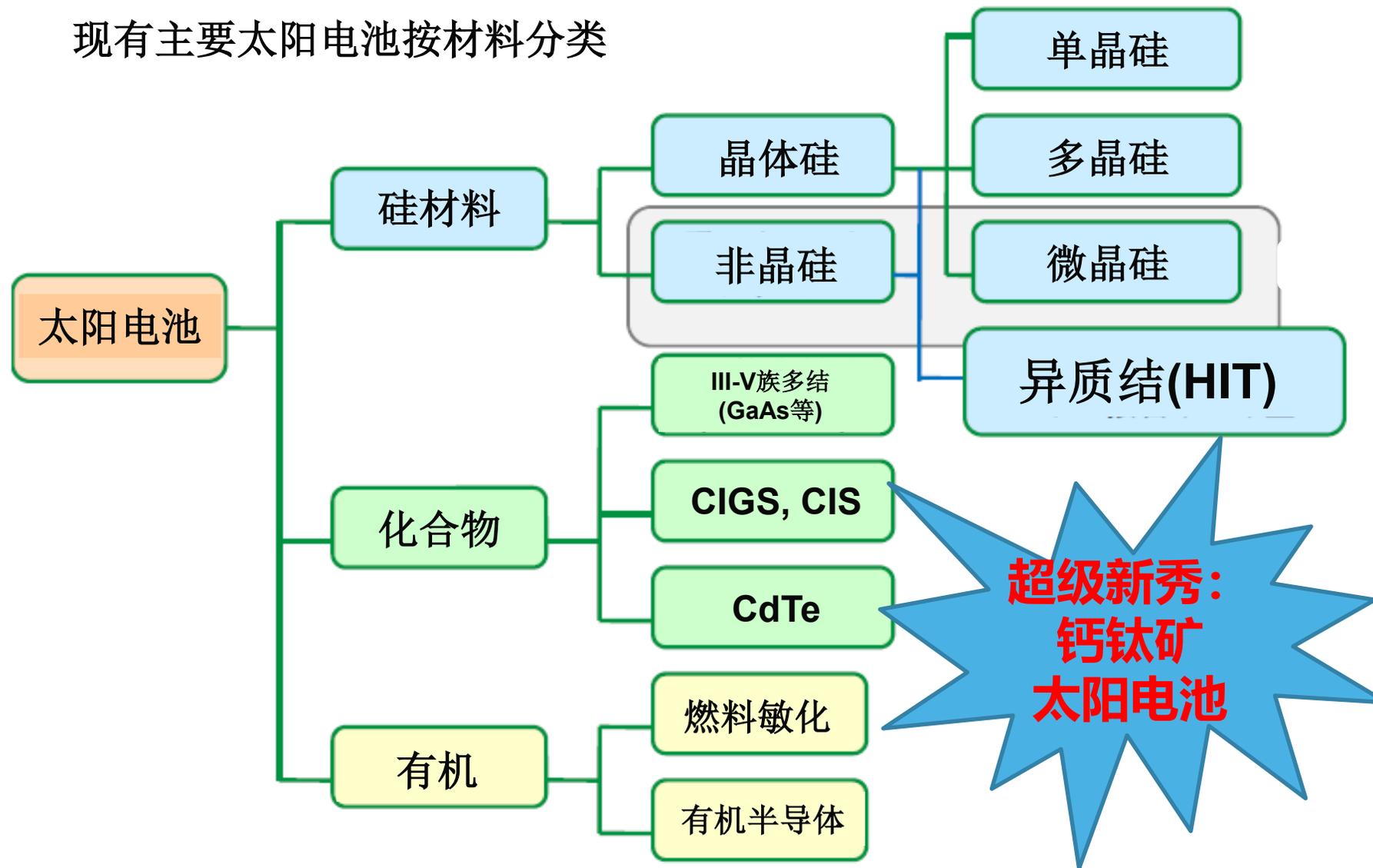
太阳电池是卫星和空间站获得能量的唯一来源

四、太阳电池的种类和特点



太阳能电池的分类：材料种类

现有主要太阳能电池按材料分类



太阳能电池的分类：材料厚度

◆按材料的厚度分类

晶体硅太阳能电池

器件的厚度**50-300 μm** ，是现在太阳能电池的主流

薄膜太阳能电池

器件的厚度只有几 μm ，节省资源，可做成柔性，将来可望得到更多普及

◆按pn结的数量分类

单结合太阳能电池

现在太阳能电池的主流

多结合太阳能电池

把特性不同的太阳能电池重叠在一起，以提高太阳能电池的整体性能

◆按动作原理分类

pn结型太阳能电池

几乎所有太阳能电池都是这种结构

燃料敏化太阳能电池

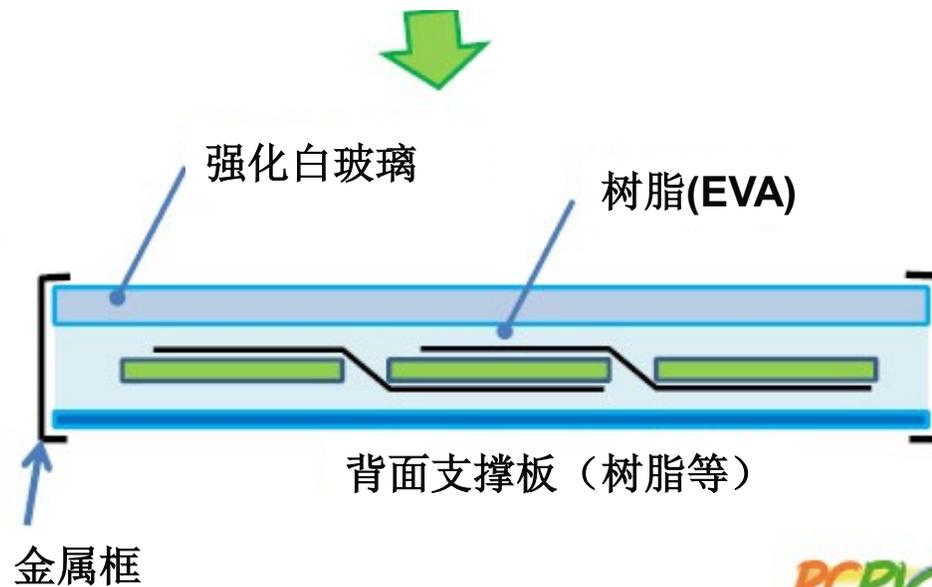
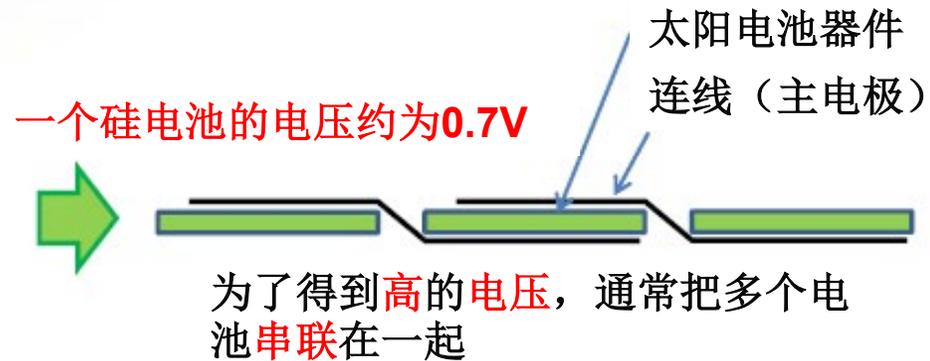
这种太阳能电池的原理稍有不同



晶体硅太阳能电池组件的构造



セル(結晶シリコン太陽電池)
一辺10~20cmほどの大きさ

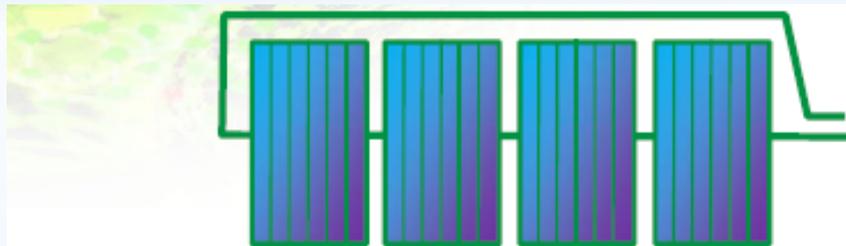


组件

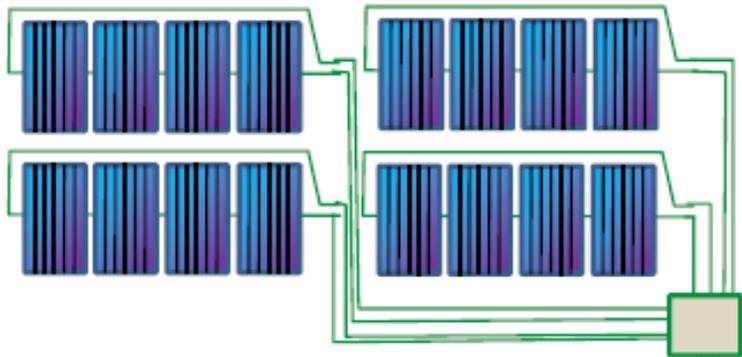
用玻璃和其他材料把电池和电极材料保护起来



太阳能电池阵列



把几个或多个太阳能电池组件**串**结在一起，称为**串联(String)**，其输出为几十到几百伏的直流电压



把几个或多个串联的太阳能电池组件**并**结在一起，称为**阵列(Array)**，使输出电流增加

直流，几百伏

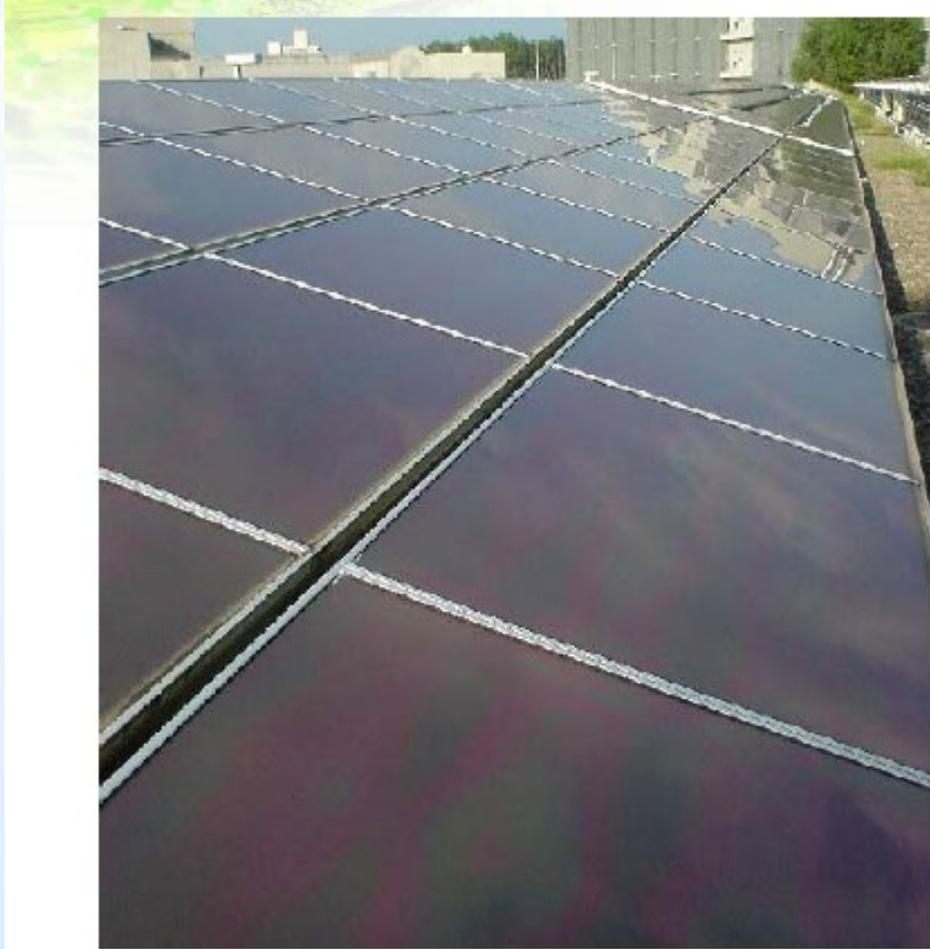
通过**功率控制器(Power conditioner)**把**直流**转换成家庭可以使用得**交流**



功率控制器(Power conditioner)



薄膜硅太阳能电池



室外用非晶硅太阳能电池组件



多结合性，柔性薄膜太阳能电池
(提供:富士アドバンステクノロジー株式会社)

最近，市场占有率增加

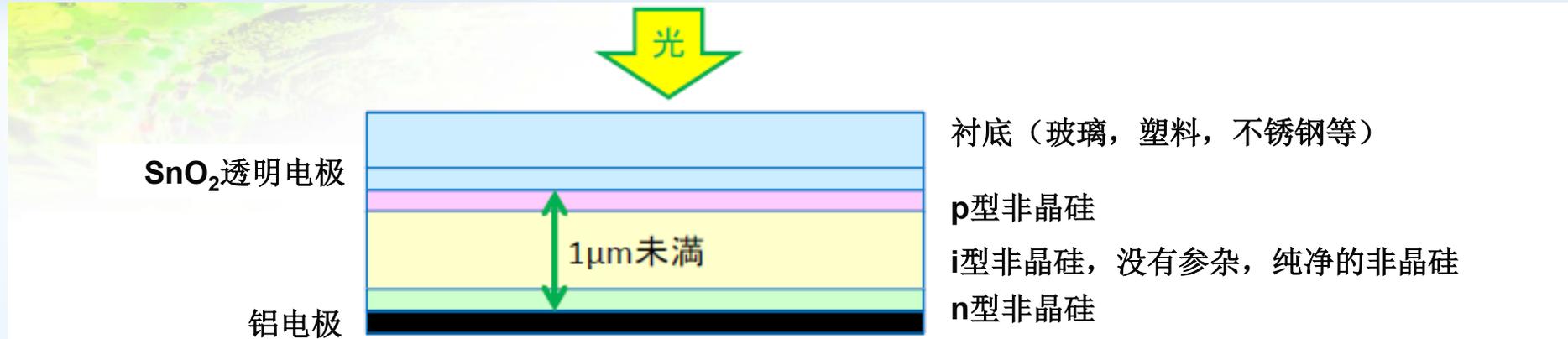
- ◆耐高温性好
- ◆薄，节省资源，低成本？
- ◆大面积，可以制成柔性

· 转换效率

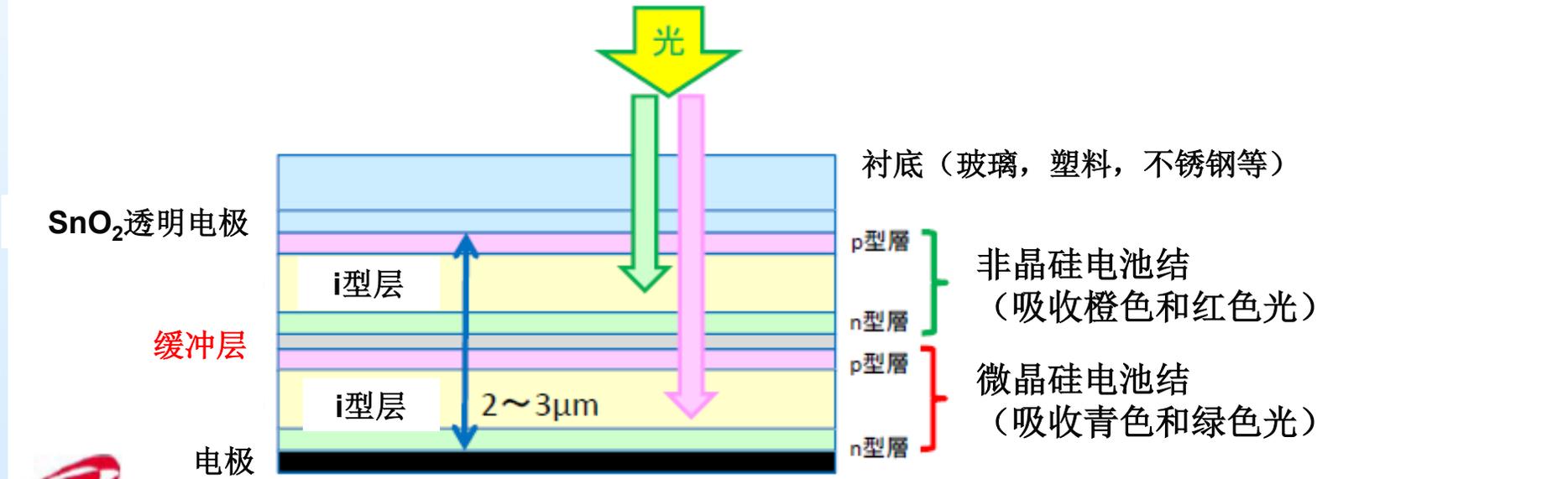
- ◆单结：6-8%
- ◆多结：10-12%
- ◆将来：15%以上？



薄膜硅太阳能电池的基本构造



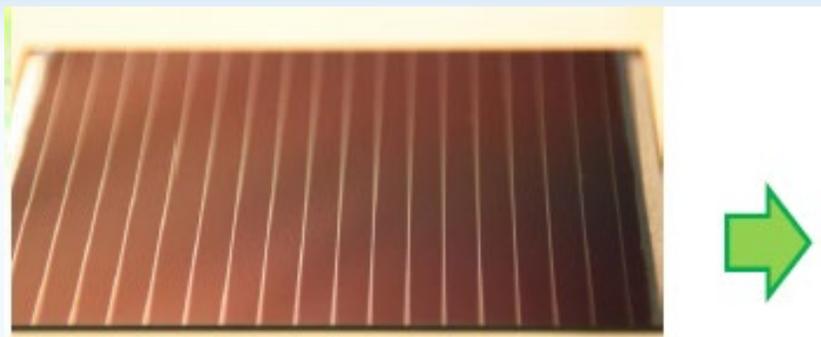
非晶硅太阳能电池的构造



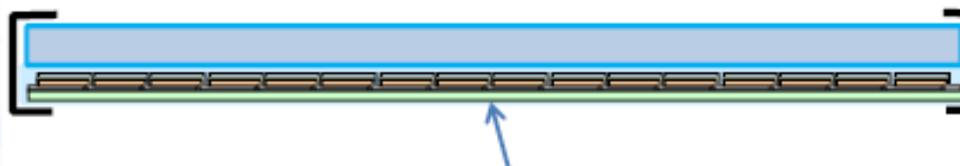
多结合型硅薄膜太阳能电池的构造



薄膜太阳能电池组件的基本构造

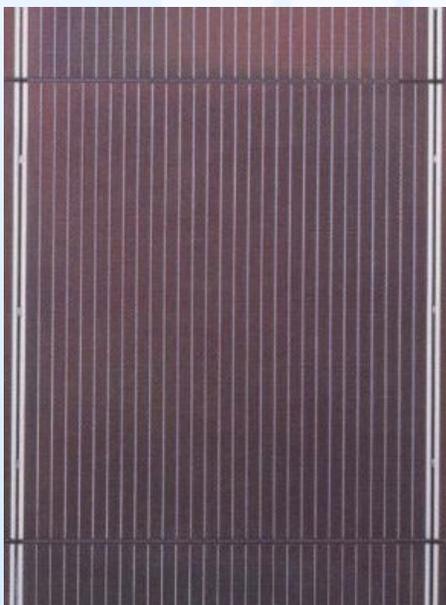


用EVA或玻璃封装保护后就制成组件



薄膜太阳能电池通常由衬底材料兼作背面支撑板

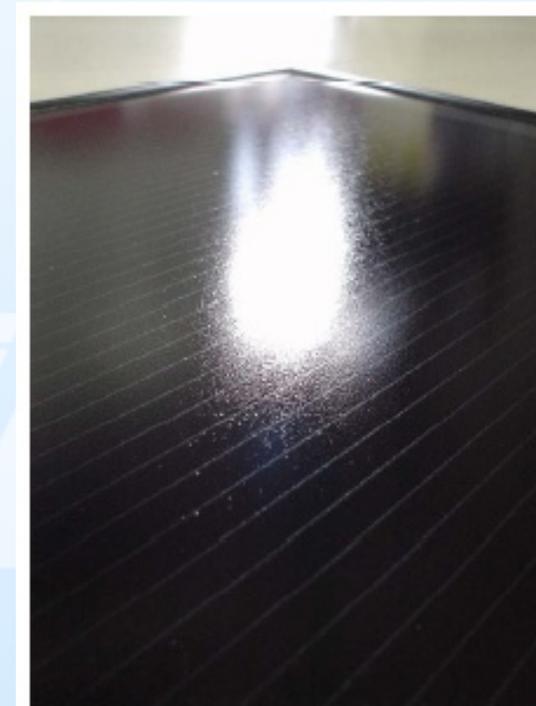
薄膜太阳能电池通常由**多个**电池**串联**而成。
封装之前称为**准组件(Sub-module)**或**电路器件(Circuit)**



硅薄膜太阳能电池组件
(非晶硅单结合)



硅薄膜太阳能电池组件
(非晶/微晶2结)



