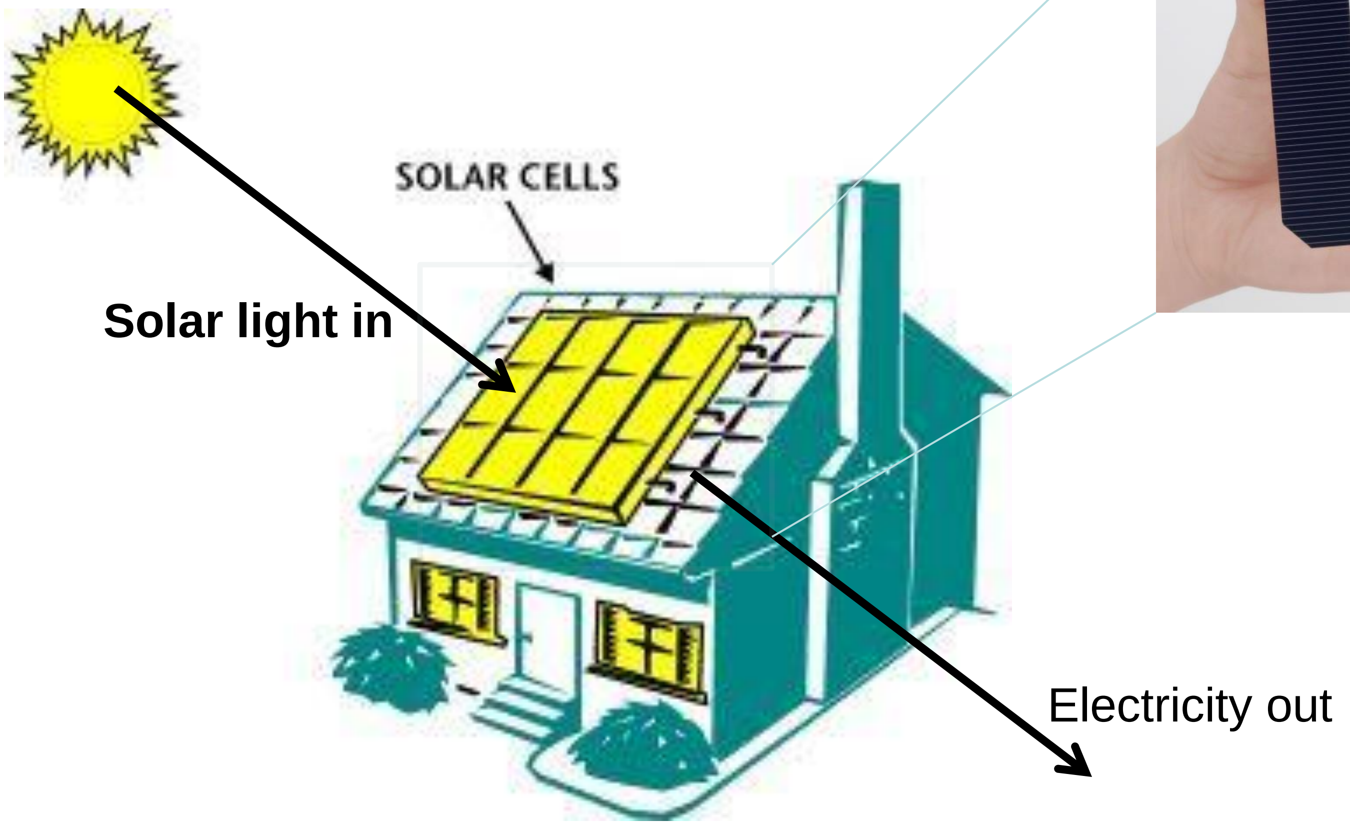
能源科技與環境概論

太陽能電池導論

Hsing-Yu Tuan（段興宇）

Department of Chemical Engineering, National Tsing-Hua University

Solar cells

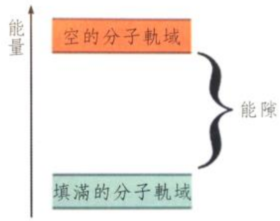


Energy conversion of light

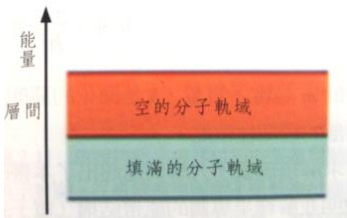
- $E(energy; J\ or\ eV) = \dfrac{h(Planck\ constant) * c(light\ speed)}{\lambda\ (wavelength)}$
- $E = \dfrac{p^2}{2m}$
- $\lambda = \dfrac{hc}{E} = \dfrac{1240\ eV\ nm}{E\ (eV)}$
- $p(momentum) = hk$(wave factor)

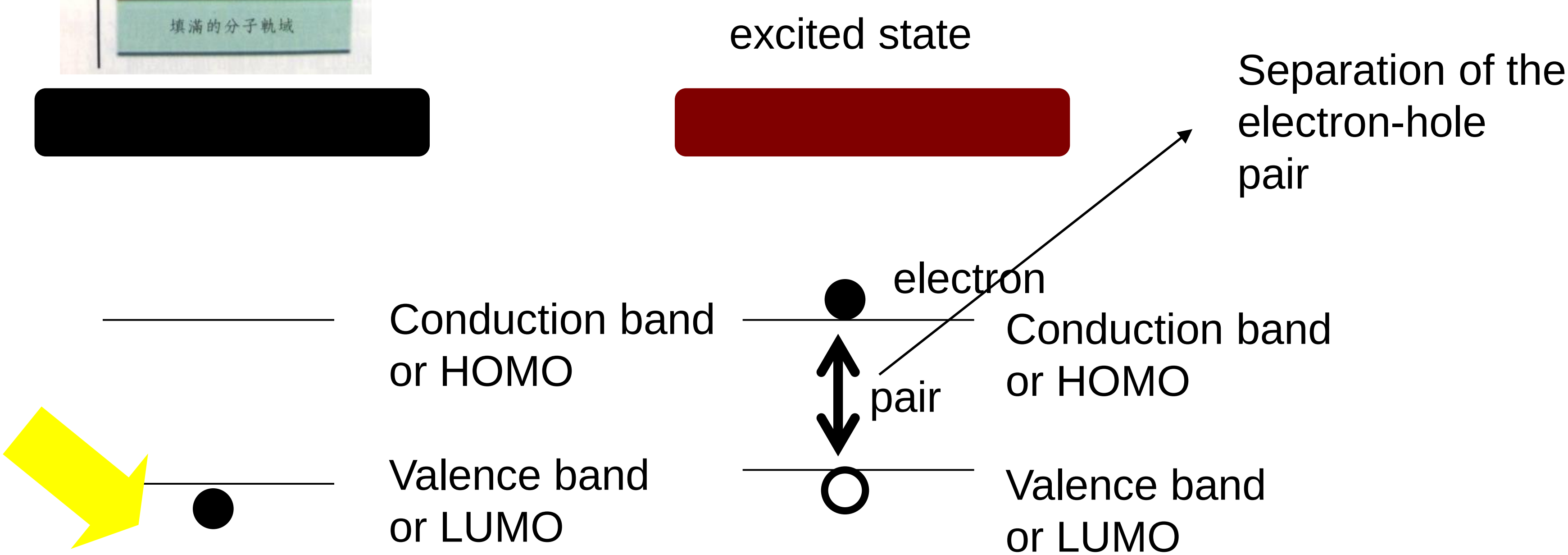
A light with a wavelength of 1100 nm corresponds to 1.12 eV