CIGS薄膜太阳能电池组件

铜铟镓硒(Cu-In-Ga-Se:CIGS)薄膜电池



AIST/RCPV

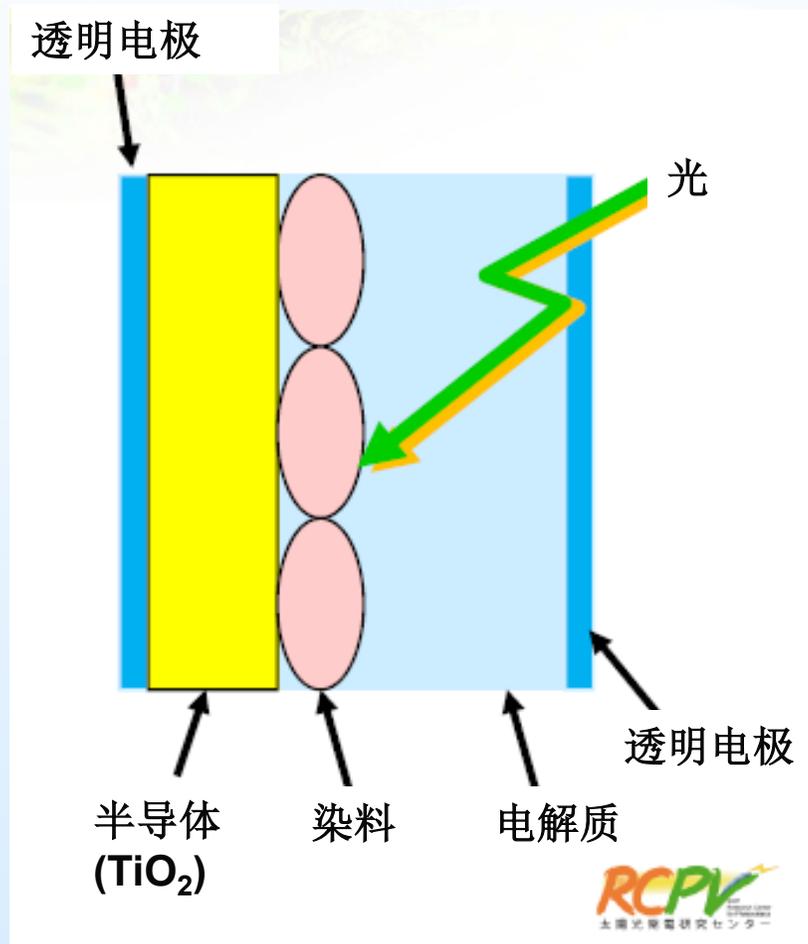
柔性**CIGS**太阳电池组件

(制作在柔性陶瓷衬底上的**CIGS**太阳电池,
转换效率达到**17.4%**)



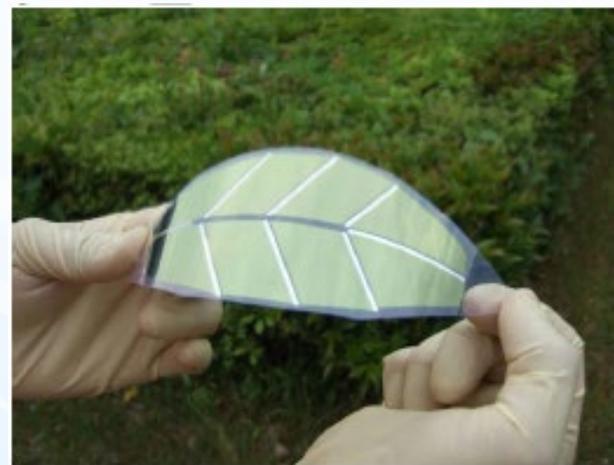
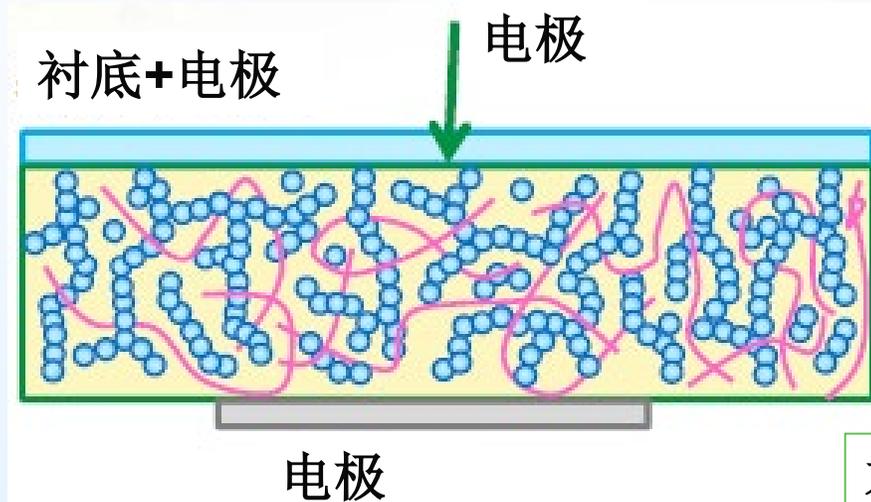
制作在玻璃衬底上的**CIGS**太阳电池组件
(Showa Shell Seikiyu)

染料敏化太阳能电池



制作简单，可以制成全彩色。
转换效率和耐久性还有待改善

有机薄膜太阳能电池



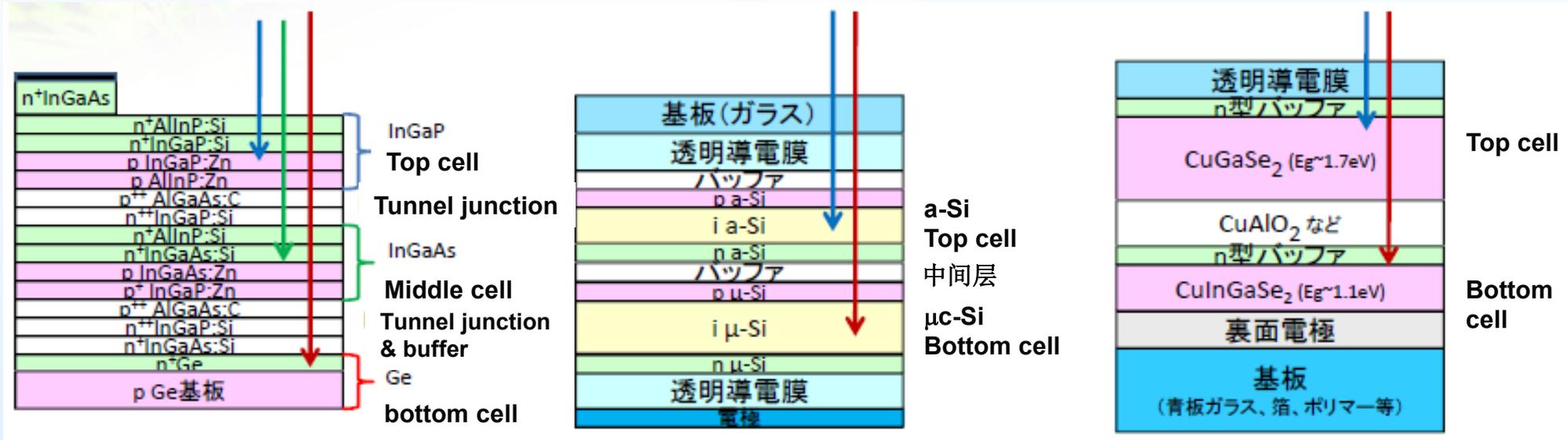
太阳能电池

- ◆ 最近几年开始研究的新型太阳能电池
- ◆ 只用涂敷就可以制作，工艺简单
- ◆ 可以制成彩色，柔性，轻量
- ◆ 虽然转换效率很低($<5\%$)，有的公司已经把它用在手机电话和玩具上(Konarka等)
- ◆ 是将来超低成本太阳能电池的一个候补



多结高效太阳能电池

把不同性质的半导体层**叠加**在一起，以扩大**光吸收范围**，提高太阳能电池的转换效率



III-V族化合物太阳能电池

- ◆ 转换效率非常高(>40%)
- ◆ 成本也很高
- ◆ 主要用在宇宙和聚光型

硅叠层太阳能电池

- ◆ 也称为混合型
- ◆ 已经有多种产品在销售

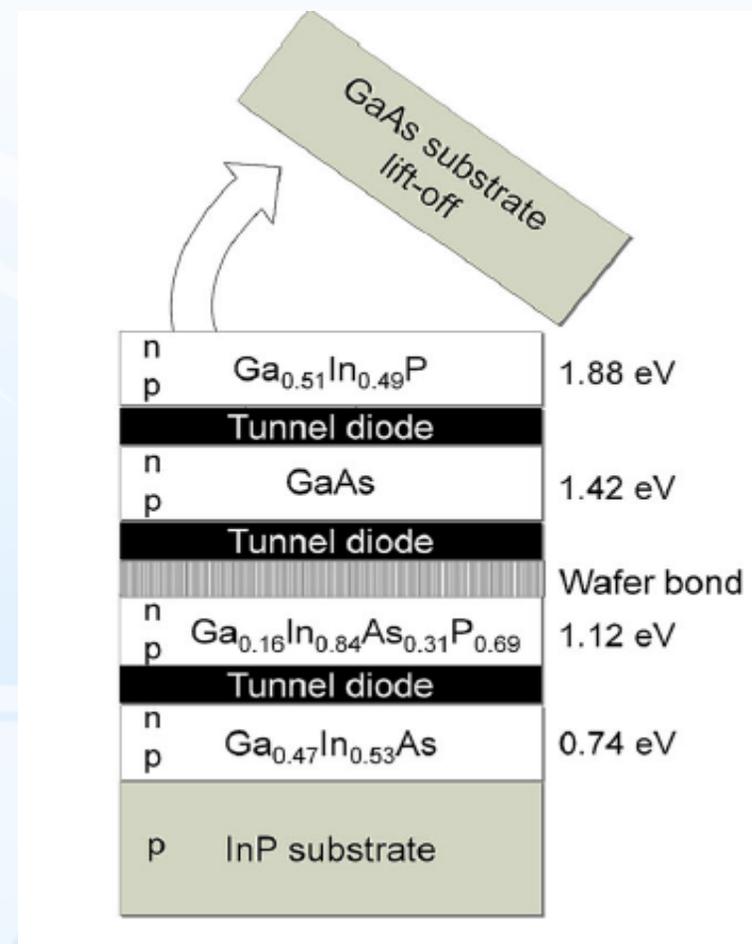
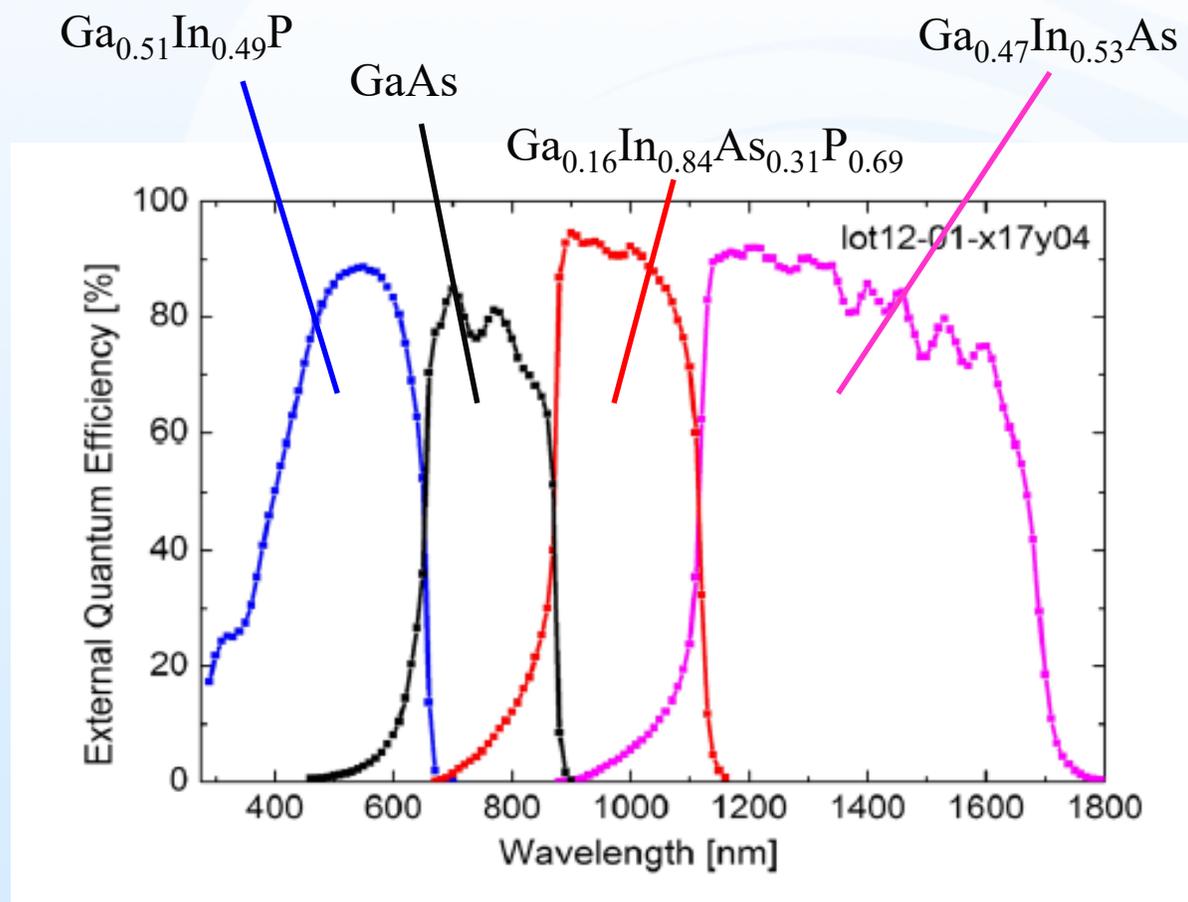
CIGS叠层太阳能电池

- ◆ 刚开始研究的新型结构
- ◆ 转换效率有望比硅电池高?

Available PV technology-New Methods

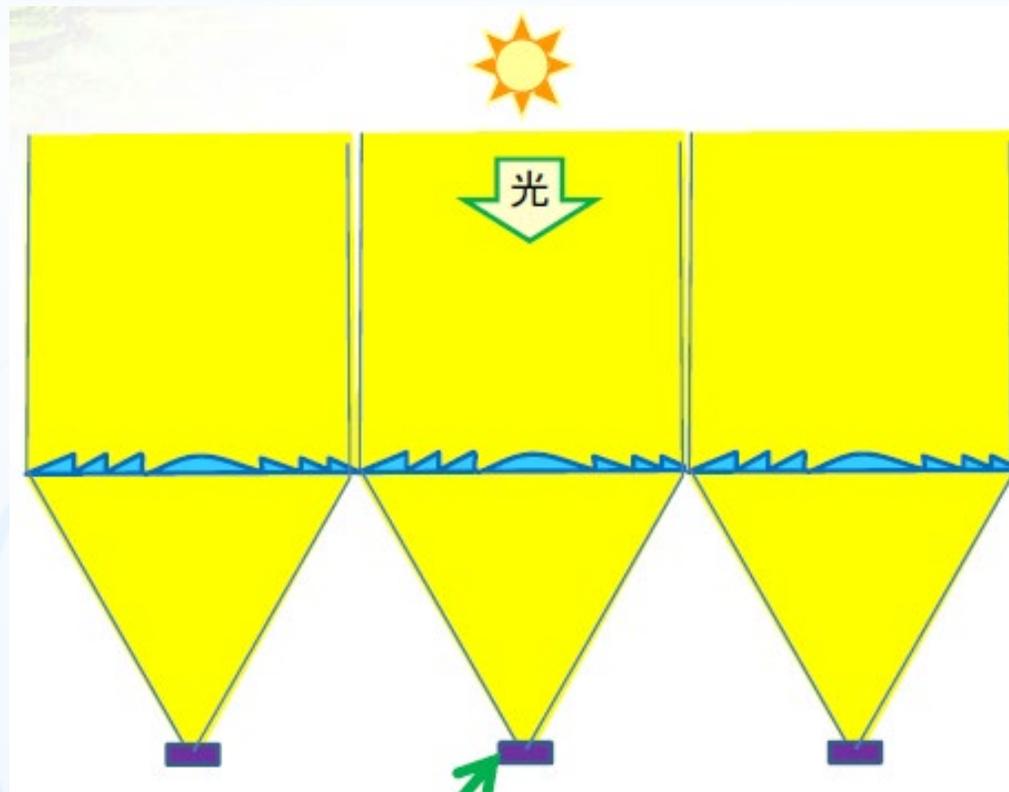
Tandem Cell

- ❖ Different E_g increased the light absorption



In 2014, Fraunhofer ISE has made this kind of four-junction cell with the world record efficiency 46%

聚光型太阳电池

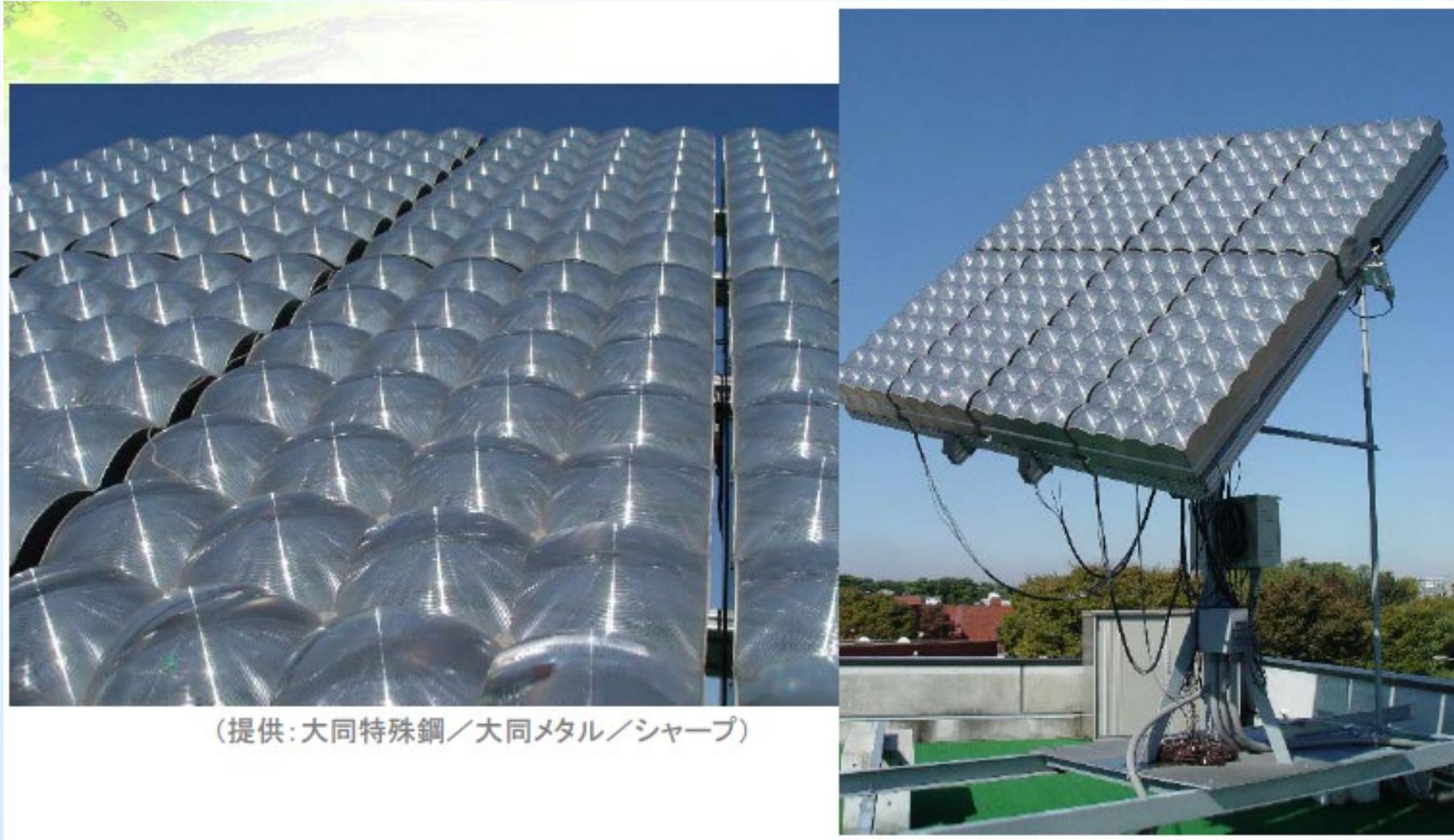


用平面透镜
聚焦几百倍

性能相对较高的太阳电池
(III-V族化合物太阳电池等)

- ◆性能相对较高的**III-V族化合物太阳电池**受透镜集聚光的**强光**照射发电
- ◆如果直射阳光丰富，和普通平板太阳电池相比，**成本性能比高**
- ◆一般采用**追踪结构**，让太阳电池一直接受**直射阳光**

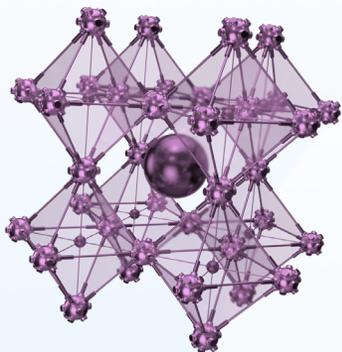
聚光型太阳电池系统



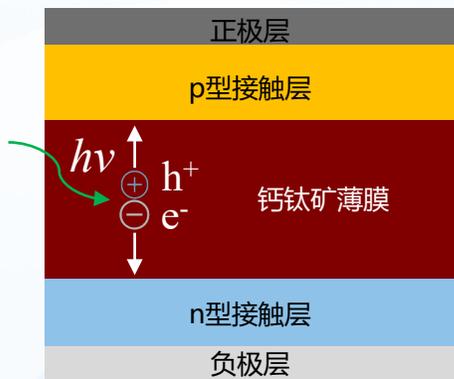
采用**追踪系统**，把直射阳光**聚焦**到太阳电池上发电

钙钛矿太阳能电池

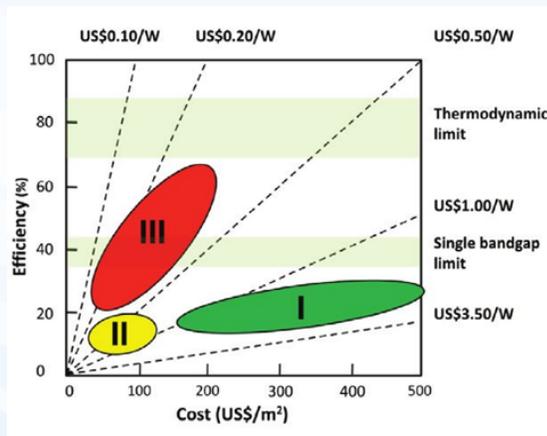
技术原理



钙钛矿材料晶体结构



钙钛矿太阳电池结构



太阳电池发展

太阳能电池

第一代：晶硅
(单晶、多晶硅电池)

第二代：薄膜
(a-Si, CdTe, CIGS等)

第三代：新概念新材料
(钙钛矿, 量子点等)

钙钛矿太阳电池特点



产品多功能性

- ✓ 强光弱光效率均高
- ✓ 效率对角度依存小
- ✓ 柔性和半透明组件
- ✓ 自定义形状和颜色



工艺简单低碳

- ✓ 基于印刷工艺制造
- ✓ 工艺温度 < 120°C
- ✓ 易于规模放大生产
- ✓ 产业链条相对较短



成本低

- ✓ 原材料成本低
- ✓ 设备投资较小
- ✓ 可回收再利用
- ✓ 功率成本比高

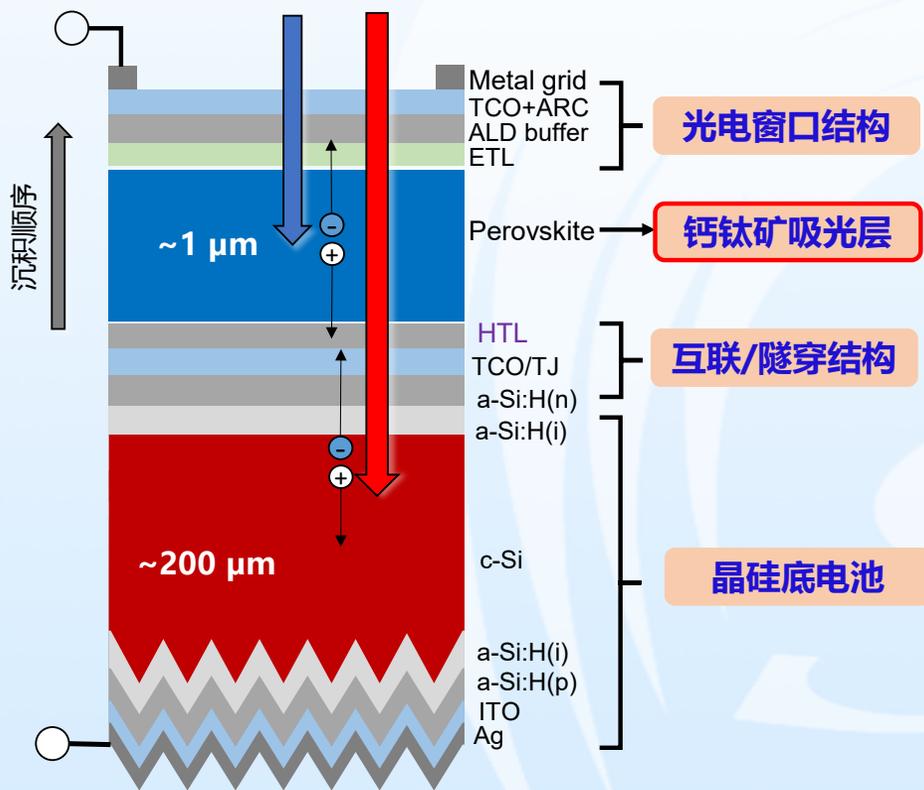


钙钛矿太阳
电 池 ——
第三代太阳
电 池?

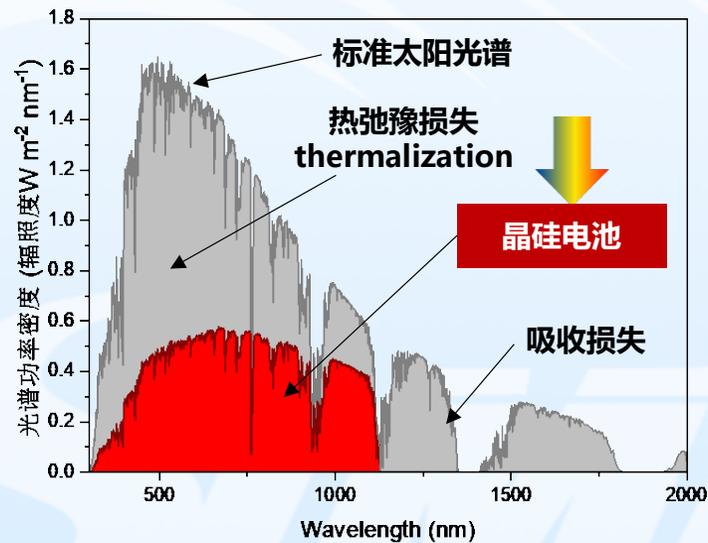
晶硅-钙钛矿叠层太阳电池

结合晶硅和宽带隙钙钛矿，构建叠层电池，以低成本的方式大幅突破晶硅电池的理论极限

革命性升级目标：额外成本<10%，效率大幅提升>30%

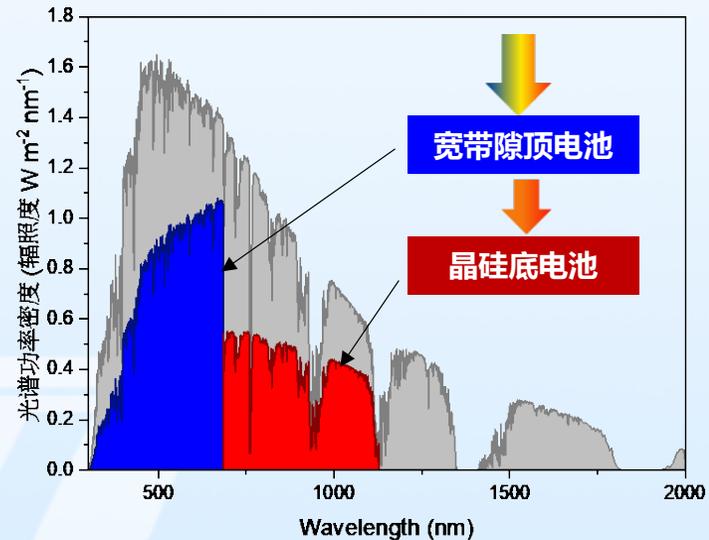


单结的光谱能量利用率



单结极限效率~29%

叠层的光谱能量利用率



叠层极限效率~40%

五、晶体硅太阳能电池的基本制作：电池-组件-系统



From sand to solar cells



中国制造世界第一

Process from raw Si to module

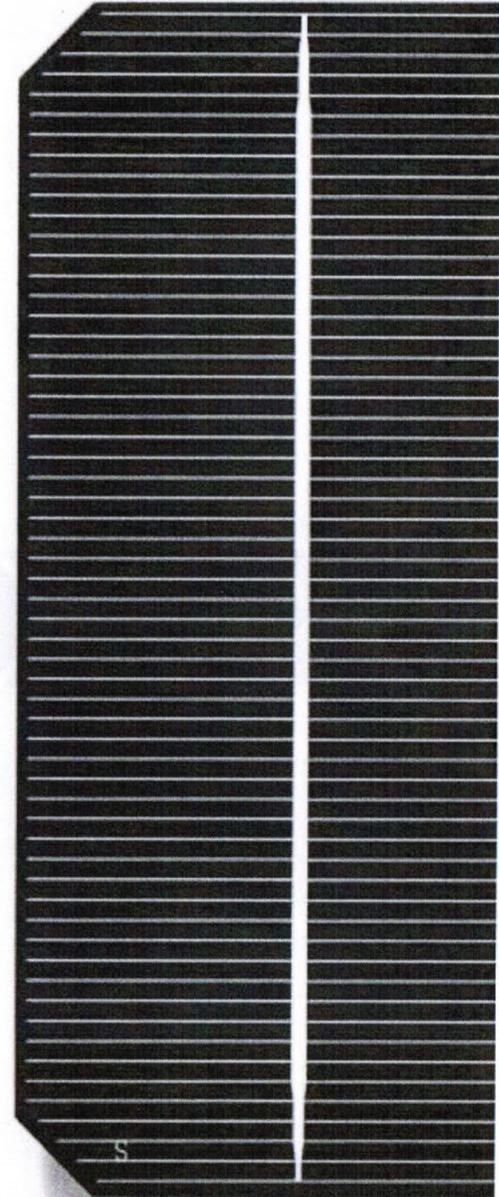
The standard technology for making cells can be broken down into the following stages:

1. Reduction of sand to MG-Si.
2. Purification of MG-Si to semiconductor-grade silicon.
3. Conversion of semiconductor-grade silicon to single-crystal silicon wafers.
4. Processing of single-crystal Si wafers into solar cells.
5. Solar cell encapsulation into weatherproof solar cell modules.

石英砂是怎么变成太阳能电池的？

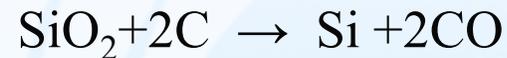


*How is quartz
turned into
power
generating
devices?*



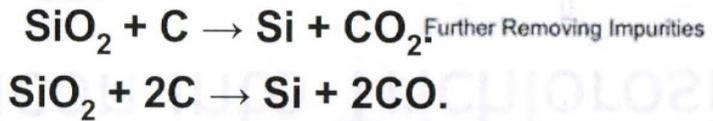
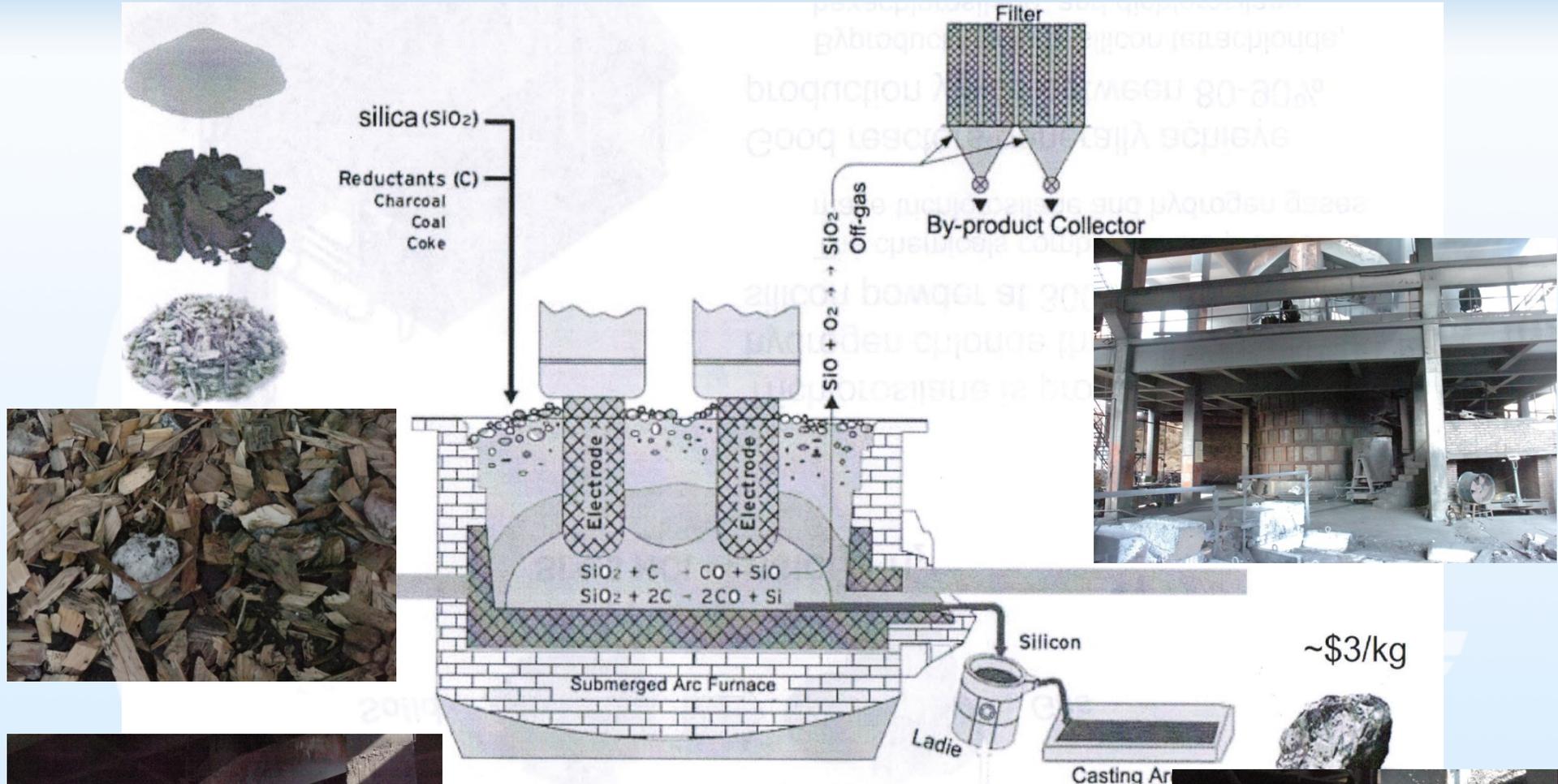
From sand to metallurgical-grade silicon

- ❖ The source material for the extraction of silicon is SiO_2 , the major constituent of sand.
- ❖ In the present commercial extraction process, the crystalline form of silicon dioxide, quartzite, is used.
- ❖ This material is reduced in large arc furnaces by carbon to produce silicon according to the reaction:



It is generally **98 to 99%** pure, with the major impurities being iron and aluminum.

石英砂→冶金硅 (Metallurgical Si: MG-Si)



Purity: 98-99%

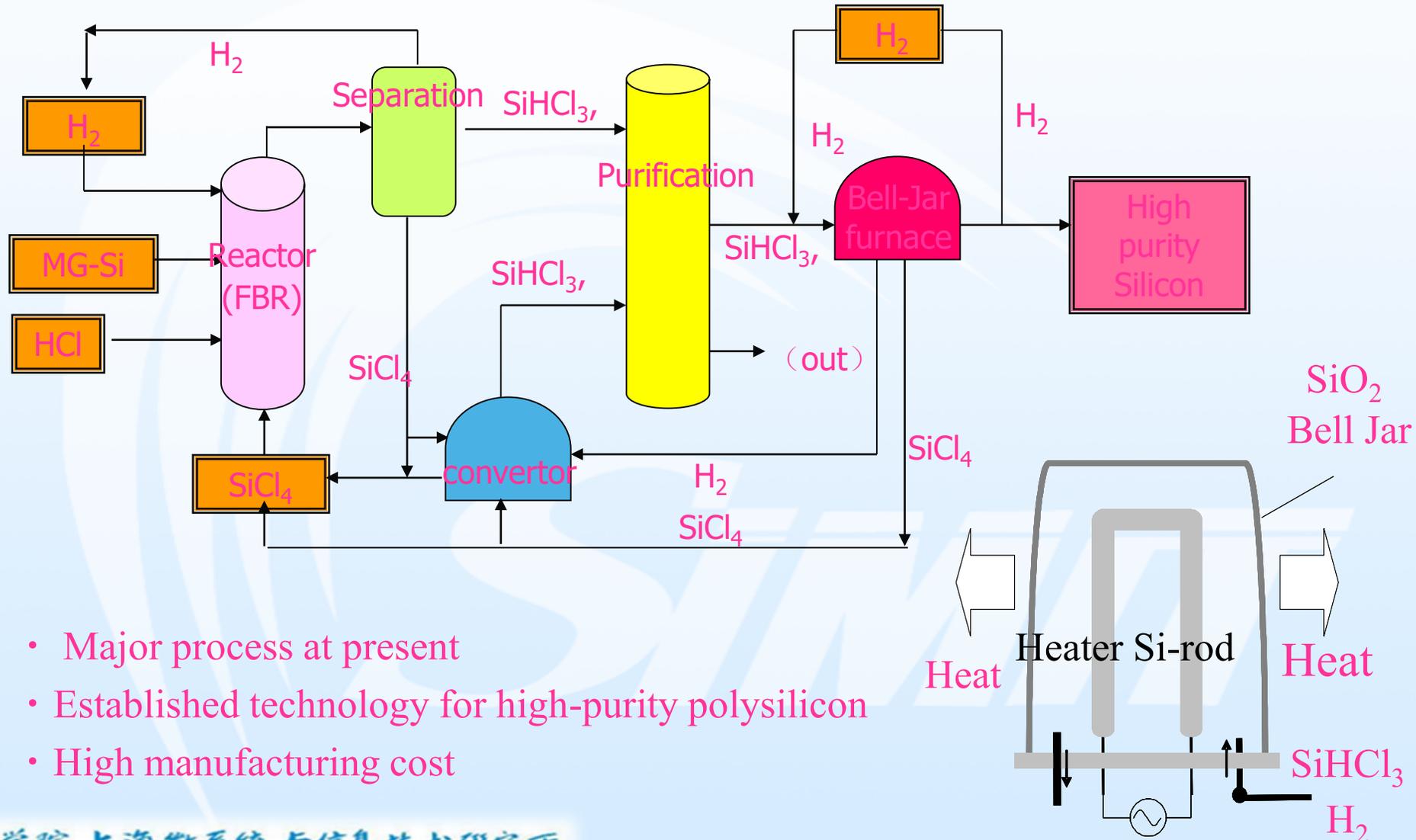
MG-Si to SeG-Si

- ❖ Si must be much purer than MG-Si for use in the semiconductor devices.
- ❖ The MG-Si is converted to a volatile compound that is condensed and refined by fractional distillation.
- ❖ Ultrapure Si is then extracted from this refined product.
- ❖ The detailed processing sequence is that a bed of fine MG-Si particles is fluidized with HCl in the presence of a Cu catalyst to promote the reaction



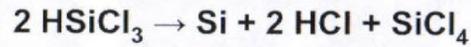
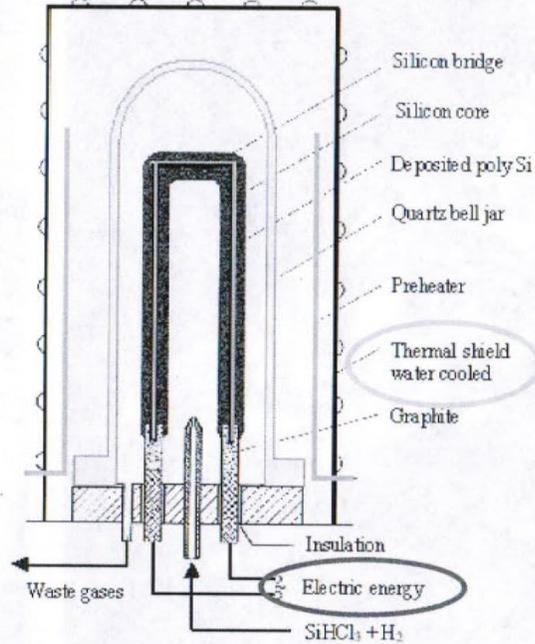
- A very small portion of the total MG-Si production is further purified to semiconductor grade (SeG) for the electronics industry.