Generate electrons from materials by photons



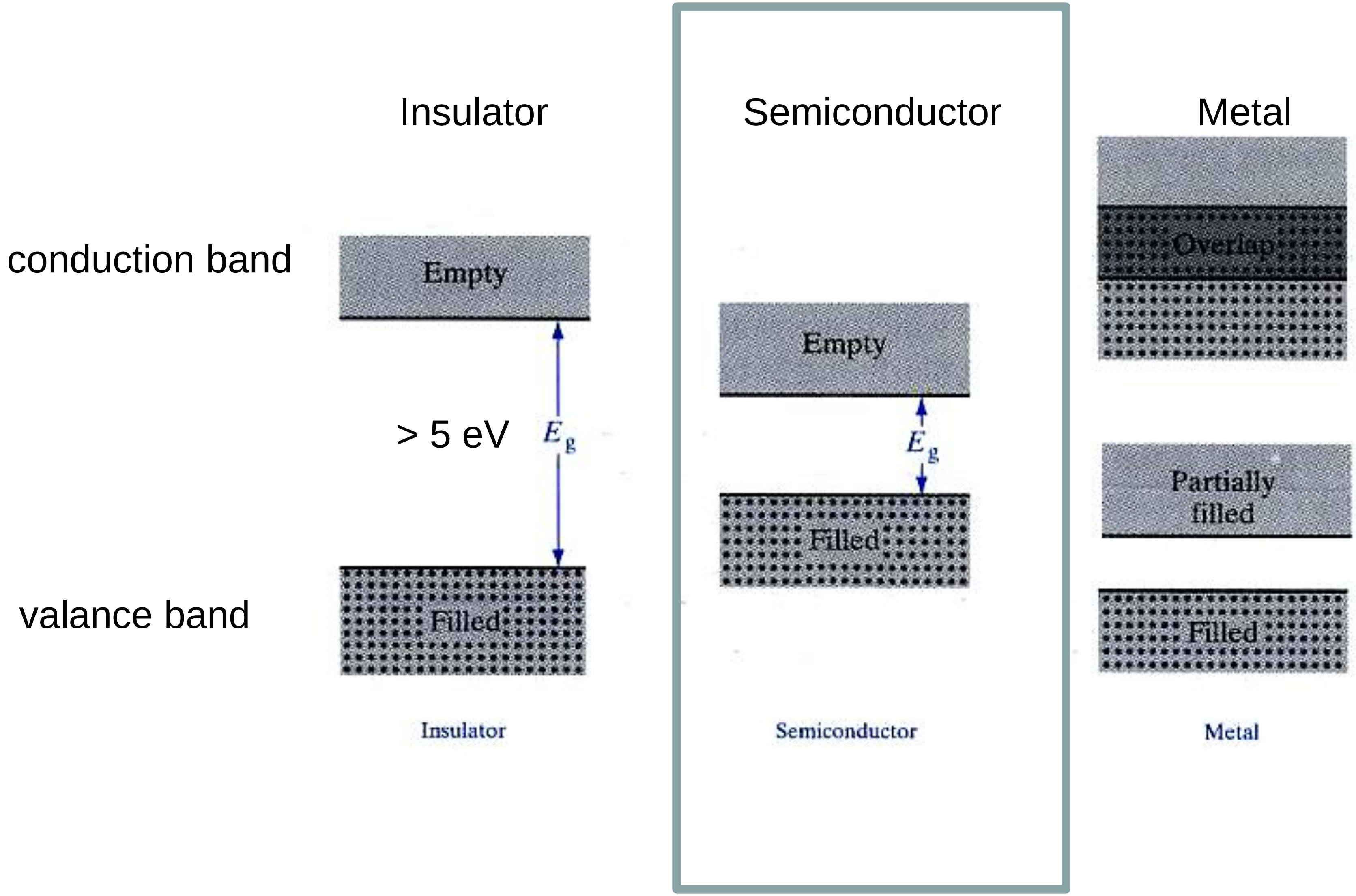
(b)





So, materials used for solar cell application need to have discrete energy gap for photogeneration of electron-hole pair

Inorganic materials: Insulator, semiconductor and metal



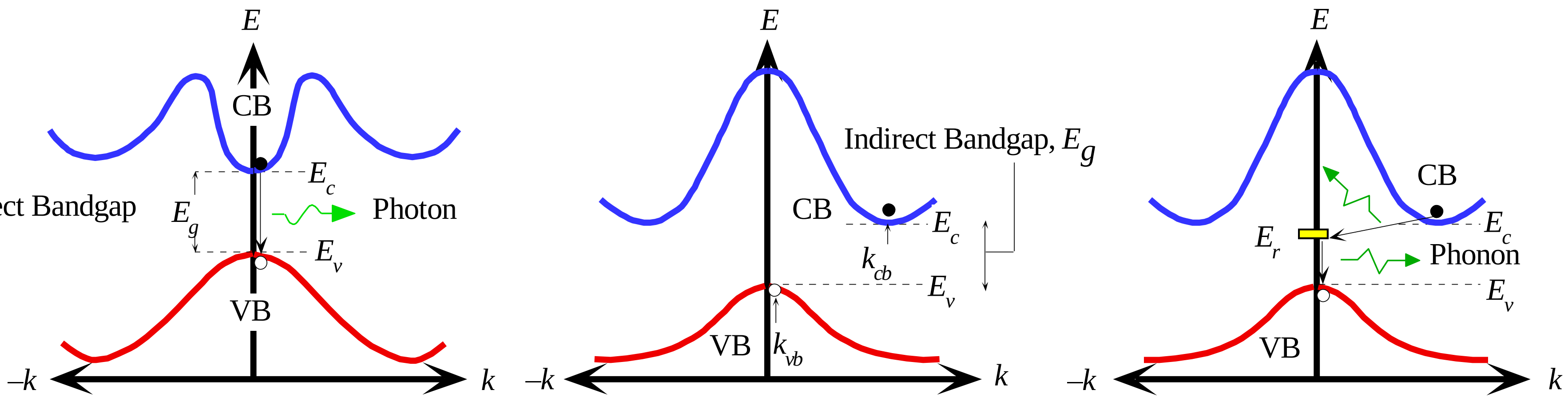
Streetman p62

Pick right materials as absorption layer

- Good absorption coefficient to harvest light
- Suitable band gap

Direct band gap and indirect band gap struct

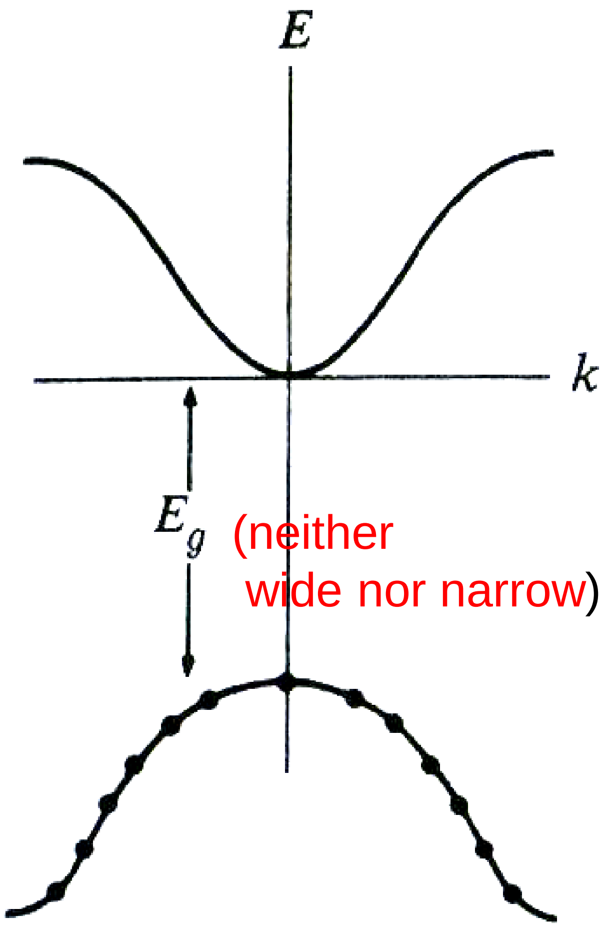
-We prefer direct semiconductor materials
since they can absorb light more efficiently



(a) GaAs (b) Si (c) Si with a recombination center

(a) In GaAs the minimum of the CB is directly above the maximum of the VB. GaAs is therefore a direct bandgap semiconductor. (b) In Si, the minimum of the CB is displaced from the maximum of the VB and Si is an indirect bandgap semiconductor. (c) Recombination of an electron and a hole in Si involves a recombination center .

Pick suitable Eg (eV)



Theoretical maximum efficiency of a semiconductor

$$\eta_{\max}(E_g) = \frac{E_g I_{inc}}{P_{inc}} = \frac{E_g \cdot \int_{\lambda<\lambda_G} S(\lambda)d\lambda}{\int_{\lambda<\lambda_G} \frac{hc}{\lambda} S(\lambda)d\lambda}$$

$S(\lambda)$ =# of photons/area*time

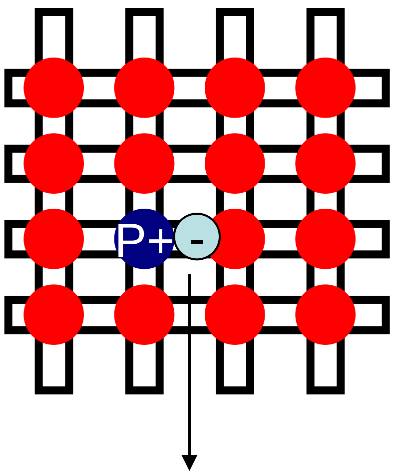
-bandgap of semiconductor should not be wide in order to get higher $\int_{\lambda<\lambda_G} S(\lambda)d\lambda$

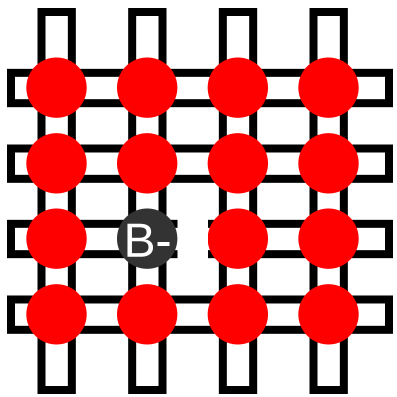
-Electrons in the valence band can absorb energy of Eg, 2 Eg, 3Eg, but the excess energy can not be transformed to electric energy but transform to heat → need higher Eg

-very narrow band gap material can absorb most wavelength from sun, but transformed energy is small.

Doping of Si: increase the conductivity of intrinsic Si

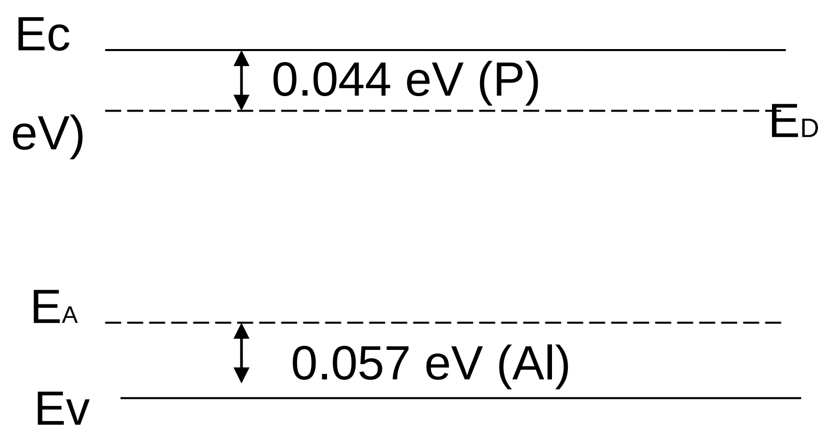
Donors: P, As, Sb (Column V elements) , n-type, → provide one additional electron
Acceptors: B, Ga, In, (Column III elements), p-type→ provide one additional hole





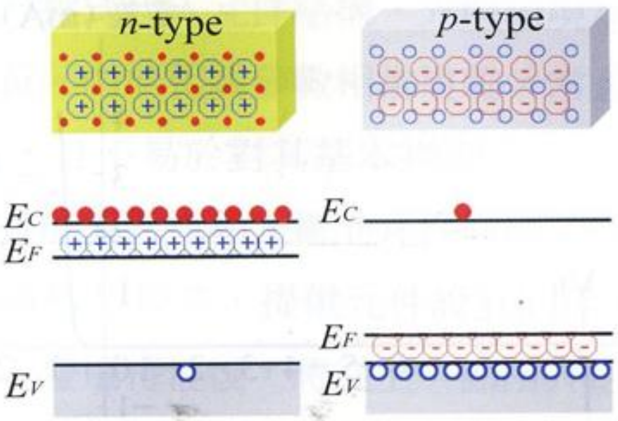
Donors	E_B	Acceptors	E_B
Sb	0.039 eV	B	0.045 eV
P	0.044 eV	Al	0.057 eV
As	0.049 eV	Ga	0.065 eV
		In	0.16 eV

-weakly bound
-bonding strength E_B~ 0.05 eV (Si bonding ~1.12 eV)

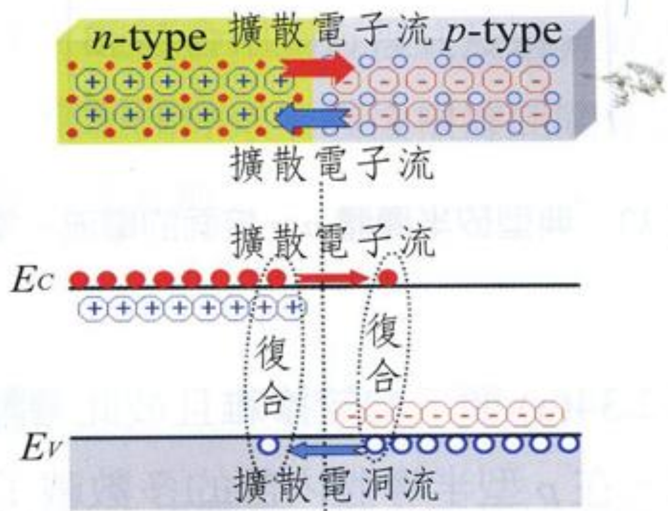


Majority carrier - electron in a n-type material
hole in a p-type material
Minority carrier – hole in a n-type material
electron in a p-type material