冶金硅→多晶硅：西门子法



- Major process at present
- Established technology for high-purity polysilicon
- High manufacturing cost

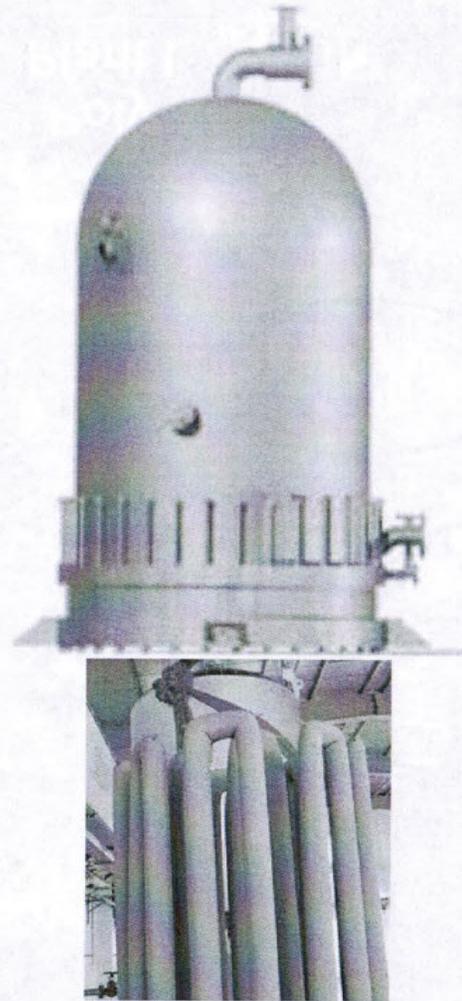
西门子法反应炉 (Reactor)



Established Technology
MEMC, Hemlock, REC, Wacker, Tokuyama

Higher purity material
larger chunks of silicon produced results in lower surface area density

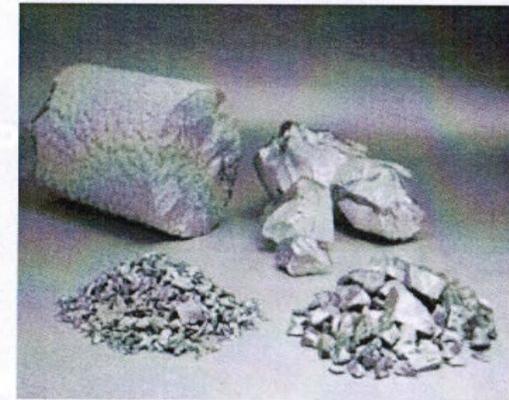
Batch Process



Polysilicon Reactors

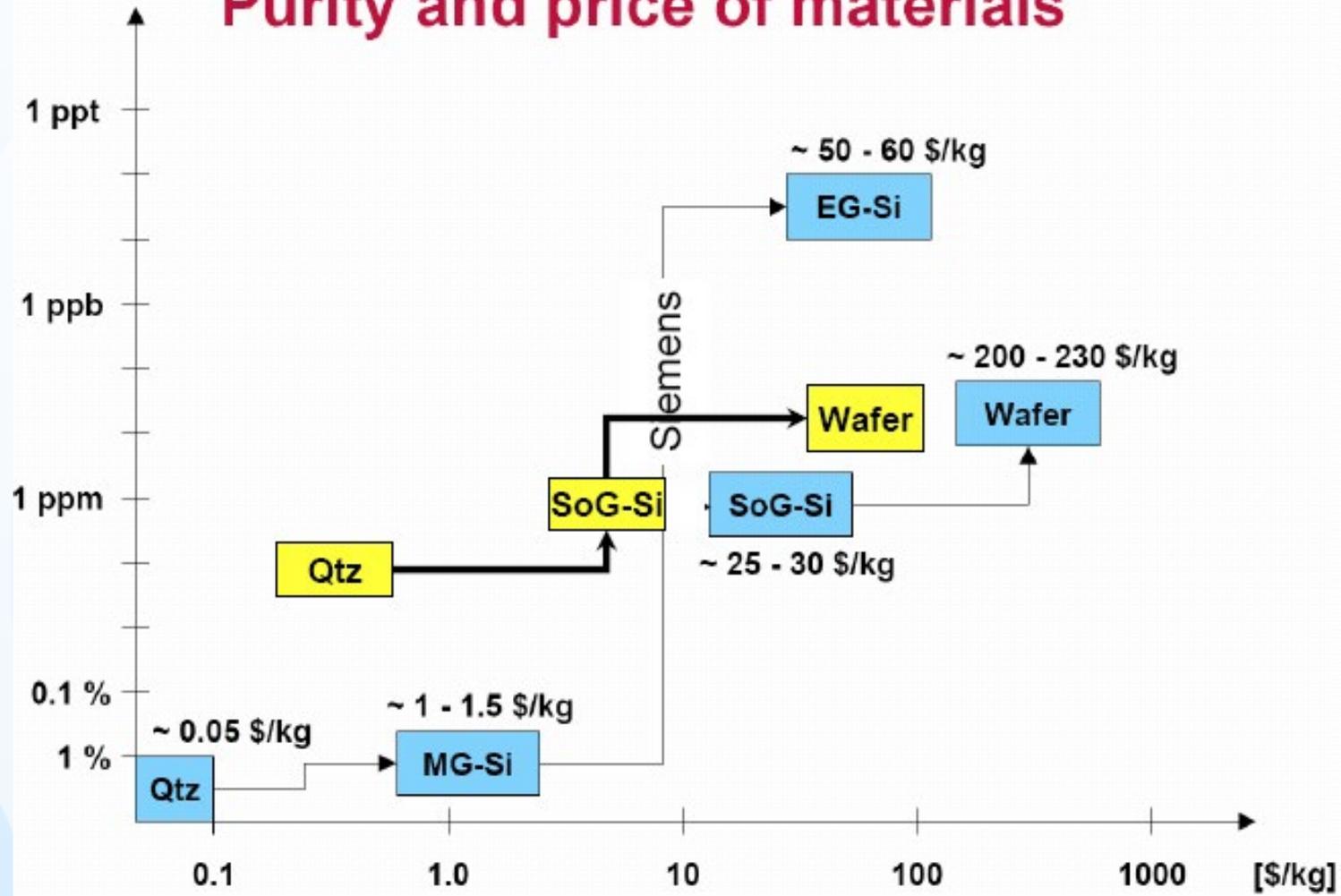


Polysilicon Chunk and Chips/Fines

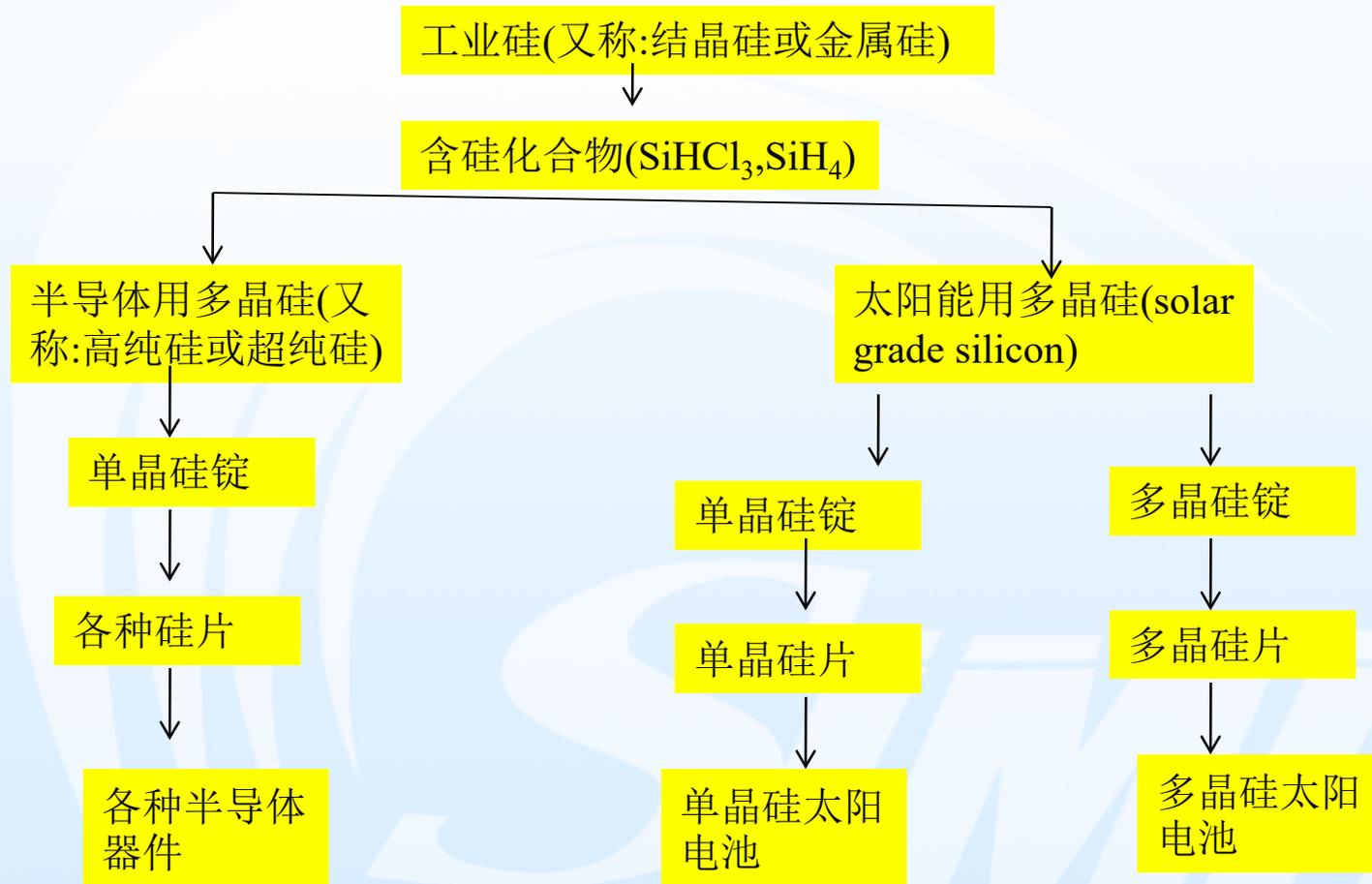


Si >99.99999999% Pure
(Impurities < 10^{-9})
~\$40/kg

Purity and price of materials



硅材料的应用领域

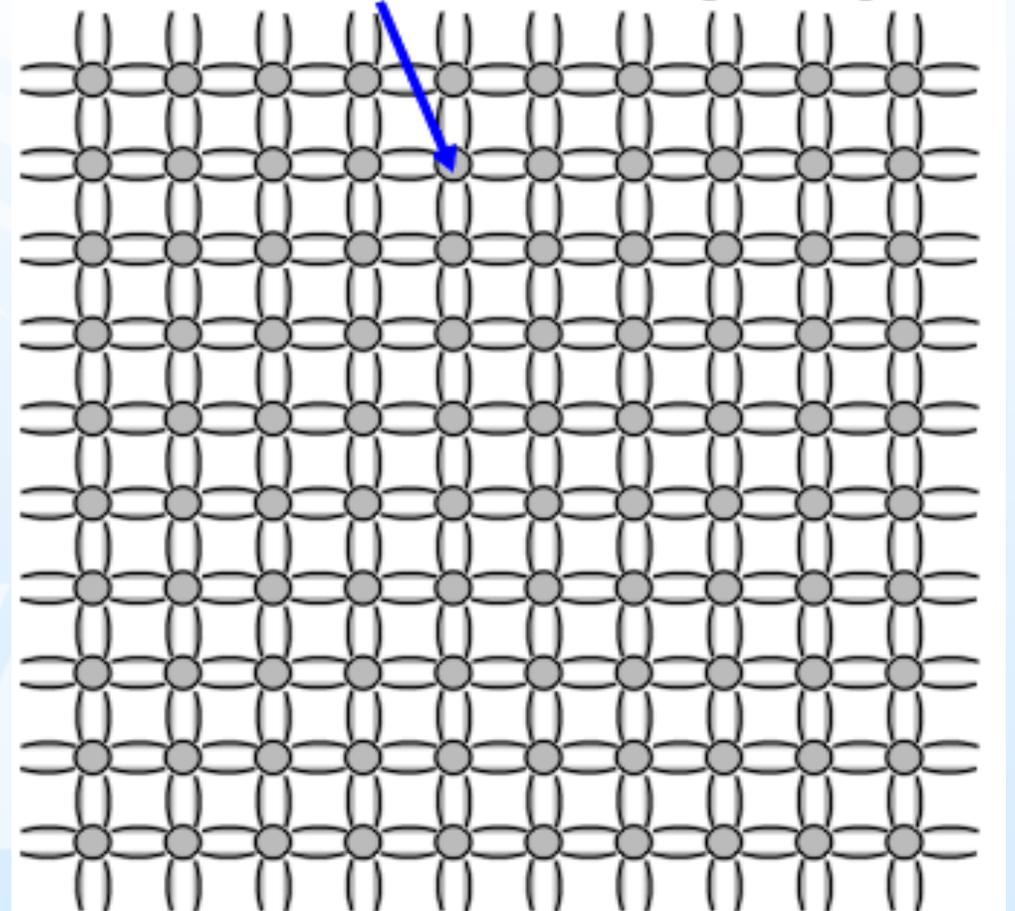


硅材料的另一应用领域在红外光学-红外滤光片

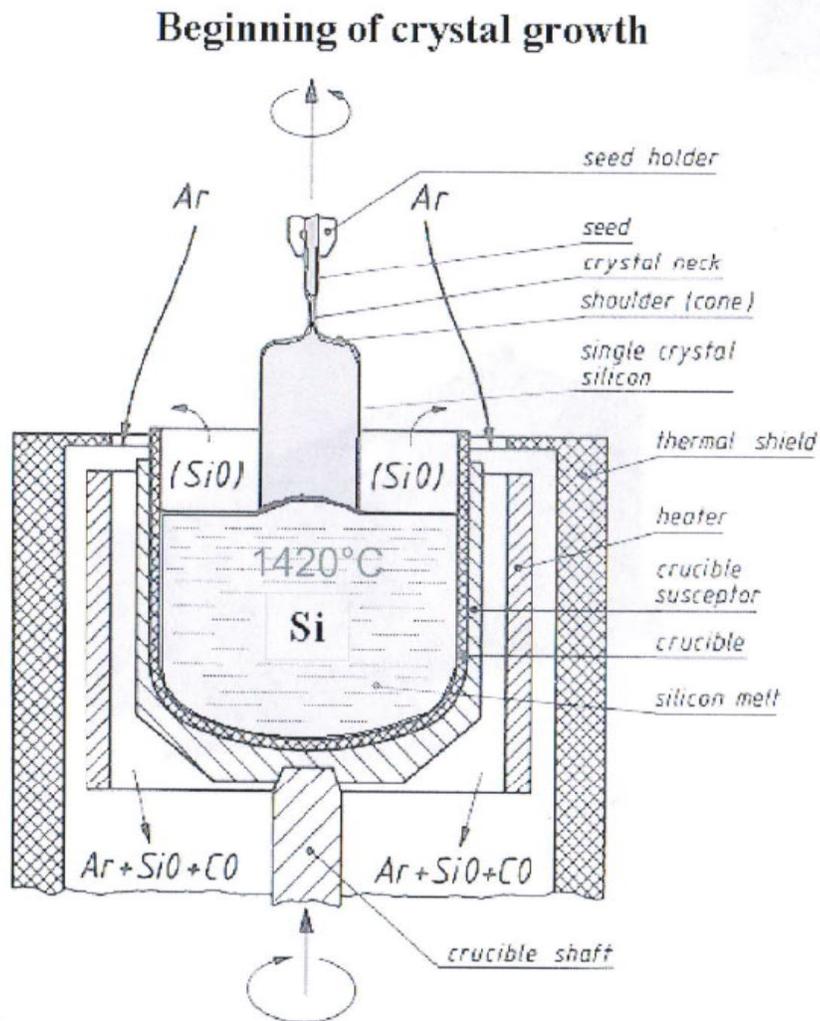
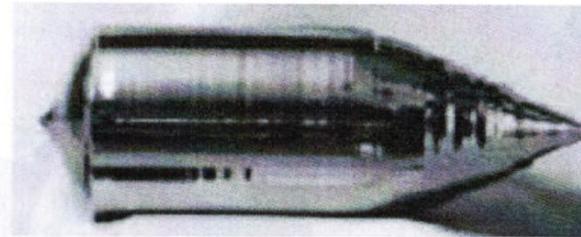
Single Crystalline Silicon

- ❖ The majority of Si solar cells are fabricated from silicon wafers, which may be either single-crystalline or multicrystalline.
- ❖ Single-crystalline wafers typically have better material parameters but are also more expensive.
- ❖ Crystalline Si has an ordered crystal structure, with each atom ideally lying in a pre-determined position.
- ❖ Crystalline Si exhibits predictable and uniform behavior but because of the careful and slow manufacturing processes required, it is also the most expensive type of silicon.

Each silicon atom is bonded to four neighbouring atoms.



Czochralski: CZ, 直拉单晶



- High purity feedstock is placed into quartz crucible for controlled melting
- Once silicon is molten, a seed crystal is dropped into the liquid and then begins to slowly rotate and pull up
- Silicon forms singular crystal around the seed in the form of a cylinder as its pulled upwards out of the melt
- Growth rate is about 1 mm/min

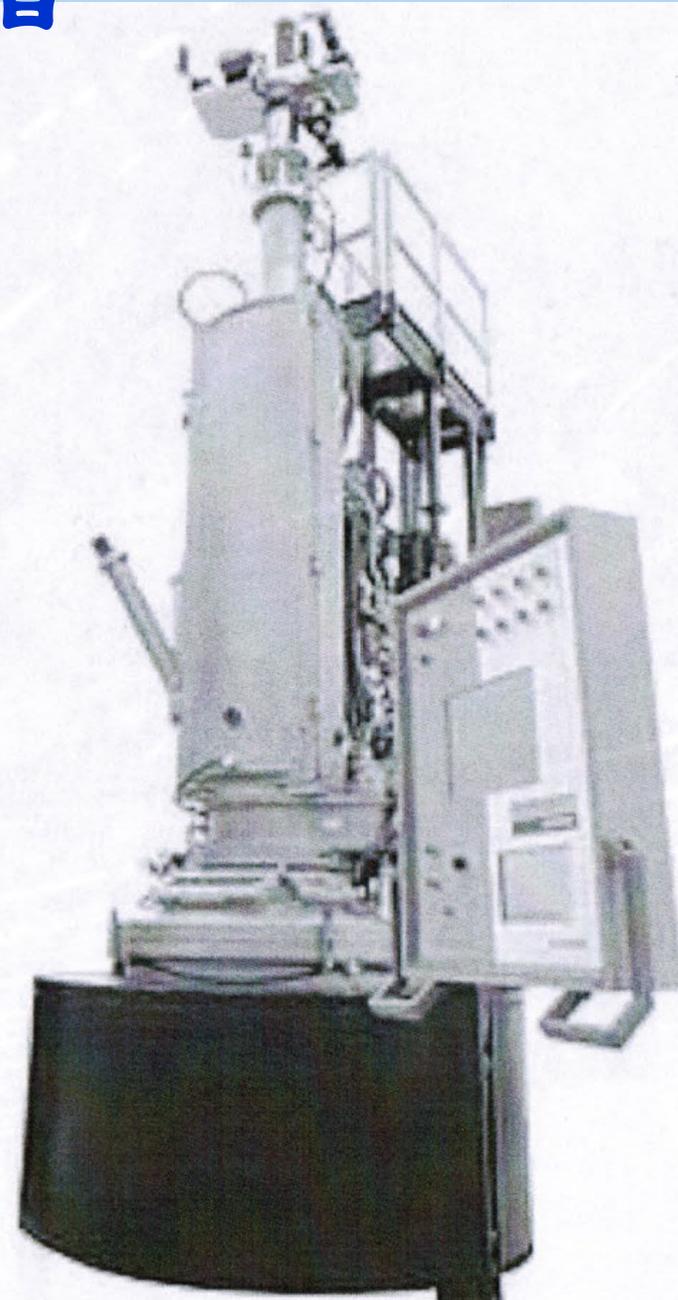
单晶硅拉晶

Quartz crucible

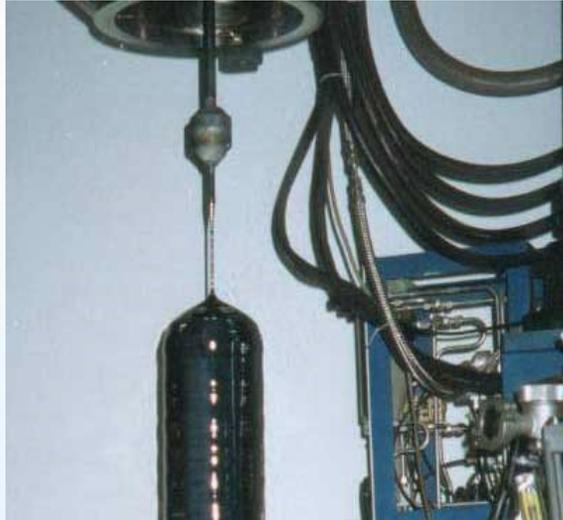


Polysilicon chunks in crucible

- High purity quartz crucibles are hand packed with chunks on high purity polysilicon



单晶硅棒



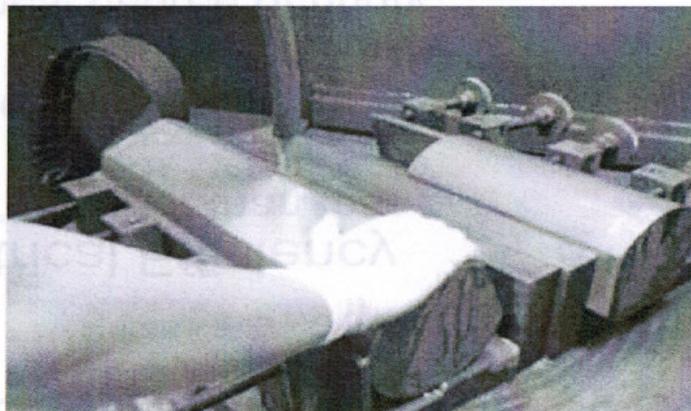
单晶硅锭的加工



Crop and grind round



Slab to square ingot ('wings' are recycled)

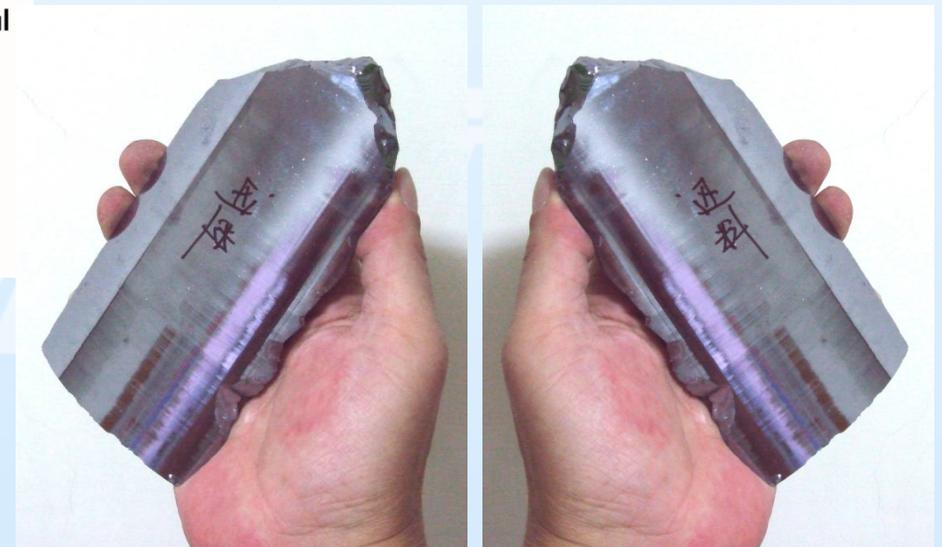
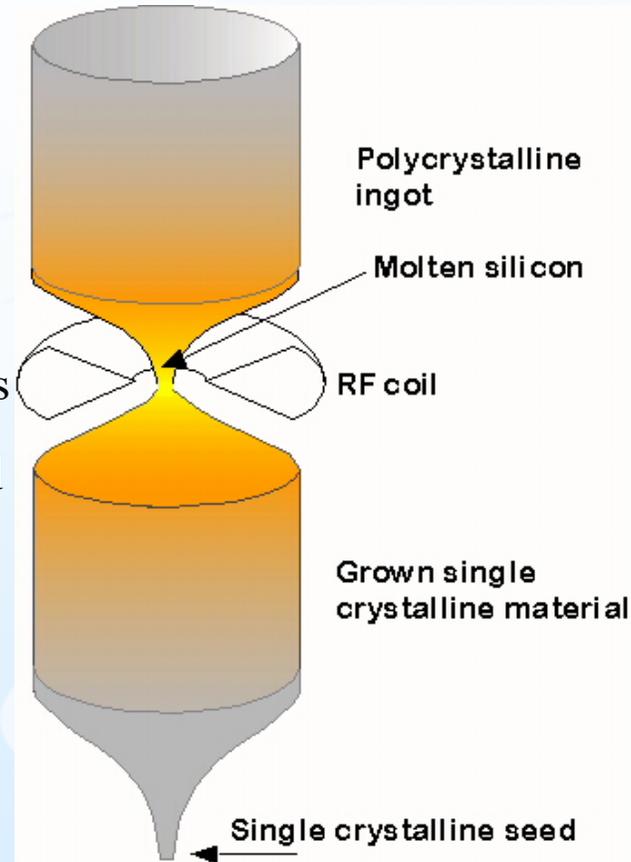


Flat grin

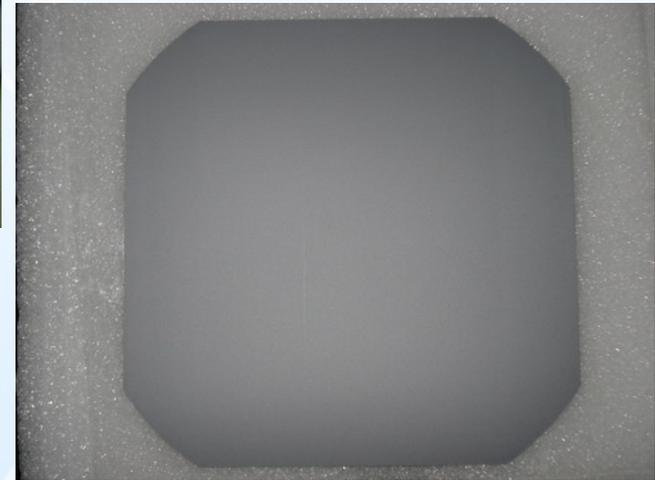


Schematic of FZ wafer growth

- ❖ To overcome these problems, **FZ** wafers may be used.
- ❖ In this process, a molten region is slowly passed along a rod or bar of Si. Impurities in the molten region tend to stay in the molten region rather than be incorporated into the solidified region, thus allowing a very pure single crystal region to be left after the molten region has passed.



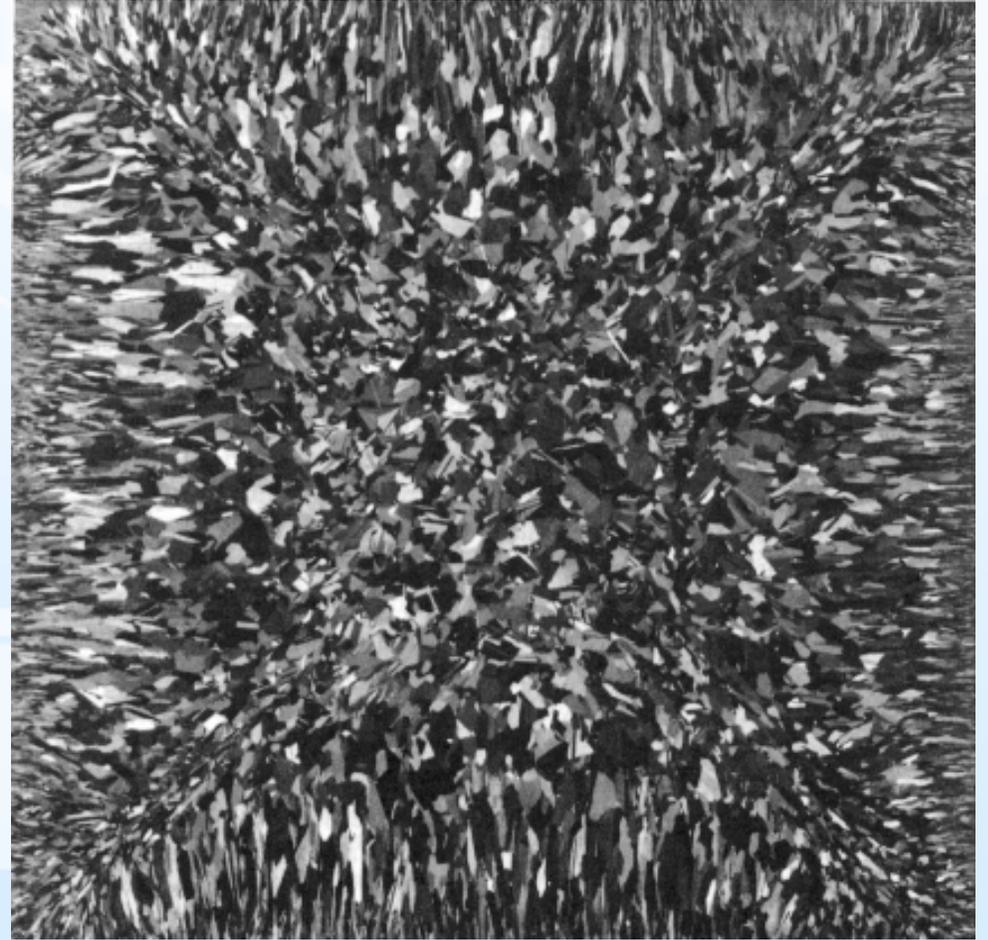
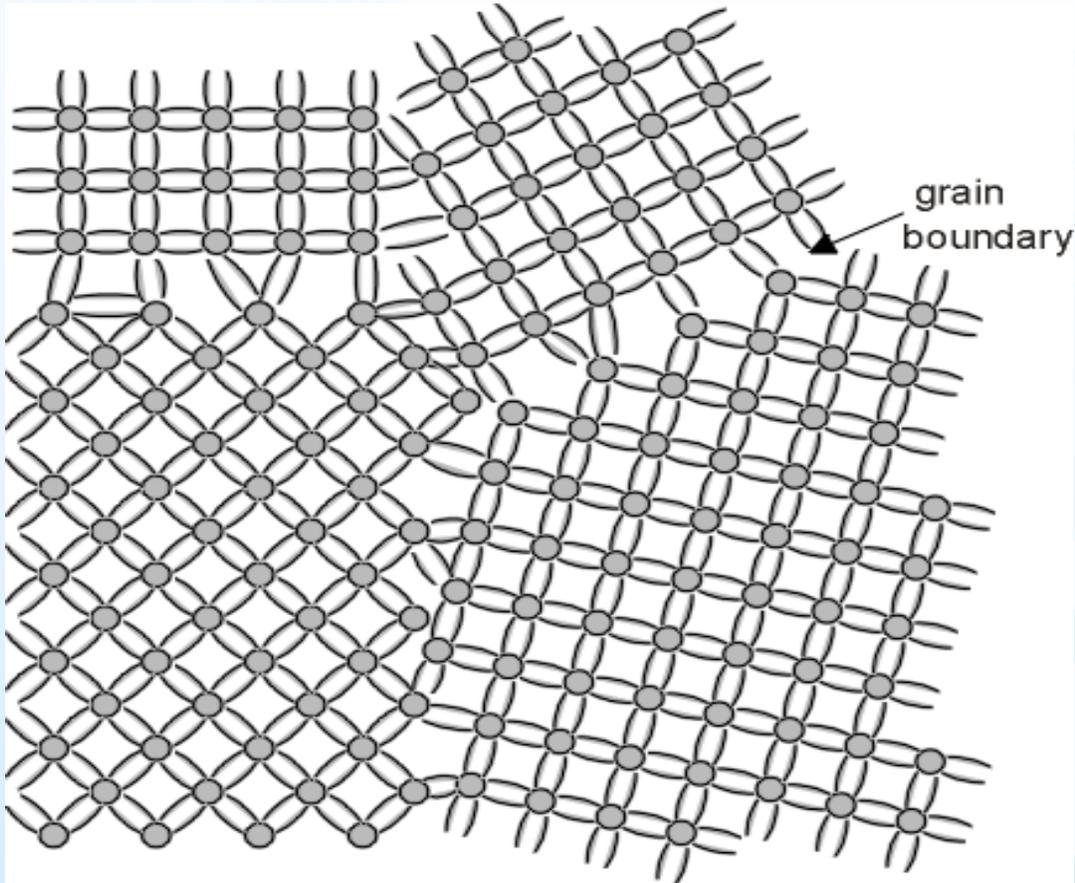
Single Crystalline Silicon



Single crystalline Si is usually grown as a large cylindrical ingot producing circular or semi-square solar cells.

The semi-square cell started out circular but has had the edges cut off so that a number of cells can be more efficiently packed into a rectangular module.

A multicrystalline wafer

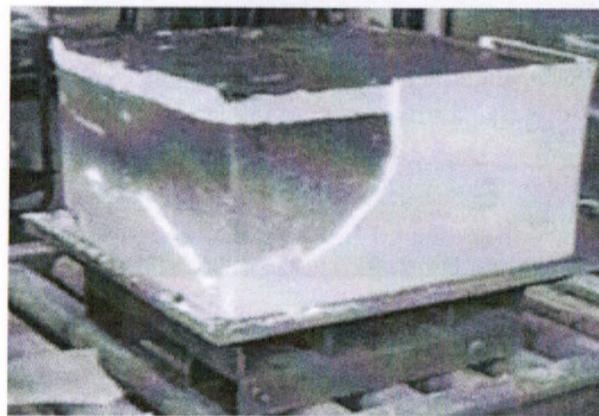
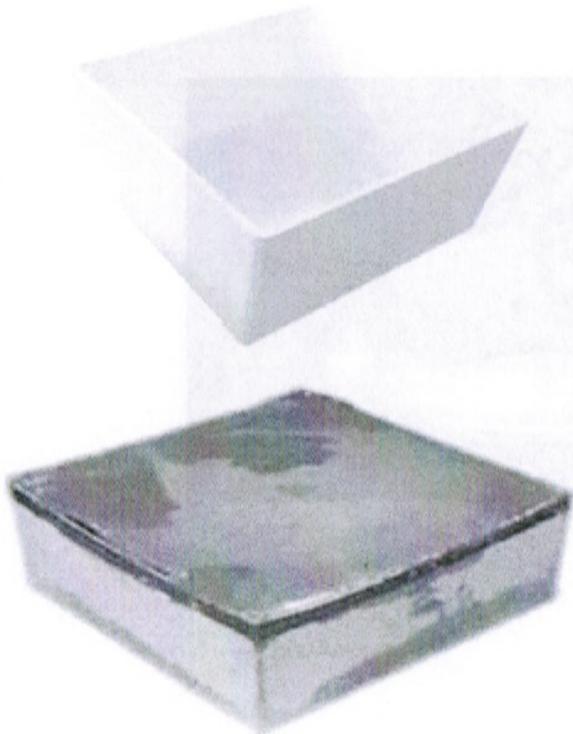


At the boundary between two crystal grains, the bonds are strained, degrading the electronic properties

Multicrystalline silicon (mc-Si)

- ❖ Techniques for the production of mc-Si are more simple, and therefore cheaper, than those required for single crystal material.
- ❖ However, the material quality of multicrystalline material is lower than that of single crystalline material due to the presence of **grain boundaries (GB)**.
- ❖ GB introduce high localised regions of recombination due to the introduction of extra defect energy levels into the band gap, thus reducing the overall minority carrier lifetime from the material.
- ❖ GB reduce solar cell performance by blocking carrier flows and providing shunting paths for current flow across the p-n junction.
- ❖ **Play the animation of mc-Si growth process.**

多晶硅铸锭 (Casting)



DSS furnaces generally sized for 270kg or 450kg charges

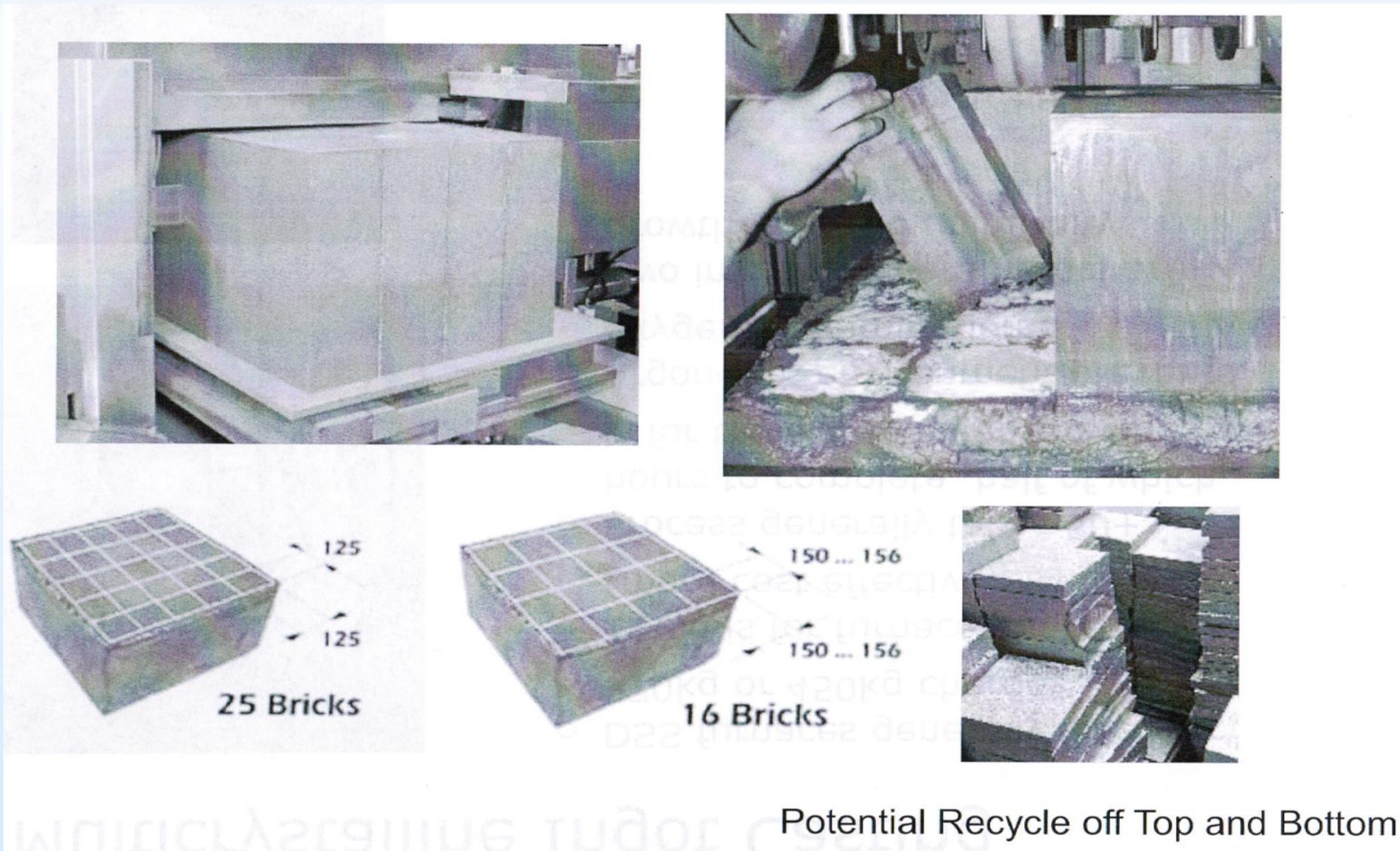
Trend is for furnaces to be larger (more cost effective)

Process generally takes 50+ hours to complete, half of which is for the actual ingot growth

Argon-rich environment prevents oxygen contamination

- Two important parameters are growth rate and uniformity

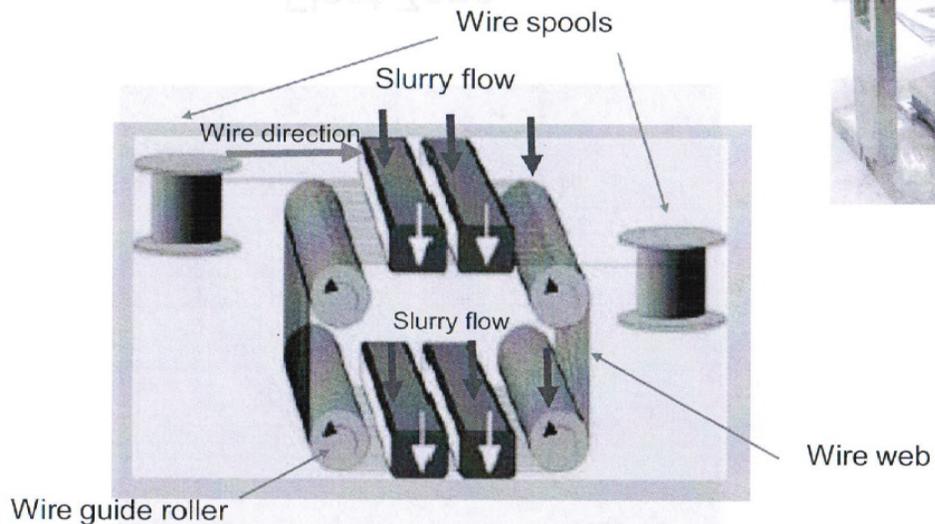
多晶硅锭分割 (Bricking)



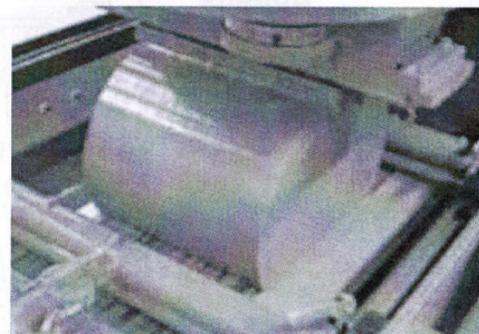
Potential Recycle off Top and Bottom

切片 (Slicing)

Wire Saw



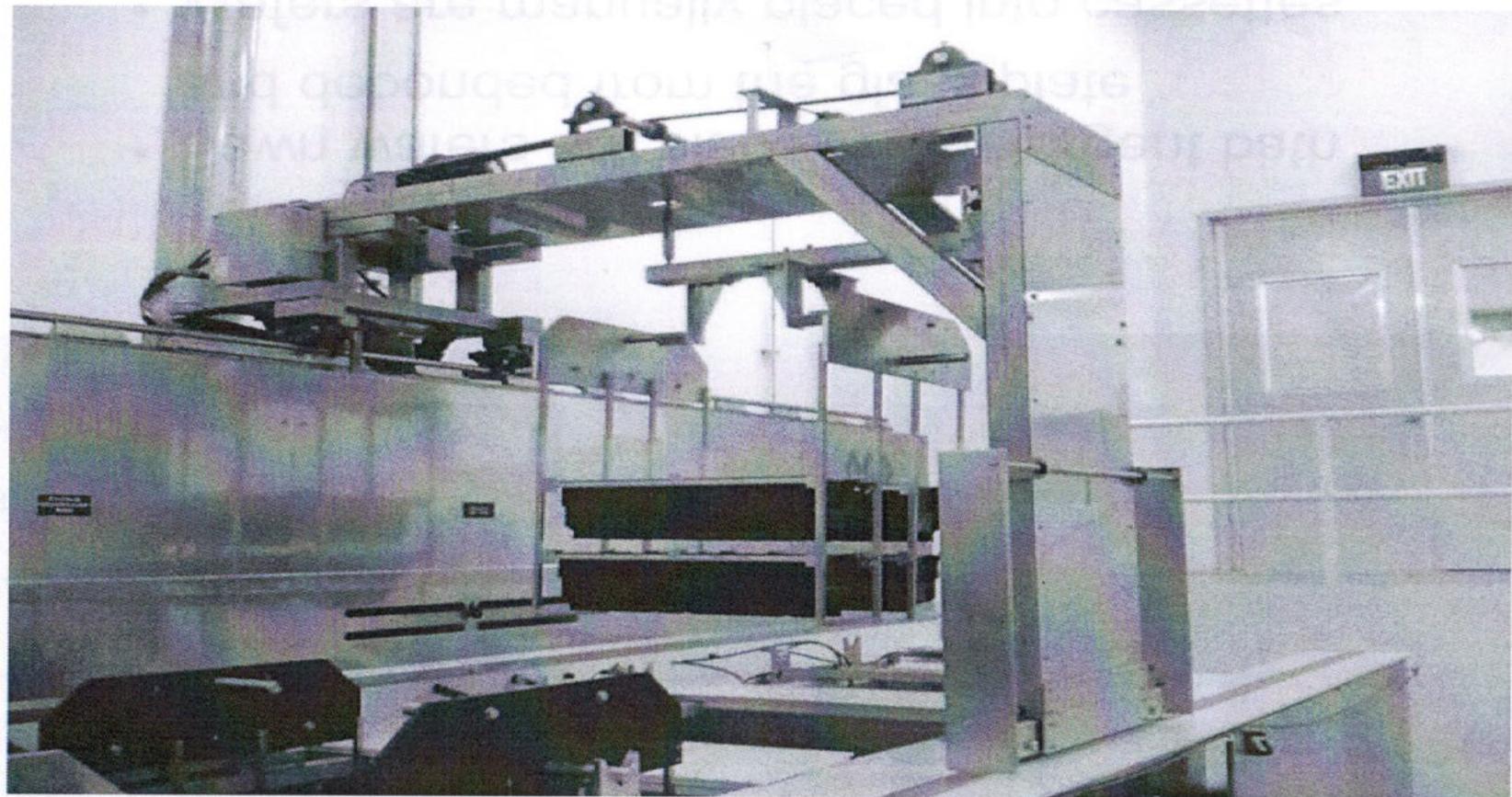
Glass Plate



- 2 to 4 square ingots are lowered through a web of fast spinning 100- 140 um diameter steel wire
- The cutting fluid is a mixture of propylene glycol (PEG) and silicon carbide particles (SiC)
- The process takes several hours and several kilometers of wire are used for each cut



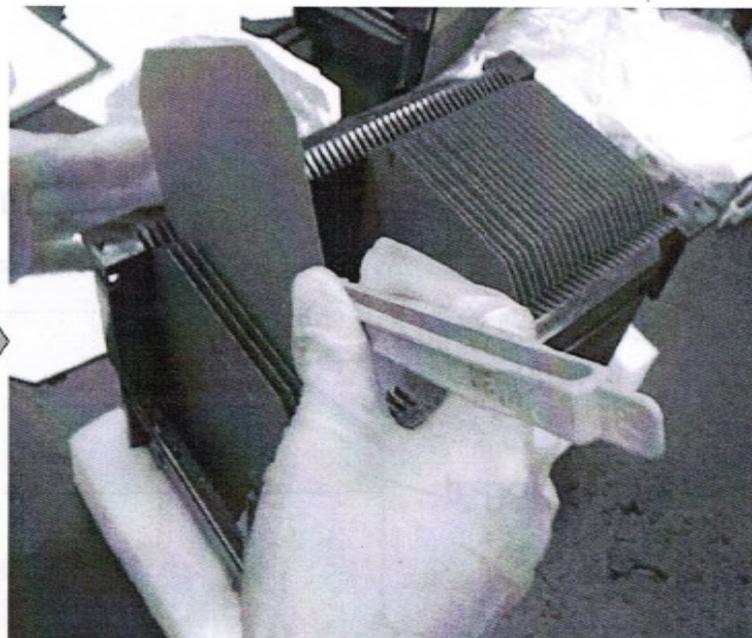
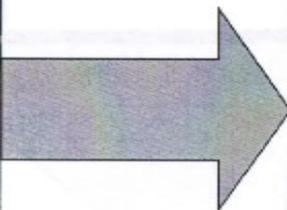
清洗 (Cleaning)



- Cassettes are moved through a sequence of water based cleaning solutions, then rinsed and dried.