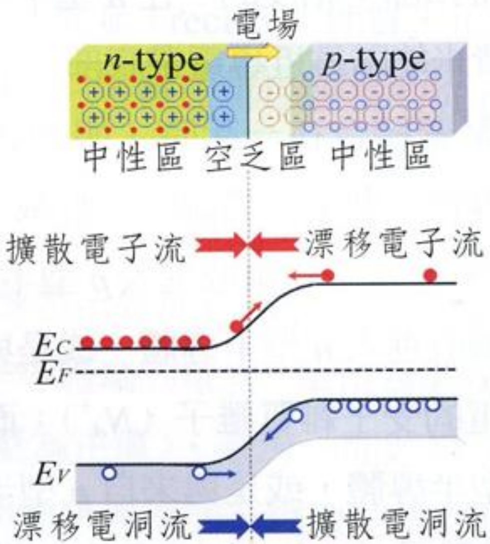
P-N junction



(a)



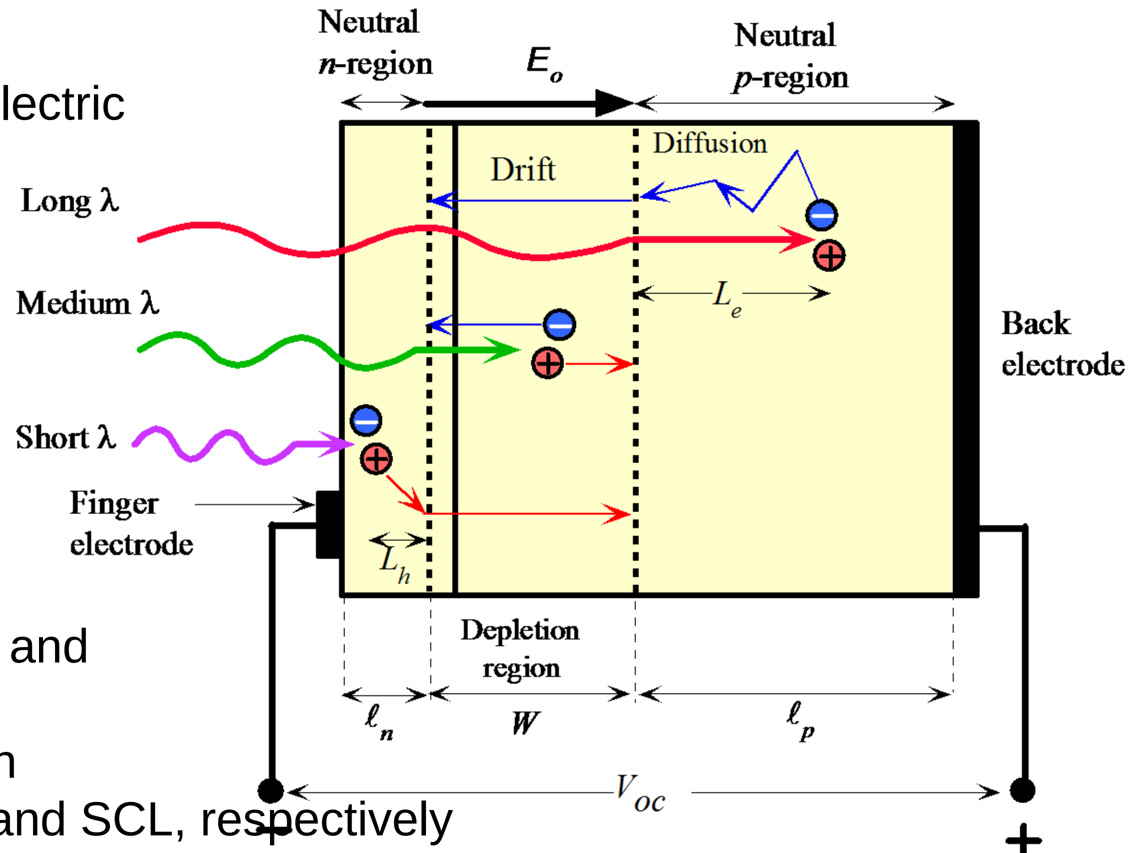
(b)



(c)

A PN junction photovoltaic device

PN junction provide a Depletion region in where an electric field is created for drifting electron and hole



-incoming photon generate EHPs and create current

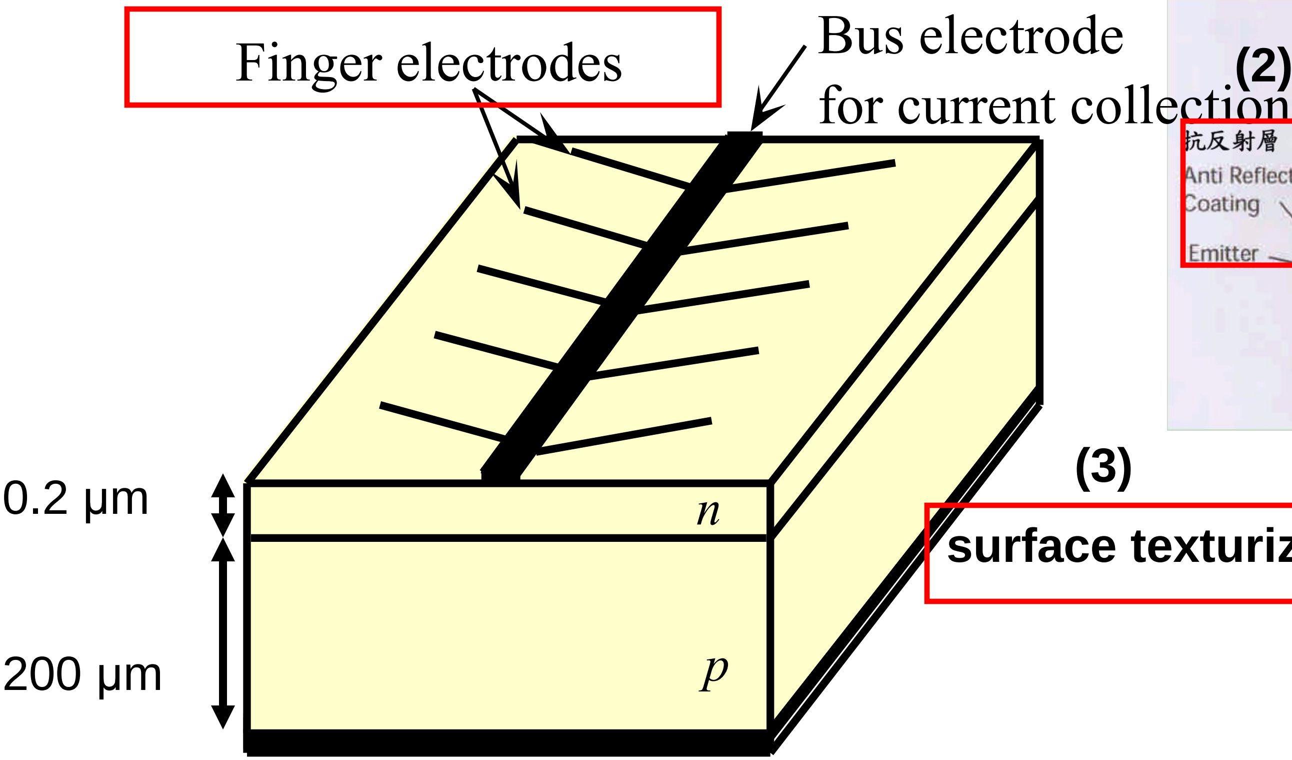
-generated electrons and hole can diffuse and drift in neural region and SCL, respectively