检验和包装

Wafer Inspection / Packaging



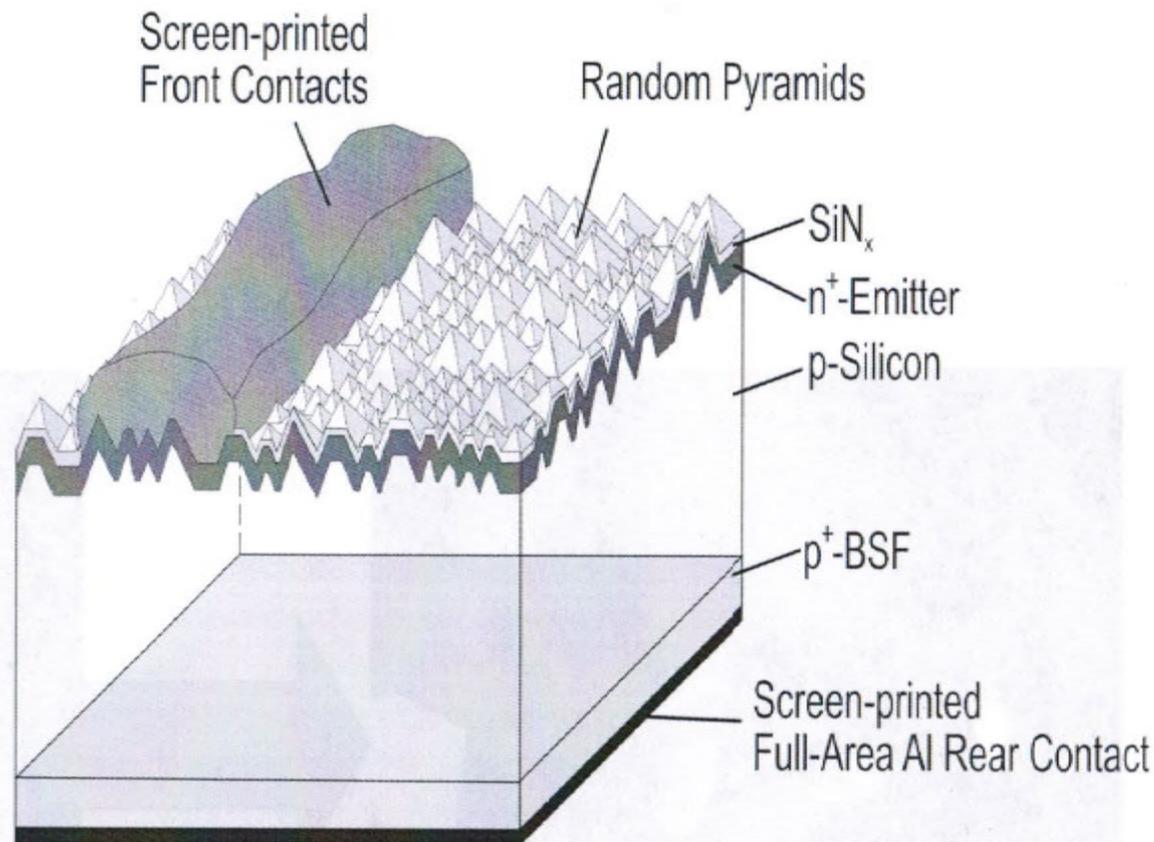
晶体硅太阳能电池的制作过程

Solar cell standard process

1. Wafer inspection
2. Saw damage etch/texturization-wet chemical etching: alkaline or acid
3. p-n-junction formation-all sided diffusion from POCl_3 .
4. Opening of the short between front side and rear side-plasma etching
5. Removal of phosphorous glass-wet chemical etching
6. AR-coating including hydrogen passivation-plasma enhanced CVD of silicon nitride
7. Printing of rear side contacts
8. Drying of rear side contacts
9. Printing aluminum paste for BSF formation
10. Drying aluminum paste
11. Printing of front side contacts
12. Drying of front side contacts
13. Sintering of contacts-cofiring front and rear side contacts sintered through the AR-coating
14. Performance measurement classification

太阳能电池的制作

- 1 Damage / Texture Etch
- 2 Diffusion
- 3 PSG Etch
- 4 AR Coating
- 5 Print/Dry Back Ag
- 6 Print/Dry Back Al
- 7 Print/Dry Front Ag
- 8 Fire Contacts
- 9 Laser Edge Isolation
- 10 Test, Inspect, Pack



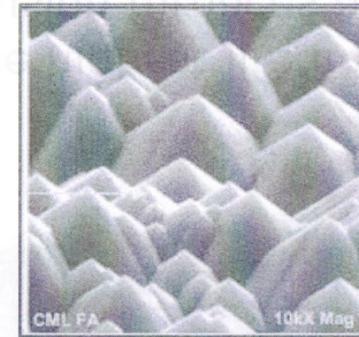
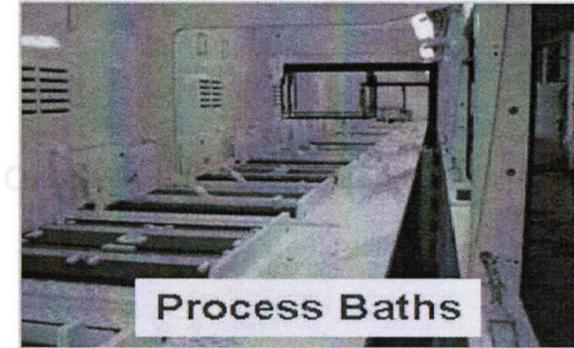
Industrial Cell Structure

去损伤，制绒

Surface Preparation Damage / Texture Etch

Damage / Texture Etch	1
Diffusion	2
PSG Etch	3
AR Coating	4
Print/Dry Back Ag	5
Print/Dry Back Al	6
Print/Dry Front Ag	7
Fire Contacts	8
Laser Edge Isolation	9
Test, Inspect, Pack	10

- An caustic or acid etch removes saw damage and textures wafers
- CZ prefers a batch caustic etch to preferentially expose (111) plans (pyramids)
- Multi-crystalline uses inline acid texture



Surface texturing to reduce reflection

- ❖ Monocrystalline-Si wafers are easily textured to reduce reflection by etching pyramids on the wafer surface with a chemical solution.
- ❖ However, it is only marginally effective on the randomly orientated grains of multicrystalline material.
- ❖ Various schemes have been proposed to texture multicrystalline materials:
 - ◆ Mechanical texturing of the wafer surface with cutting tools or lasers
 - ◆ Isotropic chemical etching based on defects rather than crystal orientation
 - ◆ Isotropic chemical etching in combination with a photolithographic mask
 - ◆ Plasma etching

It is difficult to be implemented in commercial production lines.

Clean wafer

To control unwanted impurities

- Clean factories
- Wafer cleaning
- gettering

- Cleaning involves removing particles, organics and metals from wafer surfaces
- Particles are largely removed by ultrasonic agitation during cleaning
- Organics are removed in an O₂ plasma or in H₂SO₄/H₂O₂ solutions
- The RCA clean remove metals and any remaining organics
- Metal cleaning can be understood in terms of the following chemistry
- $\text{Si} + 2\text{H}_2\text{O} \rightleftharpoons \text{SiO}_2 + 4\text{H}^+ + 4\text{e}^-$ (1)
- $\text{M} \rightleftharpoons \text{M}^{z+} + z\text{e}^-$ (2)
- If we have a water solution with a Si wafer and metal atoms and ions, the stronger reaction will dominate
- Generally (2) is driven to the left and (1) to the right so that SiO₂ is formed and M plates out on the wafer
- Good cleaning solutions drive (2) to the right since M⁺ is soluble and will be desorbed from the wafer surface

扩散：p-n结

Diffusion

Damage / Texture Etch	1
Diffusion	2
PSG Etch	3
AR Coating	4
Print/Dry Back Ag	5
Print/Dry Back Al	6
Print/Dry Front Ag	7
Fire Contacts	8
Laser Edge Isolation	9
Test, Inspect, Pack	10

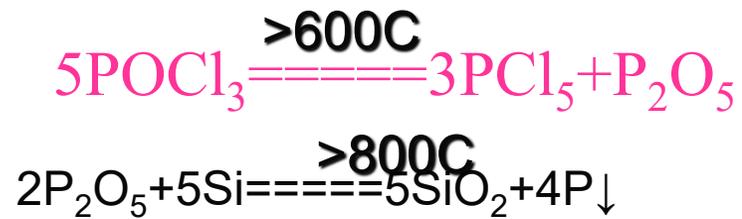


- Batch tube furnaces give highest lifetime but sometimes belt diffusion furnaces are used.
- Temperature: 800 – 1000°C
- Phosphorus oxychloride (POCl_3) dopant source

Basic Process of diffusion

- Source material transported to surface by inert carrier
- Decomposes and reacts with the surface
- Dopant atoms deposited, dissolve in Si, begin to diffuse

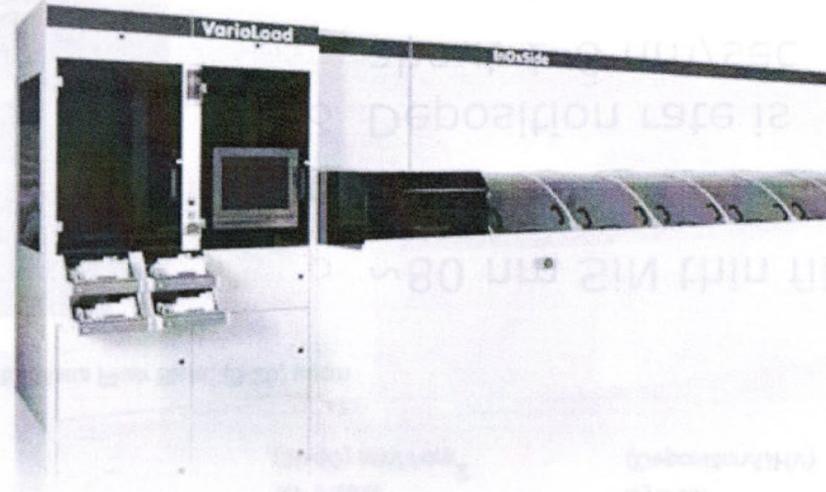
磷扩散的反应过程



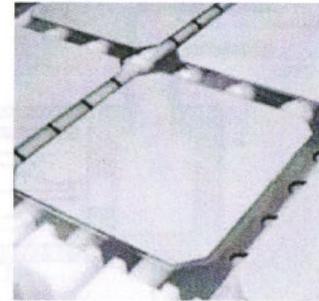
去磷玻璃

Phosphosilicate Glass Etch (PSG Etch)

Damage / Texture Etch	1
Diffusion	2
PSG Etch	3
AR Coating	4
Print/Dry Back Ag	5
Print/Dry Back Al	6
Print/Dry Front Ag	7
Fire Contacts	8
Laser Edge Isolation	9
Test, Inspect, Pack	10



- Wafers are transported on rollers through etchants
- Some PSG etchers now include a single side sided back etch for edge isolation

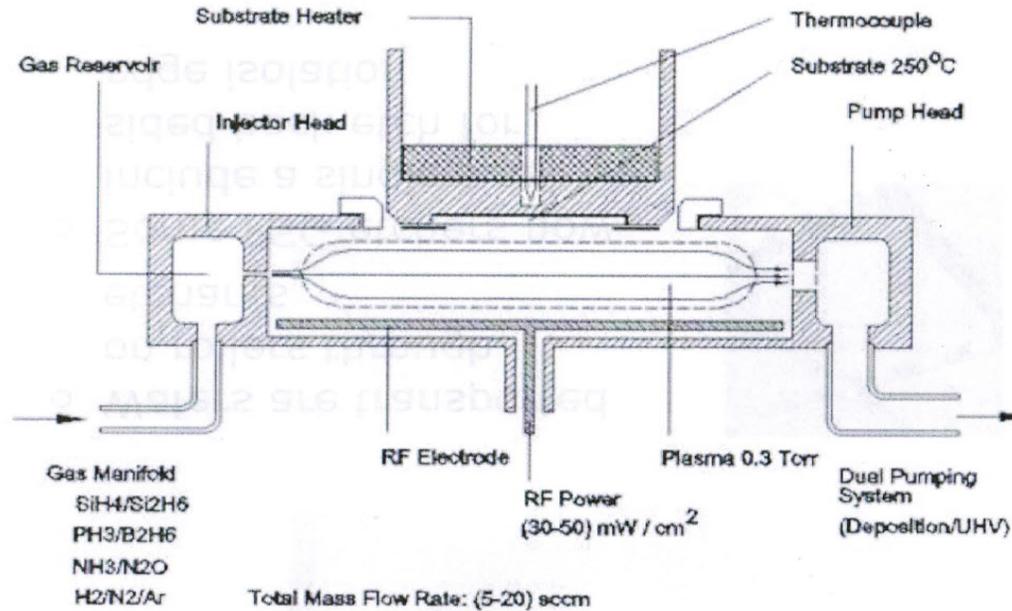


表面减反射薄膜

(Anti-reflection coating)

AR Coat

- Damage / Texture Etch 1
- Diffusion 2
- PSG Etch 3
- AR Coating 4
- Print/Dry Back Ag 5
- Print/Dry Back Al 6
- Print/Dry Front Ag 7
- Fire 8
- Laser Edge Isolation 9
- Test, Inspect, Pack 10

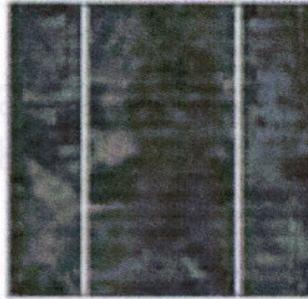


- ~80 nm SiN thin film
- Deep blue in color
- Deposition rate is about 1-6 nm/sec
- Temp 200- 400 C

电极制作：丝网印刷

Screen Print

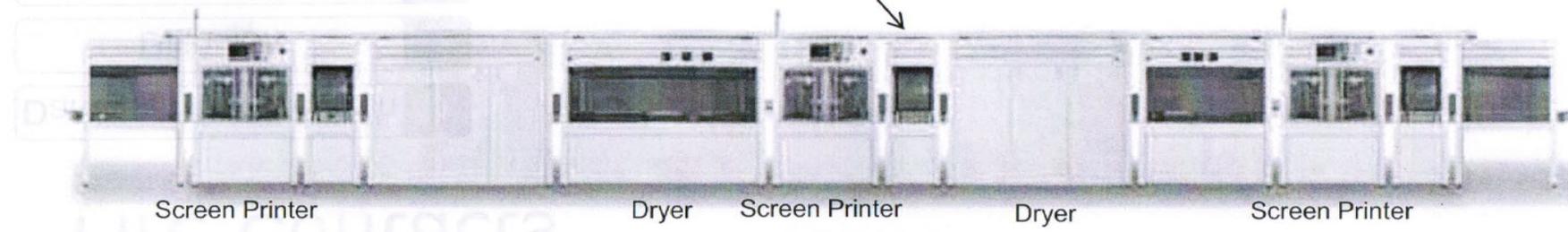
Damage / Texture Etch	1
Diffusion	2
PSG Etch	3
AR Coating	4
Print/Dry Back Ag	5
Print/Dry Back Al	6
Print Front Ag	7
Fire Contacts	8
Laser Edge Isolation	9
Test, Inspect, Pack	10



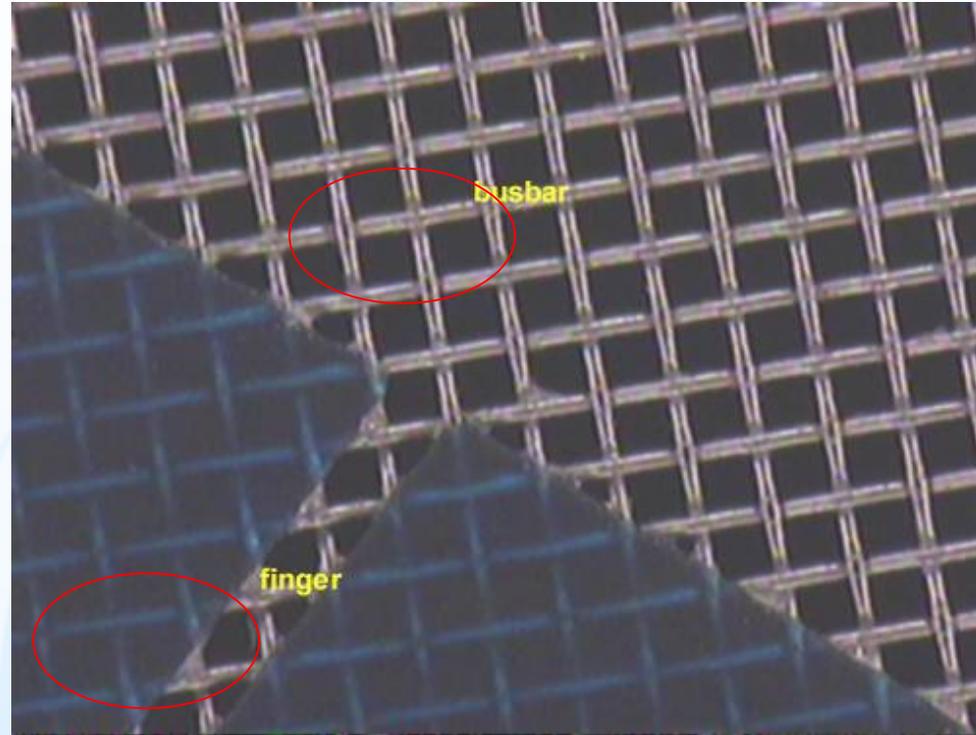
- Metal pastes are printed 12-15 um thick, 70-100 um minimum feature size
- Drying Profile: 250-300C, ~60 seconds
- Front side contamination must be avoided

Automated Optical Inspection System

Applied Materials Baccini Print Line

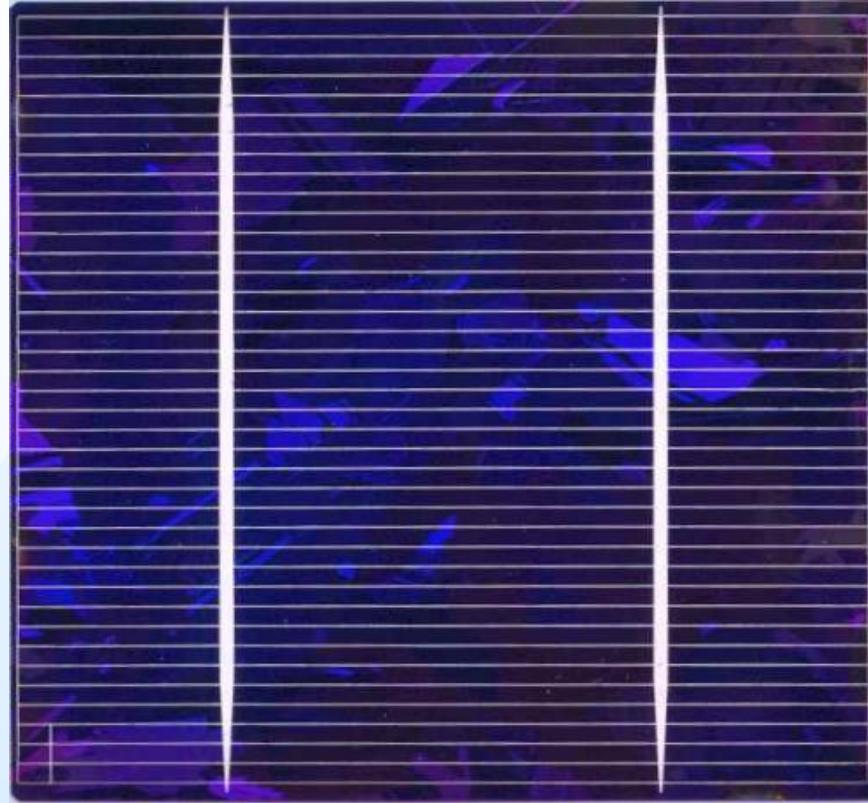


Screen printing



Close up of a screen used for printing the front contact of a solar cell. During printing, metal paste is forced through the wire mesh in unmasked areas. The size of the wire mesh determines the minimum width of the fingers. Finger widths are typically **100 to 200 μ m**.