-Opencircuit voltage (Voc) develops between the terminals of the device because the electrion reaches the neutral n and p, respectively.

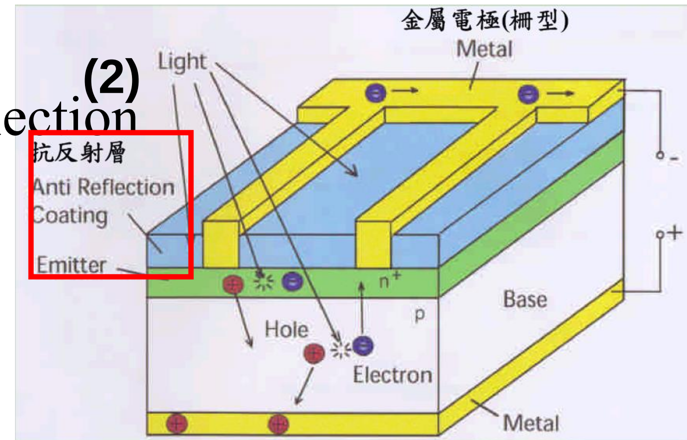
The principle of operation of the solar cell (exaggerated features to highlight principles)

Device structure of a Si solar cell

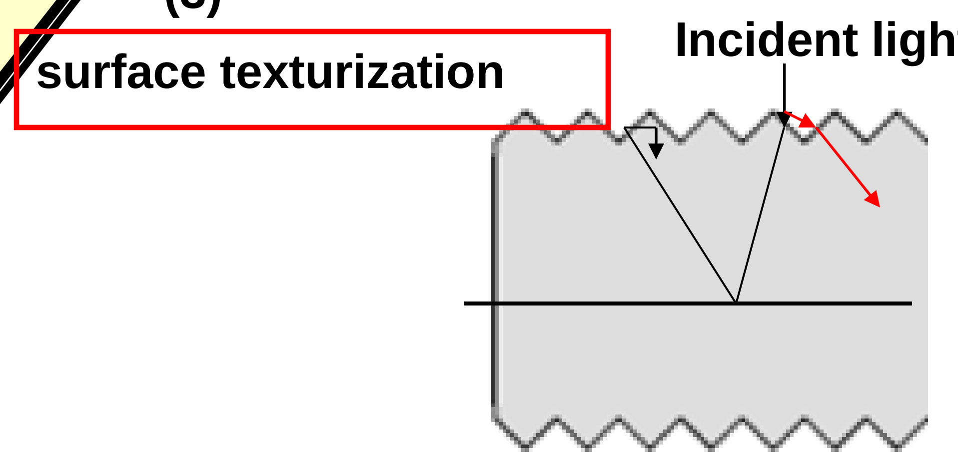
(1)



(2)



(3)



In order to capture more light

- finger electrodes were made to allow light pass through the device
- a thin antireflection coating on the surface reduces light reflection and allow more lighte to enter the device

-surface texturization to for multiple light reflection and increase light path

Schematic of a semocnoductor solar cell

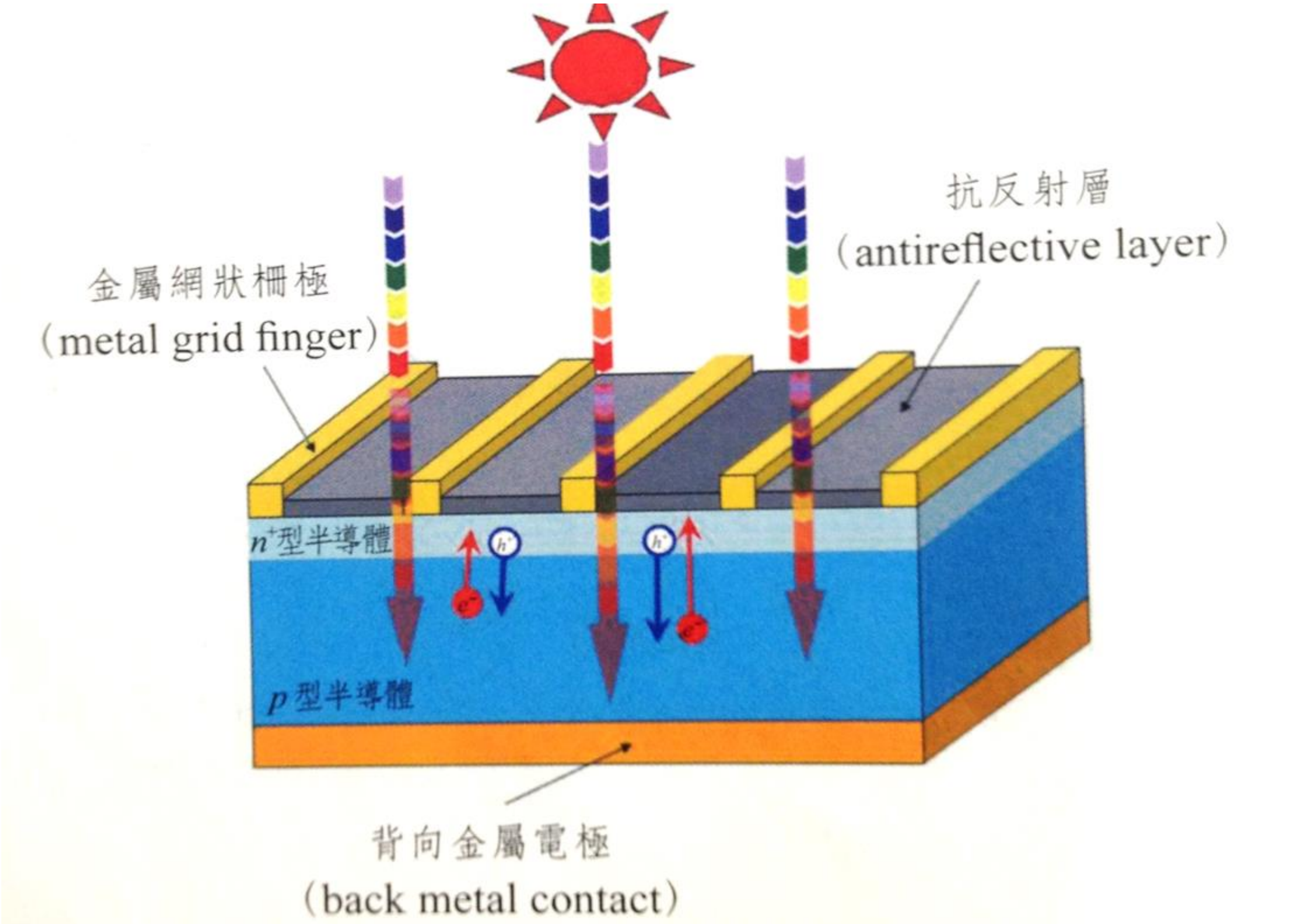
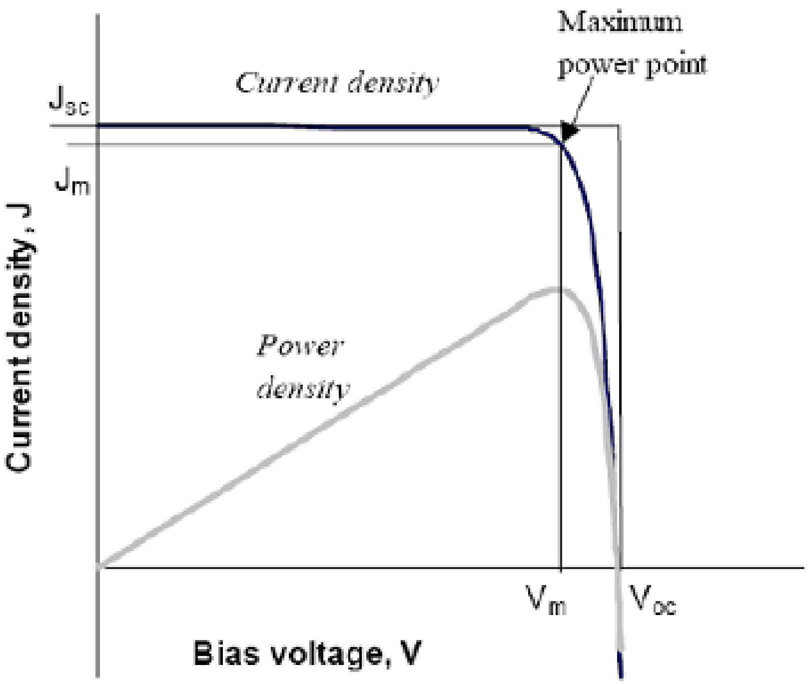


圖 2.1　半導體太陽電池結構示意圖

IV curve of a solar cell



$$\eta = \frac{Maximum \quad PV \quad output \quad power(P_{mp})}{Incident \quad solar \quad power(P_{in})} \times 100\%$$

$$= \frac{V_{mp} \times J_{mp}}{P_{in}} \times 100\%$$

$$= \frac{V_{oc} \times J_{sc}}{P_{in}} \times \frac{V_{mp} \times J_{mp}}{V_{oc} \times J_{sc}} \times 100\%$$

$$= V_{oc} \times J_{sc} \times FF / P_{in} \times 100\%$$

$$P_{mp} = J_{mp} \times V_{mp}; FF = \frac{J_{mp} \times V_{mp}}{J_{sc} \times V_{oc}}$$

Voc (open circuit voltage)

-when output current approaches zero,
the voltage develops between two terminals
ideally Voc~Eg at 0K and inverse proportional
to temperature

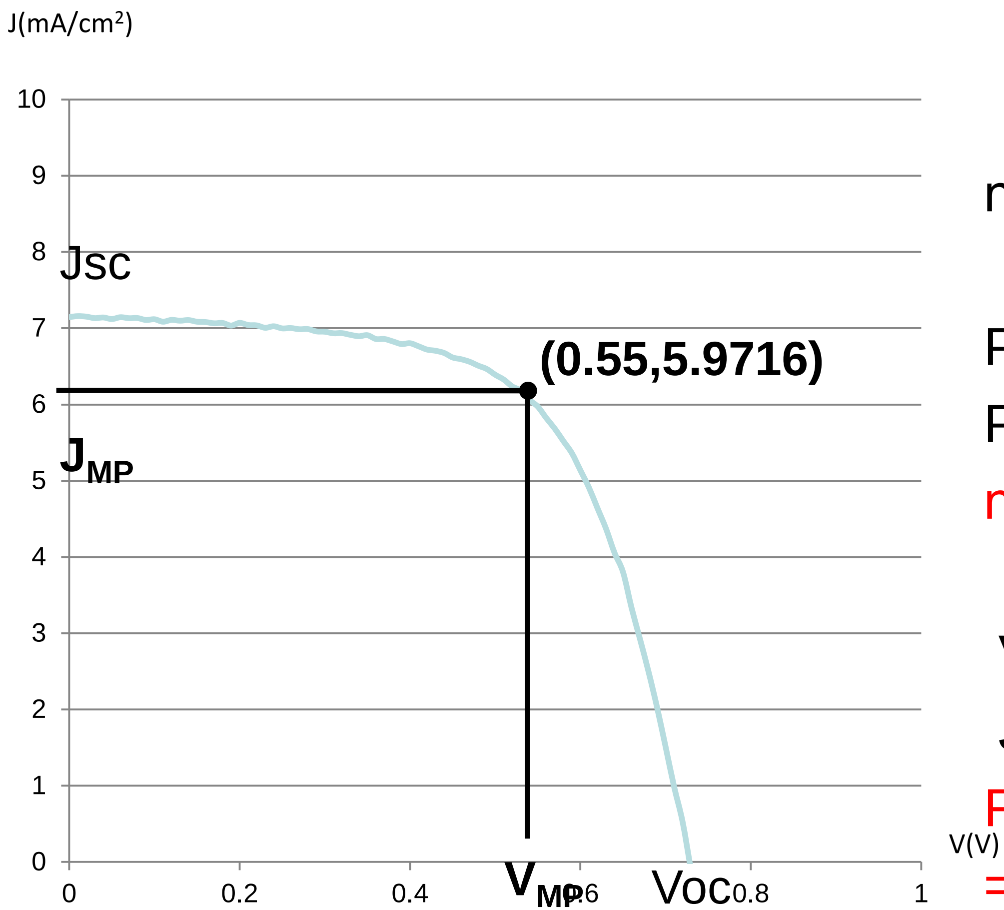
Jsc (short-circuit current)

-like the device connect the device with metal
close to photogenerated current

FF (fill factor): We want FF close to 1

η : Efficiency
Voc : Open Circuit Voltage
Jsc : Short Circuit Current Density
F.F. : Fill Factor
Pin : incident solar power (1000W/m^2 or 100mW/cm^2)

Solar cell efficiency :an example



η and FF in this device ?