Front surface of a multi crystalline Si solar cell

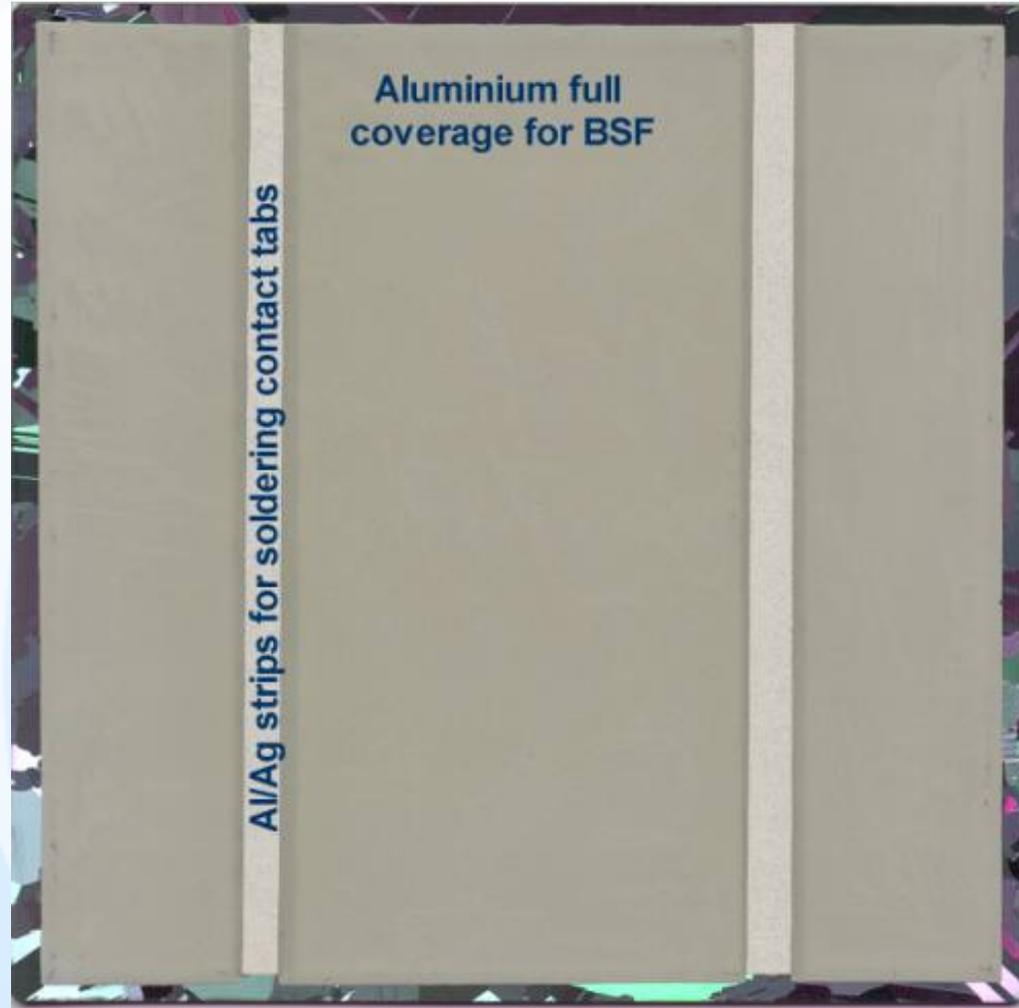


Front view of a completed screen-printed solar cell. As the cell is manufactured from a multicrystalline substrate, the different grain orientations can be clearly seen. The square shape of a multicrystalline substrate simplifies the packing of cells into a module.

Rear contact

- ❖ A full Al layer printed on the rear of the cell, with subsequent alloying through firing, produces a **BSF** and improves the cell bulk through **gettering**.
- ❖ However, a second print of **Al/Ag** is required for **solderable** contact.
- ❖ In most production, the rear contact is simply made using a Al/Ag grid printed in a single step.

Screen printing



电极烧结

Fire Contacts

Damage / Texture Etch	1
Diffusion	2
PSG Etch	3
AR Coating	4
Print/Dry Back Ag	5
Print/Dry Back Al	6
Print/Dry Front Ag	7
Fire Contacts	8
Laser Edge Isolation	9
Test, Inspect, Pack	10



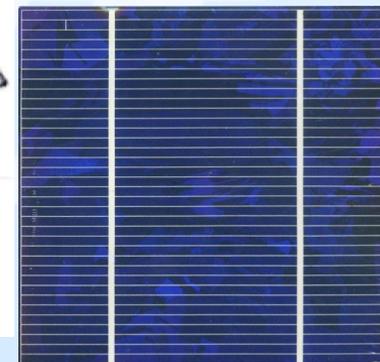
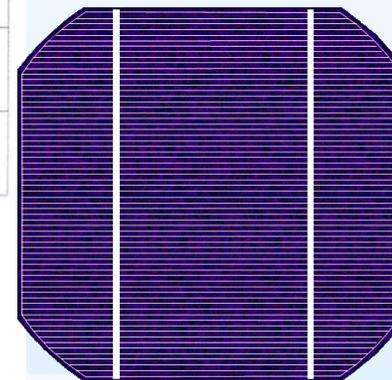
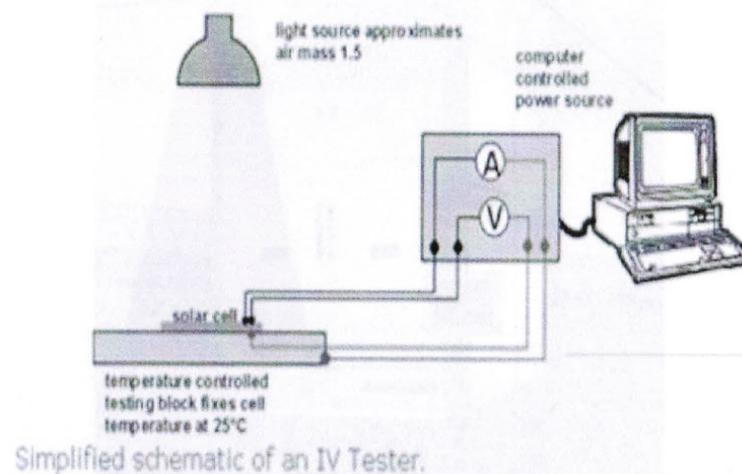
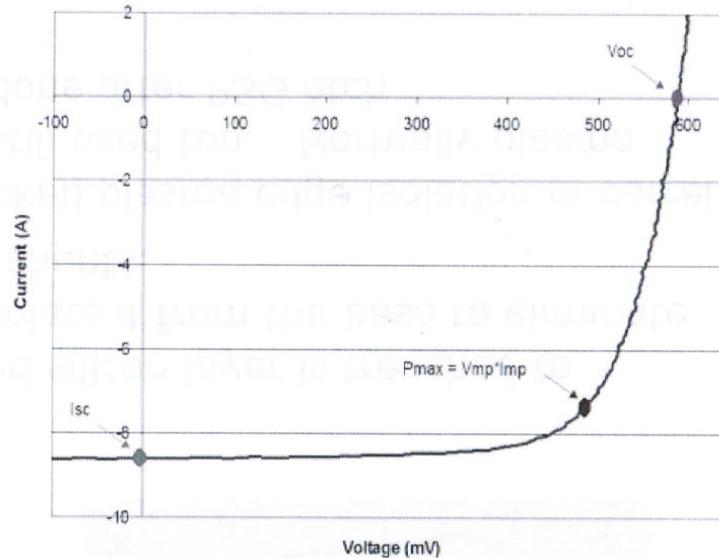
Fire at 810–940C, 1–3 seconds

Silver paste sheet rho: $\sim 4.0 \text{ m}\Omega/\text{sq}$ at 12 μm thick

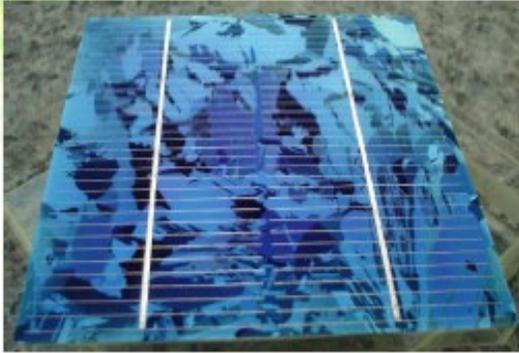
检验, 分级

Test & Inspect

- Damage / Texture Etch 1
- Diffusion 2
- PSG Etch 3
- AR Coating 4
- Print/Dry Back Ag 5
- Print/Dry Back Al 6
- Print/Dry Front Ag 7
- Fire Contacts 8
- Laser Edge Isolation 9
- Test, Inspect, Pack 10



太阳能电池组件

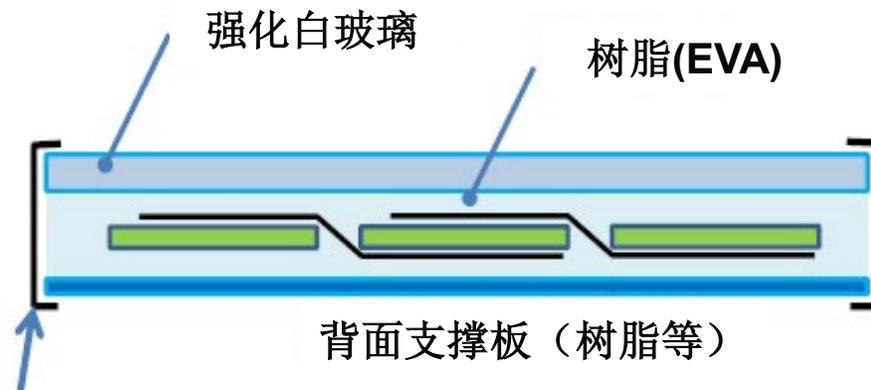


电池器件（多晶硅太阳能电池）
大小为12-15cm的方块

一个硅电池的电压约为
0.6V



为了得到**高**的电压，通常把多个
电池**串联**在一起



金属框

背面支撑板（树脂等）

组件

用玻璃和其他材料把电池和电极材料保护起来

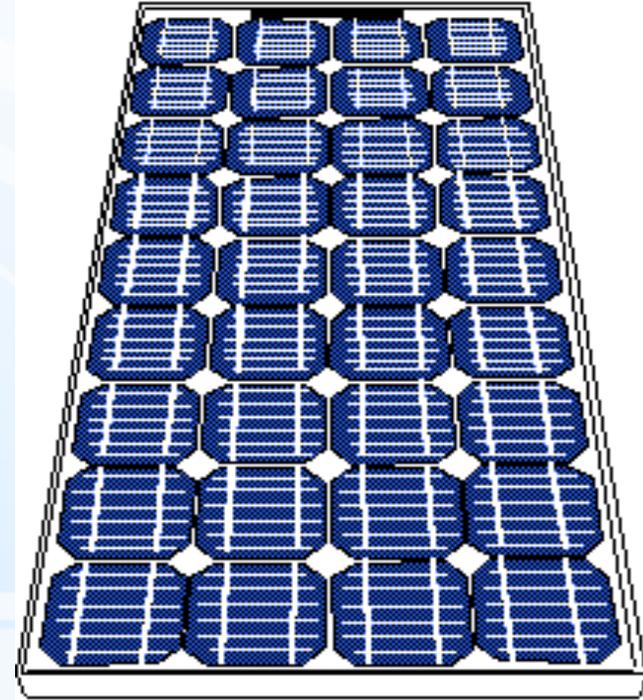


Why are PV cells encapsulated?

- ❖ Protect people from high voltage and current
- ❖ Protect the electrical elements of the module from the external environmental - cell, wiring etc.
- ❖ Allow for mechanical support, mounting and orientation of the PV device
- ❖ Help minimize cell temperature during operation
- ❖ **Allow as much as light as possible to reach the cells**
- ❖ Help facilitate and optimize shipping, staging, mounting, installation and on-going maintenance
- ❖ And a degree of chemical protection.

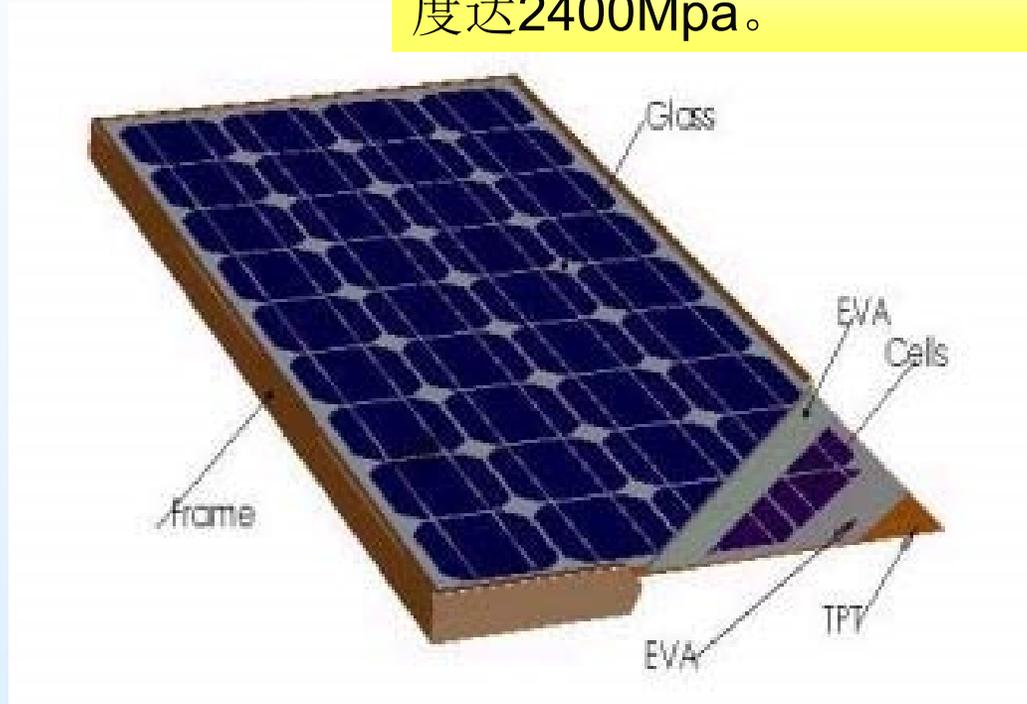
Module structure

- ❖ A PV module consists of a number of interconnected solar cells (typically 60 or 72 or 90 connected in series) encapsulated into a single, long-lasting, stable unit.



A typical bulk Si PV module used in outdoor remote power applications.

由氟塑料、涤纶复合而成的Tedlar(TPT)背膜组成。高真空加热层压工艺及配备经防腐处理铝合金(表面氧化)边框、水密接线盒，抗紫外老化和抗风强度达2400Mpa。



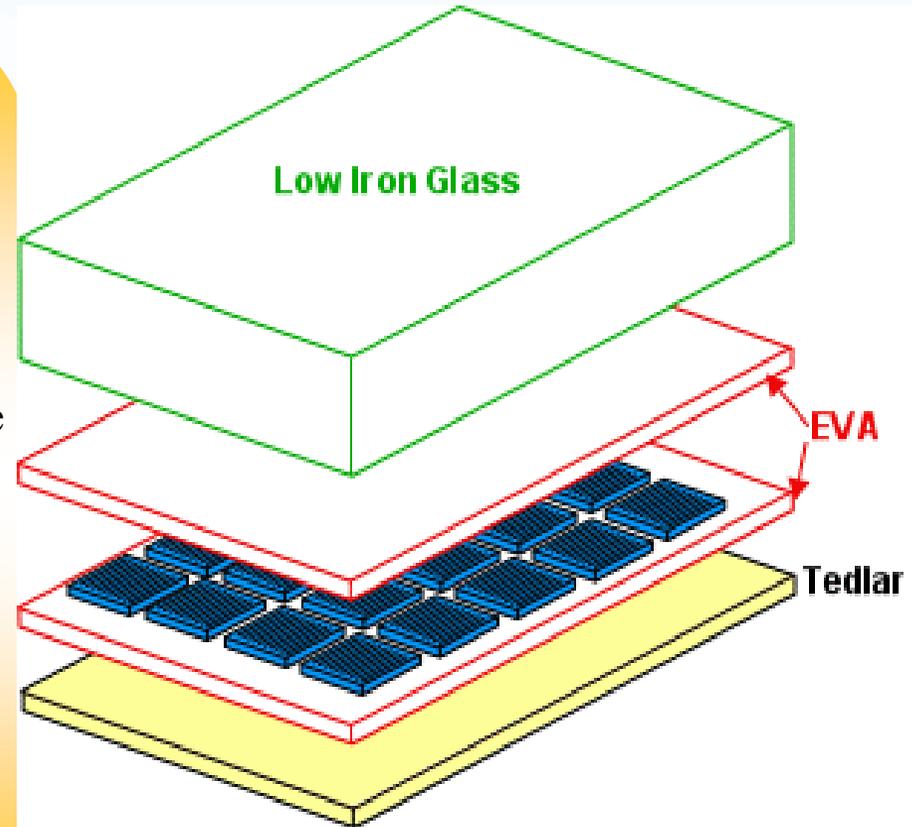
A heavy-duty anodized Al frame provides strength and convenient mounting access. For each 18 cells series strings, one bypass diode is installed.

Cells are laminated between high transmissivity, low-iron, 3mm tempered glass and sheet of tedlar-polyester-tedlar (TPT) material by two sheets of ethylene Vinyl acetate (EVA). This protects against moisture penetrating into the module. A versatile junction box provides flexibility of connections.

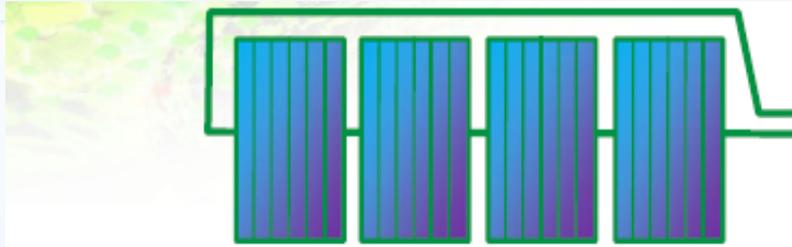
Module materials

- ❖ Most bulk silicon PV modules consist of a transparent top surface, an encapsulant, a rear layer and a frame around the outer edge.
- ❖ Top surface is usually glass due to its self cleaning properties
- ❖ Encapsulant—EVA (ethyl-vinyl-acetate) is somewhat UV stable and resists most moisture
- ❖ Rear layer—Tedlar, provides a light weight seal on the back
- ❖ Glass rear for some applications but it is expensive and heavy
- ❖ Other materials have limited acceptance

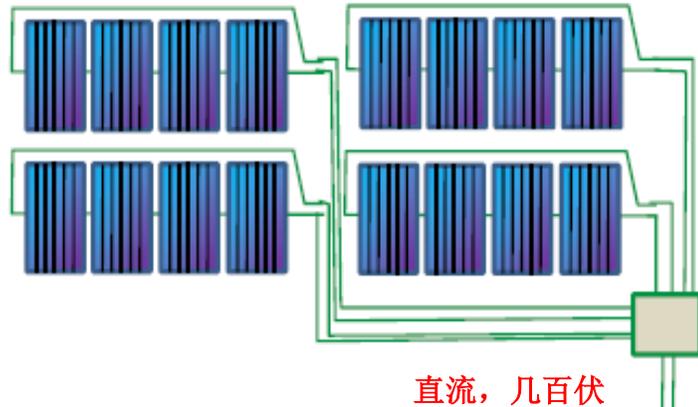
Typical bulk silicon module materials



太阳能电池阵列：系统

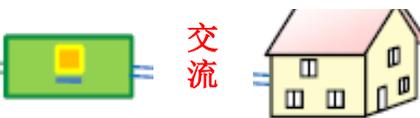


把几个或多个太阳能电池组件
串联在一起，称为**串联**
(String)，其输出为几十到几
百伏的直流电压



把几个或多个串联的太阳能电池组
件**并联**在一起，称为**阵列**
(Array)，使输出电流增加

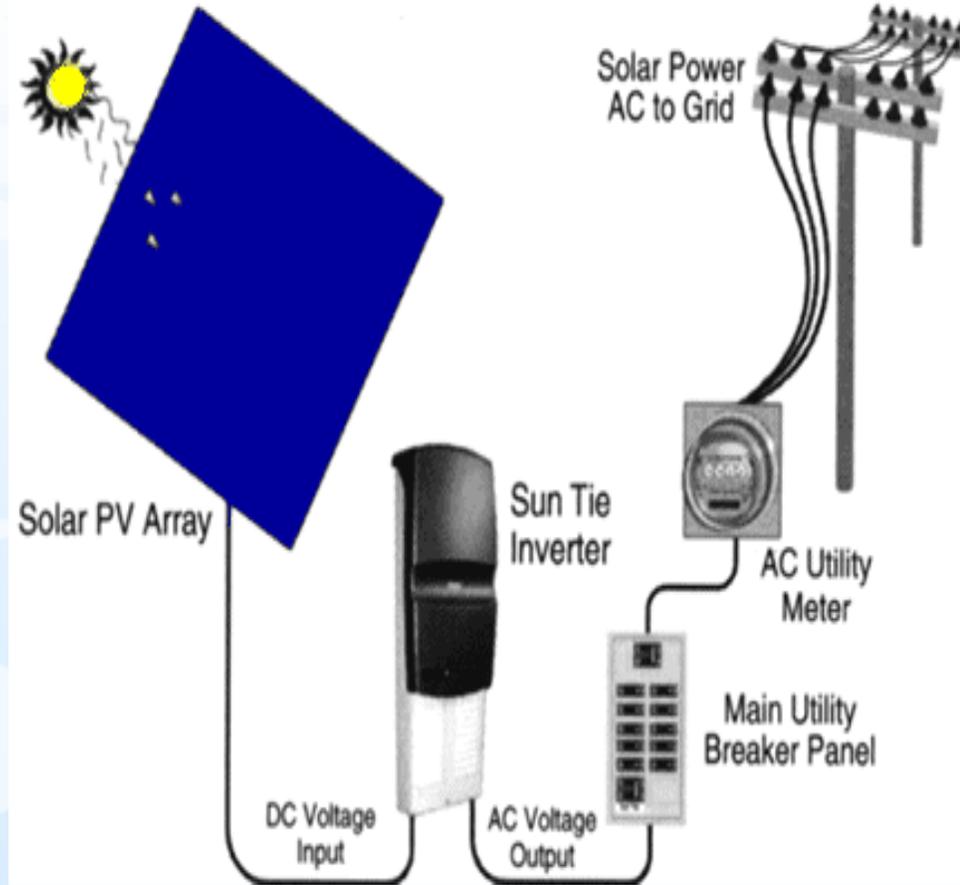
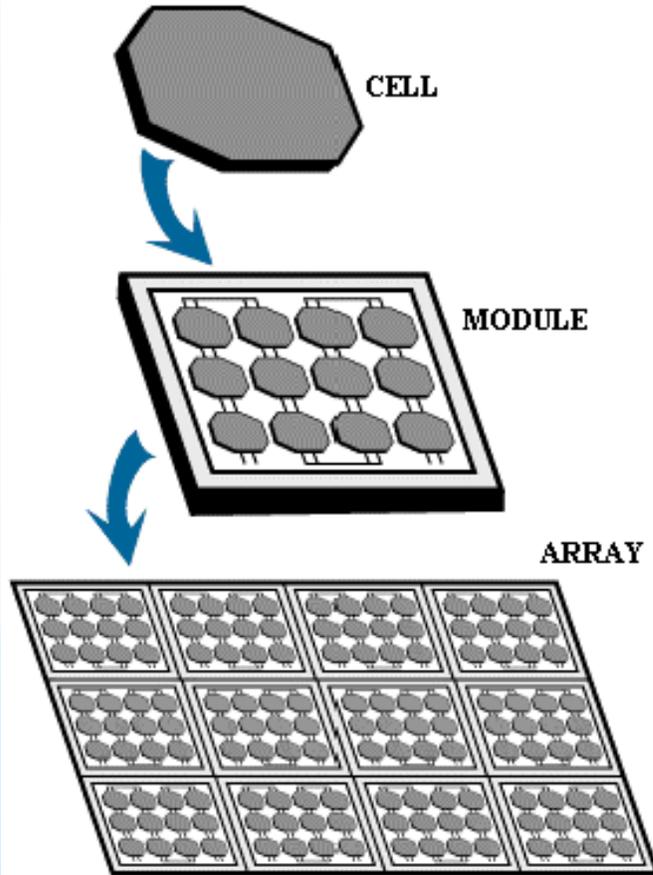
通过**功率控制器(Power
conditioner)**把**直流**转换成家庭可
以使用得**交流**