$\eta = P_{MP} / P_{in}$ x100%$= FF * V_{oc} J_{sc} / P_{in}$ x100%

（輸出電功率/入射光功率)

P_{in} =100 mW/cm^2

$P_{MP} = V_{MP} * J_{MP}$ =0.55*5.9716=3.28mW/c

η =3.28/100*100%=3.28%

V_{oc}=0.72 V

J_{sc}=7.1464 mA/cm^2

$FF = V_{MP} * J_{MP} / V_{oc} * J_{sc}$

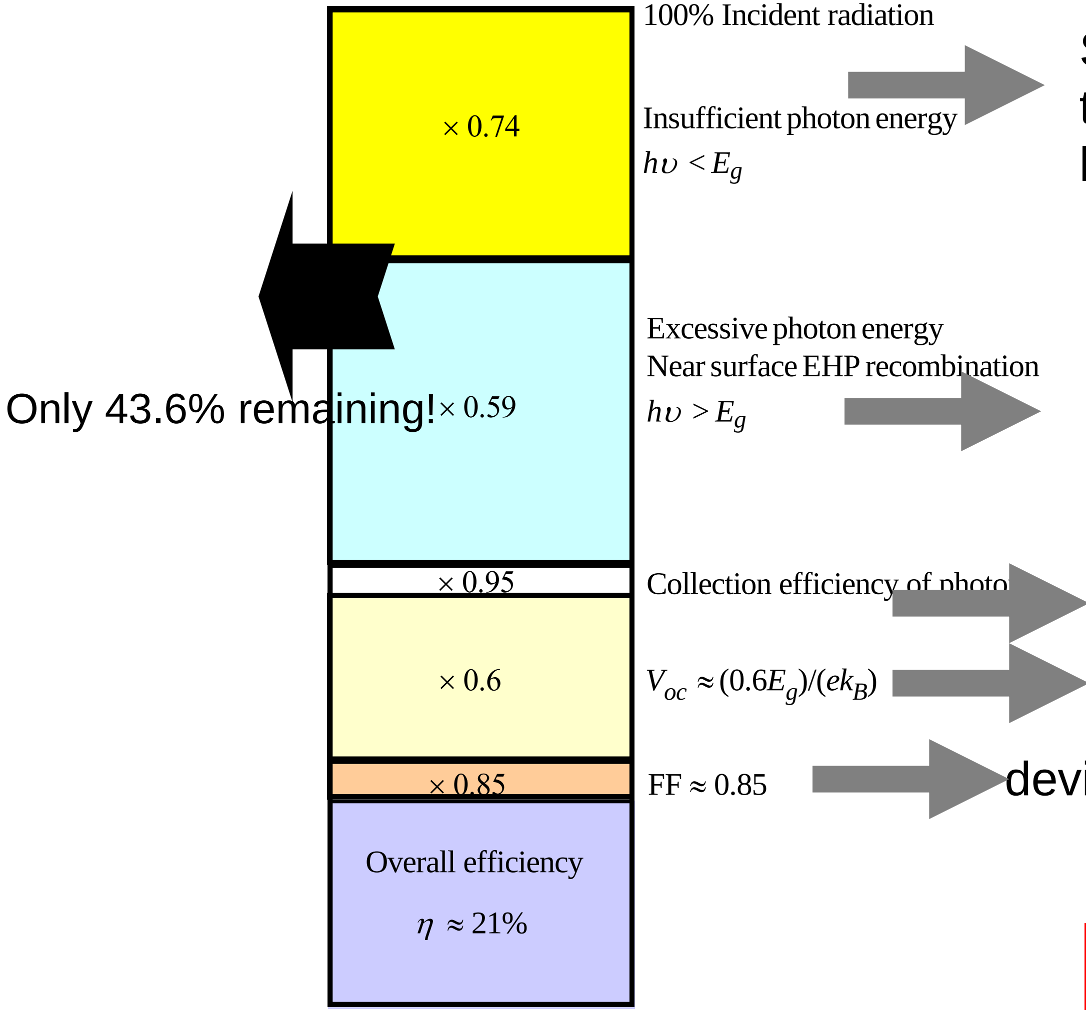
=3.28/(0.72*7.14)=0.63

Voc: 開路電壓 (open circuit voltage), 當輸出電流趨近於零，相對太陽電池兩電極端點沒有連接所得到的電壓

Jsc:短路電流(short circuit current)

如將照光的pn二極體兩端的金屬電極用金屬線連接, 造成短路, 此短路電流等於光電流

Various losses of solar energy of a Si solar cell during processing



Silicon band gap is 1.1 eV, and the device loses all photon energy less than 1.1 eV

Excessive photon energy
Near surface EHP recombination

Antireflection coating is not perfect

Voc is inverse proportional to temperature, so not equals to Eg

device fabrication resistance

Accounting for various losses of energy in a high efficiency Si solar cell. Adapted from C. Hu and R. M. White, *Solar Cells* (McGraw-Hill Inc, New York, 1983, Figure 3.17, p. 61).

The highest efficient of a real photovoltaic device that uses a single crystal of Si
Is about 24.7% (澳洲新南威爾斯大學）

Single/poly crystalline Si solar cell fabrication process

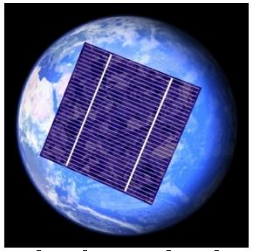
Process Introduction P-type ingot was cut

Damage Etch etch in a strong acidic or alkaline solution

Texturing etch in a weak acidic or alkaline solution

P-doping liquid glass containing P is distributed on one side of the wafer by spraying or spinningand heated

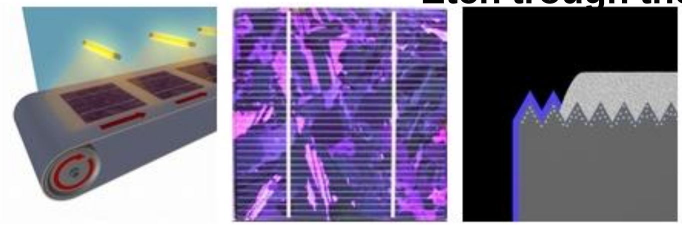
Emitter Diffusion (the wafer are placed in a belt furnace And heated about 900 ˚C