功率控制器(Power conditioner)



Photovoltaic System Cell-Module-Array-System



六、太阳电池的应用

GW级光伏电站

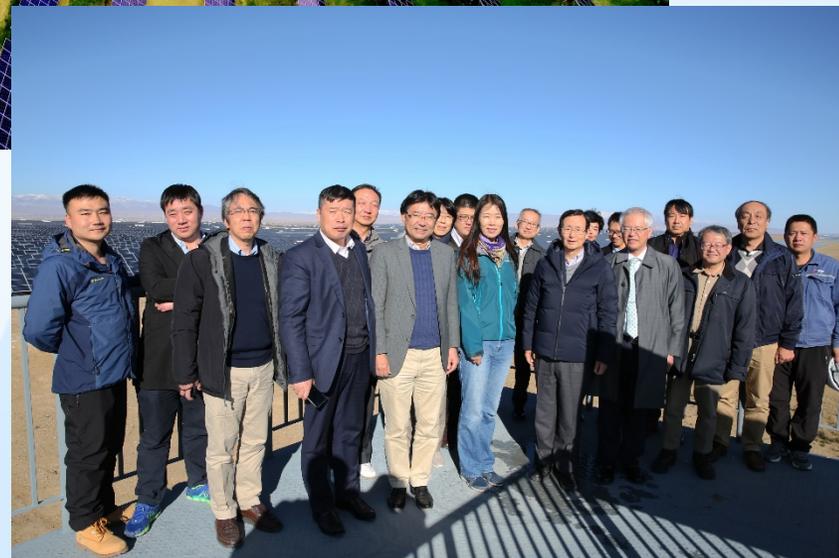
青海省，共和市(DPI Solar)



850MW (2015)



2.5GW (2019)→6.5GW (2020)



富有特色的GW级光伏电站

Panda PV plant



大同熊猫电站鸟瞰图

山西省大同市



大型水上光伏电站



- Module: 150MW, in which 5MW is for test of different modules
- **SIMIT will provide 100kW SHJ module for test.**



安徽省淮南市
三峡新能源



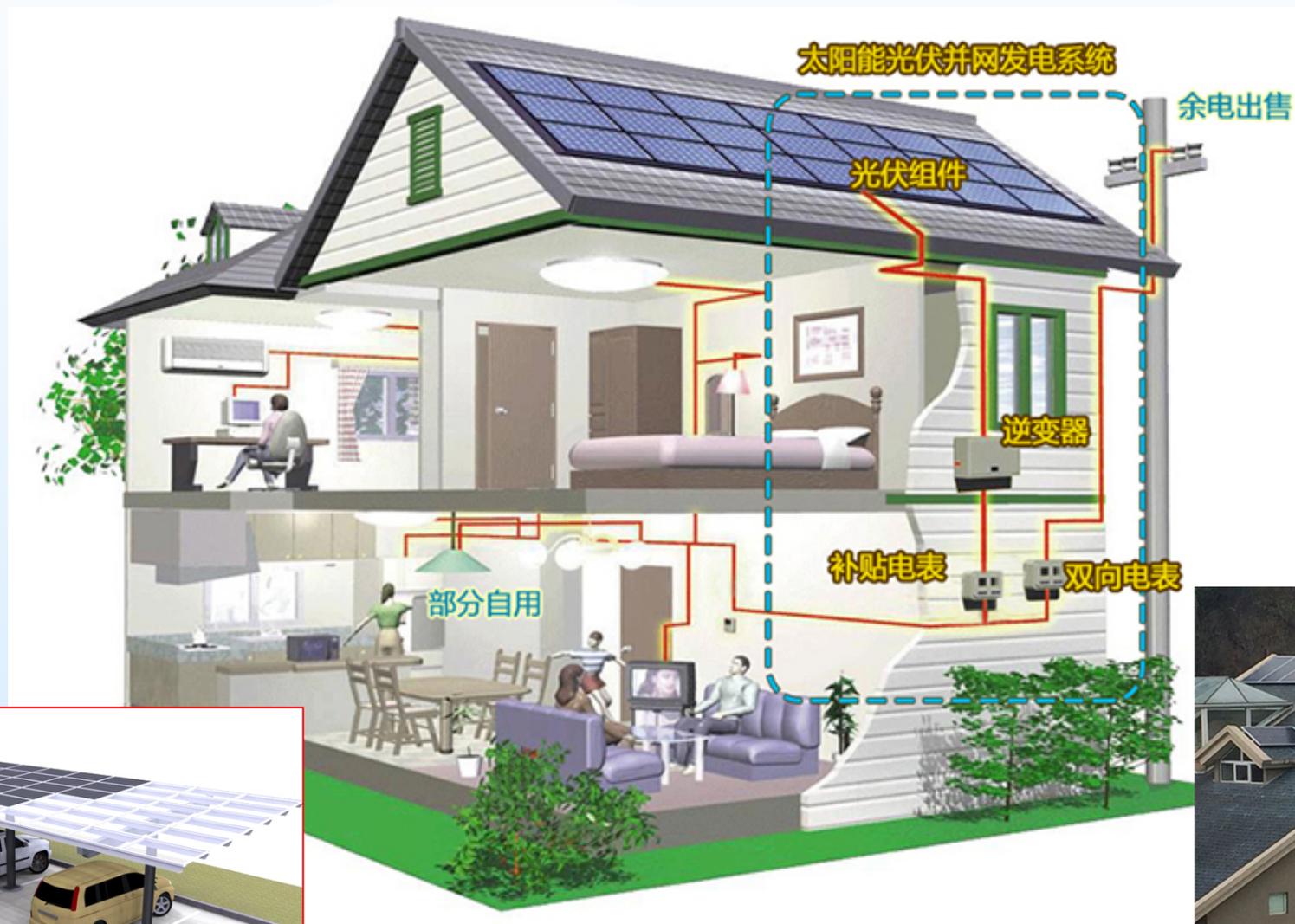
光伏建筑一体化



建筑光伏
BIPV&BAPV



未来的家庭用电模式



南京江宁揽翠山庄
6KW 光伏屋顶电站



光伏停车棚

光伏技术研究所
Photovoltaic Technology Research Institute



江苏中电云商有限公司

车载光伏 (Vehicle integrated PV: VIPV)



PV car
(Hanergy)

PV on electrical bus (SIMIT flexible PV)



PV on electrical micro bus



车载、船载光伏



太阳能车拉力赛



星球太阳能号

完全以太阳能为动力，是目前世界上最大的太阳能船。

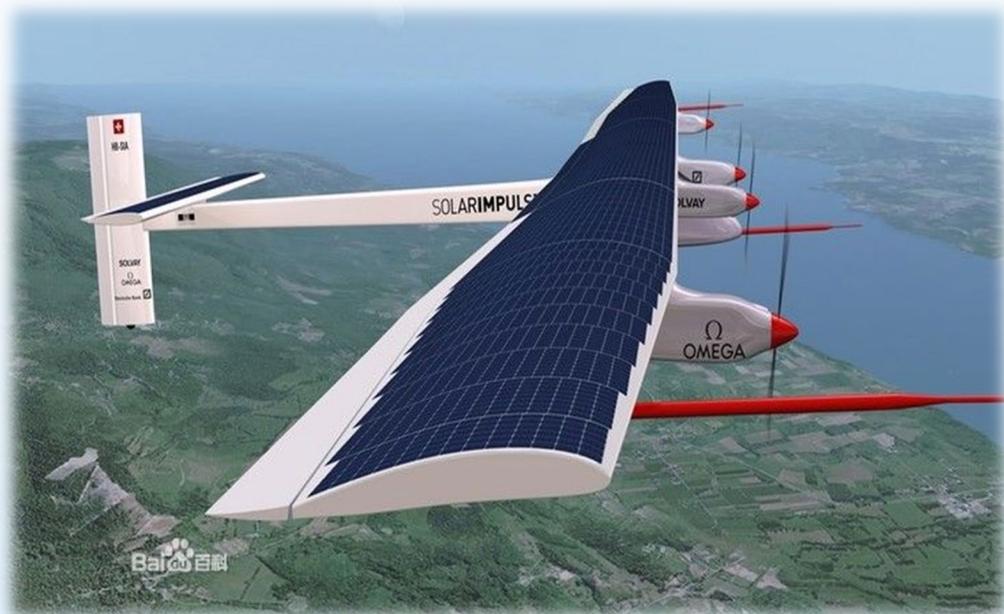
—— 来自瑞士



家用太阳能车



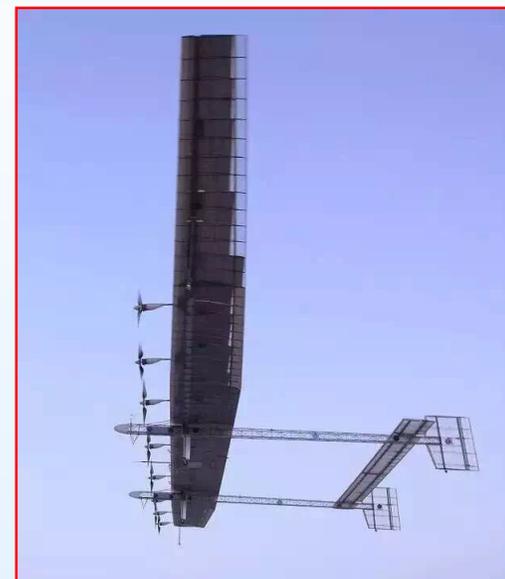
太阳能飞机、飞艇



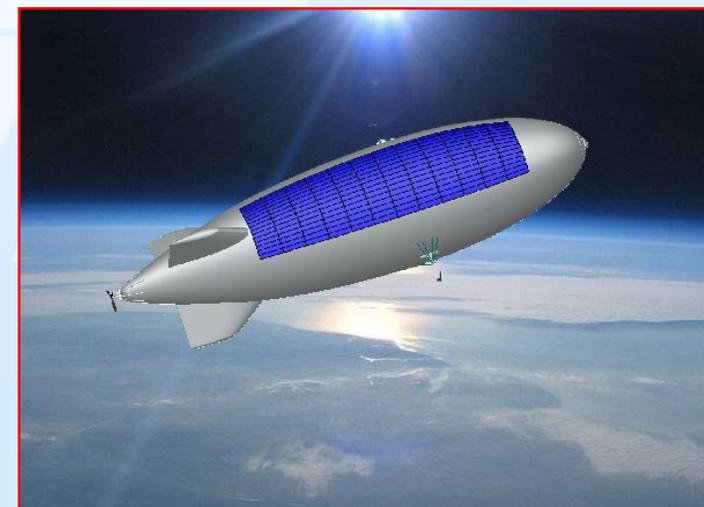
太阳动力号 Solar Impulse -- 来自瑞士



我国首架太阳能无人机：彩虹T4



2013年7月6日，首次横穿美国



太阳能飞艇

各种光伏应用 (PV sharing)



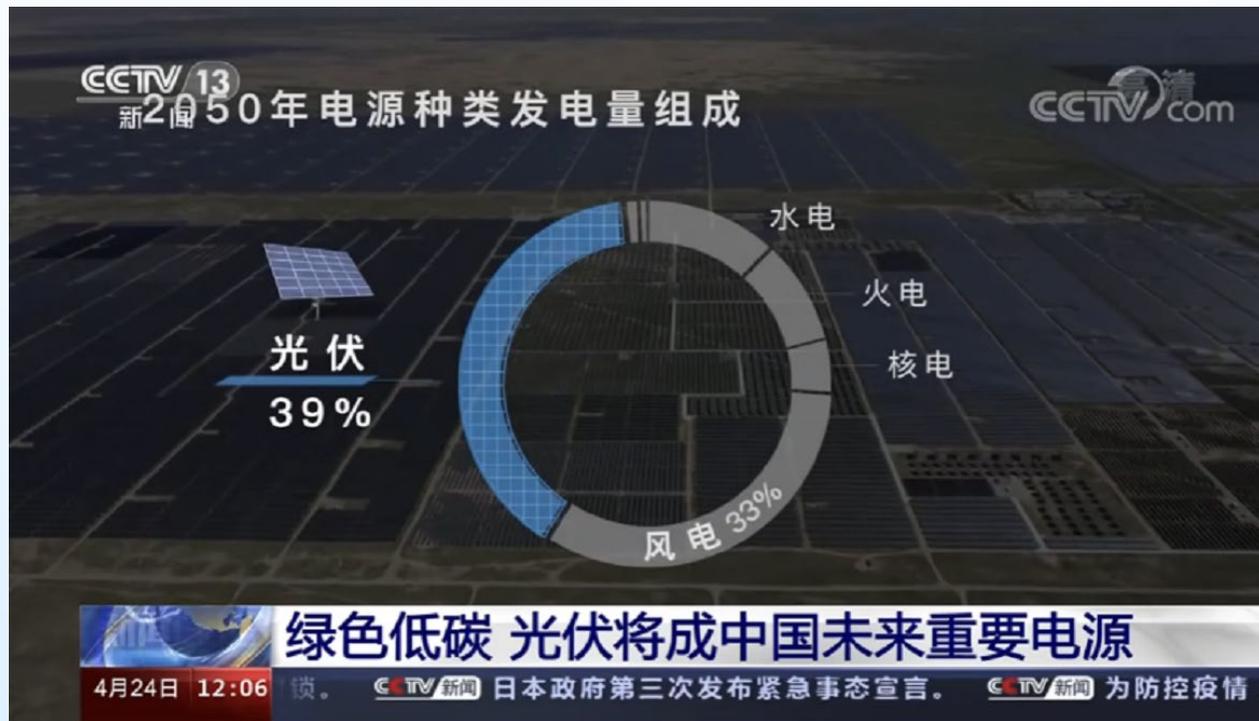
生活中的光伏



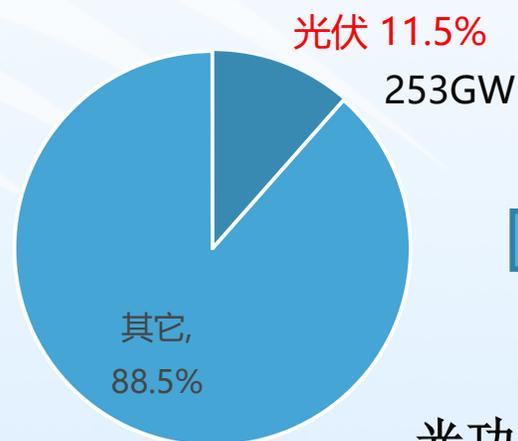
七、太阳电池的未来发展趋势



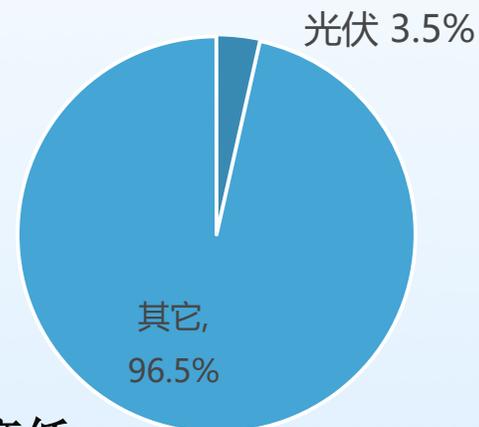
光伏的发展趋势



光伏装机占比



光伏发电占比



光功率密度低

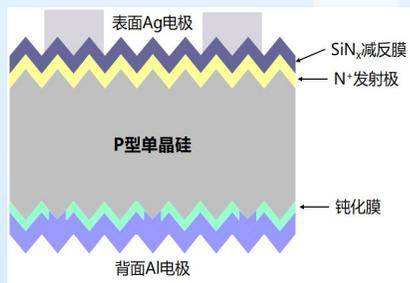
- 更高转换效率的太阳电池及光伏组件技术
- 更高发电量的太阳电池及光伏组件技术

光伏产业的发展趋势

现有产业主流技术

p型单晶

单晶PERC:
~23%

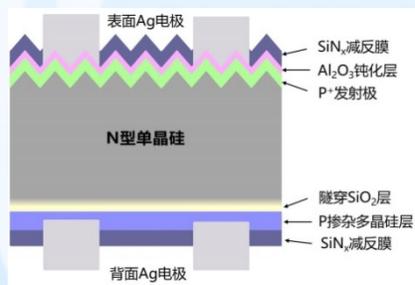


产能: >200GW
市场占有率: >90%

正在导入生产的新技术

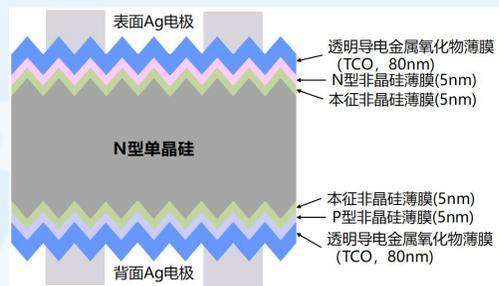
n型单晶

隧穿接触钝化TOPCon:
>24%



产能: >50GW

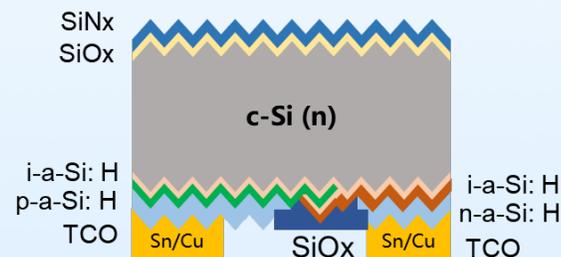
硅异质结HJT:
>25%



产能: >10GW

研发中的新技术

全背接触钝化太阳电池
HBC/TBC/HPBC: >26%



研发中

构建稳定可靠的可再生能源体系

源网荷储一体化多能互补，提升可再生能源消纳能力

风光储一体化：探索增量

风光水（储）一体化：稳妥推进增量

风光火（储）一体化：严控增量

存量——积极实施：风光水火储提升

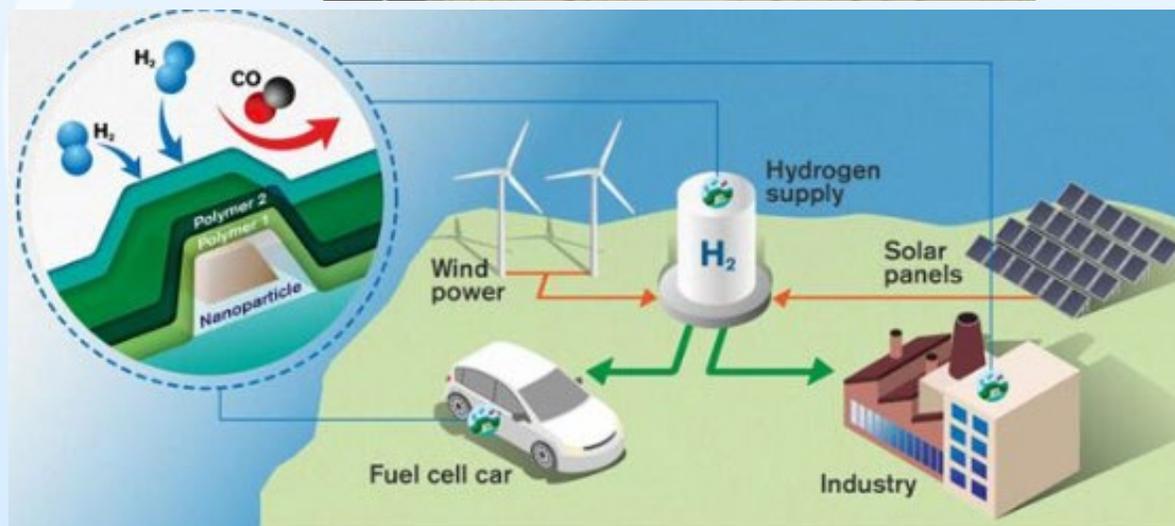


光伏+光热

光伏治沙

可再生能源+储能

可再生能源+氢能



面向碳达峰碳中和的太阳能光伏技术研究开发

高效率低成本晶体硅太阳电池技术

逐步达到晶体硅太阳
电池的理论转换极限



钙钛矿、有机薄膜新型太阳电池技术

Q&A

SIMIT