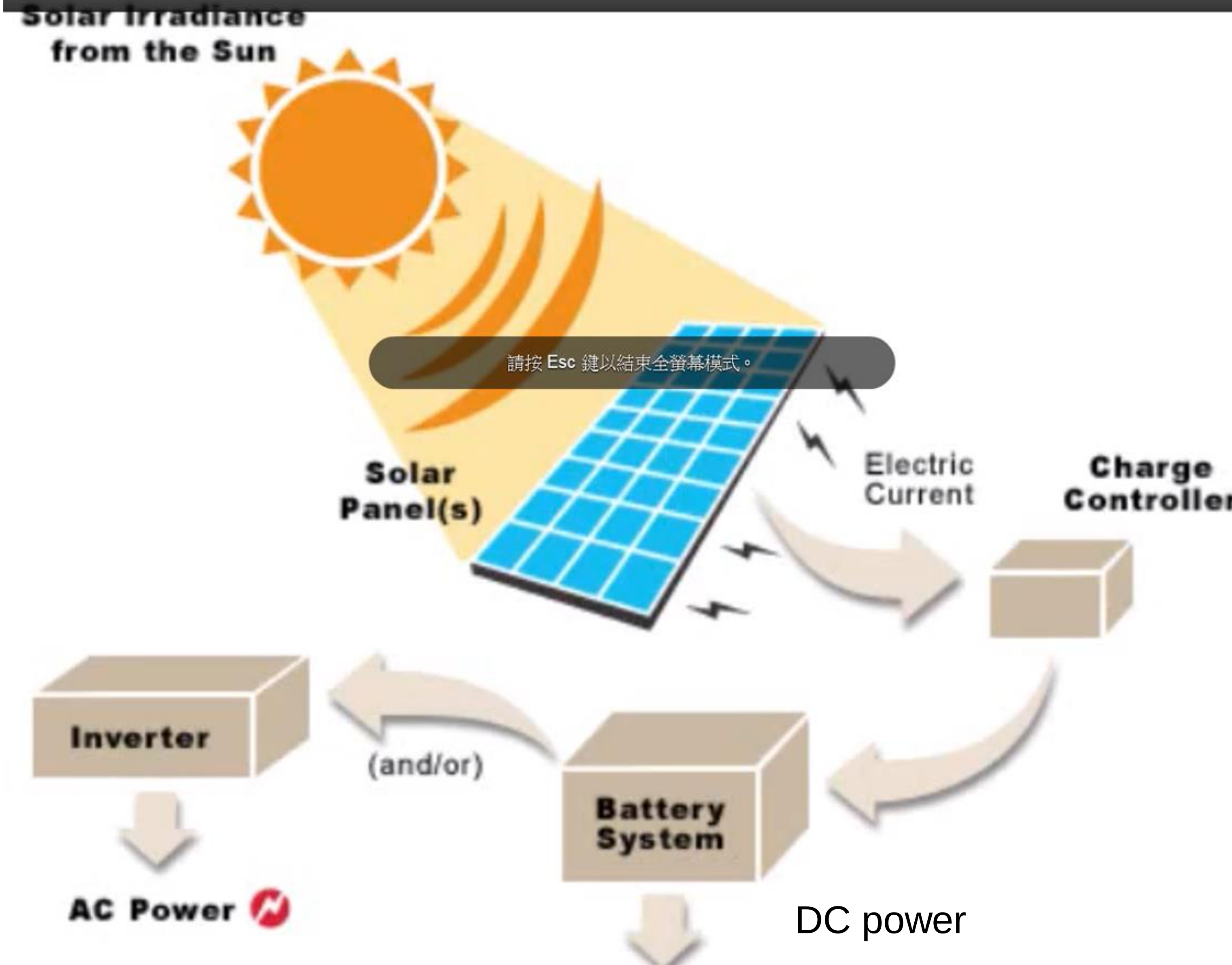
Anti Reflection Coating The reflectivity is still round 30%,H:SiNx is deposited on the cell to reduce more the reflectivity

Contact Formation metal contacts are made by screen printing

Sintering and Firing Metallic contacts are heated and Etch trough the antiflecton coating



Solar cells installation



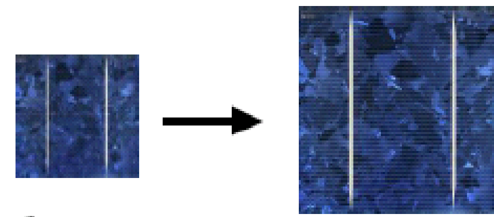
DC power

Next step of crystalline Si solar cell

Vision

Less Si:
thickness from 300 to 150 µm

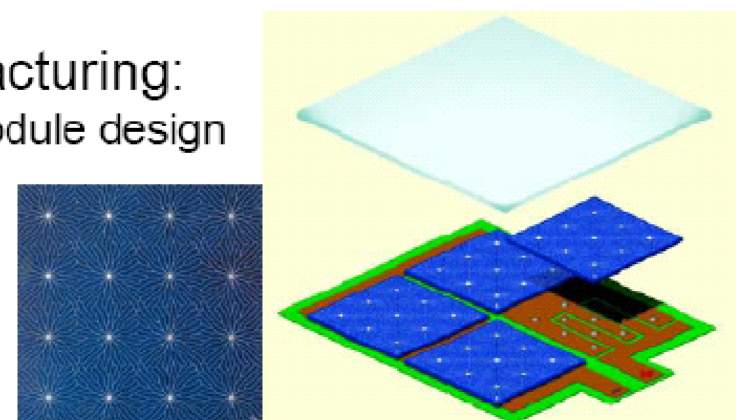
Larger:
from 125 to 210 mm



Cost reduction mc-Si PV technology

Efficiency:
from 15 to 18%

Easy manufacturing:
new cell and module design



貳、發展現況(續)

五、我國太陽光電產業鏈

Industry

Up Stream		Mid Stream	Down Stream	
Poly-Silicon	Ingots/ Wafer	Solar Cell	PV Module	PV System & Installa
Solar Grade Silicon	**Si Ingot & Wafers**	**Wafer-based Solar Cell** －Mono-Si, Multi-Si, GaAs **Thin-film Solar Cell** －a-Si/μ-Si, CIS, －Dye Sensitized Solar Cell **CPV Solar Cell**	**PV Modules**	**Installation** **System Parts** **－Inverter, BOS…** **Equipment** **Product**

Company

Solar Grade Silicon:

福聚太陽能
友達晶材
寶德能源
實聯能源
科冠
山陽科技

6 Companies

歷年廠家數：
2005＝40
2006＝50
2007＝76
2008＝100
2009＝123
2010＞160

Si Ingot & Wafers:

- 中美晶
- 綠能
- 合晶
- 統懋
- 峰毅
- 茂迪
- 旭晶能源
- 晶耀
- 達能
- 國碩
- 昱成光能
- 友達晶材

12 Companies

Solar Cell:

- 矽晶電池：茂迪、益通、旺能、昱晶、新日光、昇陽、茂矽、太陽光電、太極、燿華、長生能源、旭泓、亞崙、尚陽、強茂、樂福、聯景、元晶、英穩達、友達
- 矽薄膜電池：綠能、聯相、富陽、宇通、八陽、旭能
- CIGS電池：綠陽、新能、太陽海、正峰新、亞化、威奈聯合、台積電
- 聚光型電池：全新、華上、禧通、台達電、晶電、宏捷、華旭、億芳、瀚昱、海德威、太聚、綠源、吉泰、亞飛、禾晶
- DSSC：健鼎、福盈、永光、長興、台塑

＞54Companies

PV Modules:

- 頂晶
- 知光
- 英懋達
- 生耀
- 科風
- 茂暘
- 錸德
- 有晴
- 大晶
- 全能
- 安集
- 茂鑫
- 強茂
- 有成
- 綠晁
- 鼎笙

17Companies

PV System & Installation:

Installation：茂迪、台達電、廣運、友達、聯相、宇通、富陽、永盛能源、有成、綠能、大金、東城、冠宇宙、太陽動力、鼎鼎、聚恒、金華成、中國大陸電器、羅森、全面性、伸浦、崇越、統昱、永旭、台邦、傳典、高鋒、華旭環能、工易、耀能、上揚、錸德、光寶綠能、詠通、華城、亞力、駿成、曜晟、寶球、明宜、元太、伸浦、新世紀、金頓、海灣、泰新、安慶、昇暉、雄雞

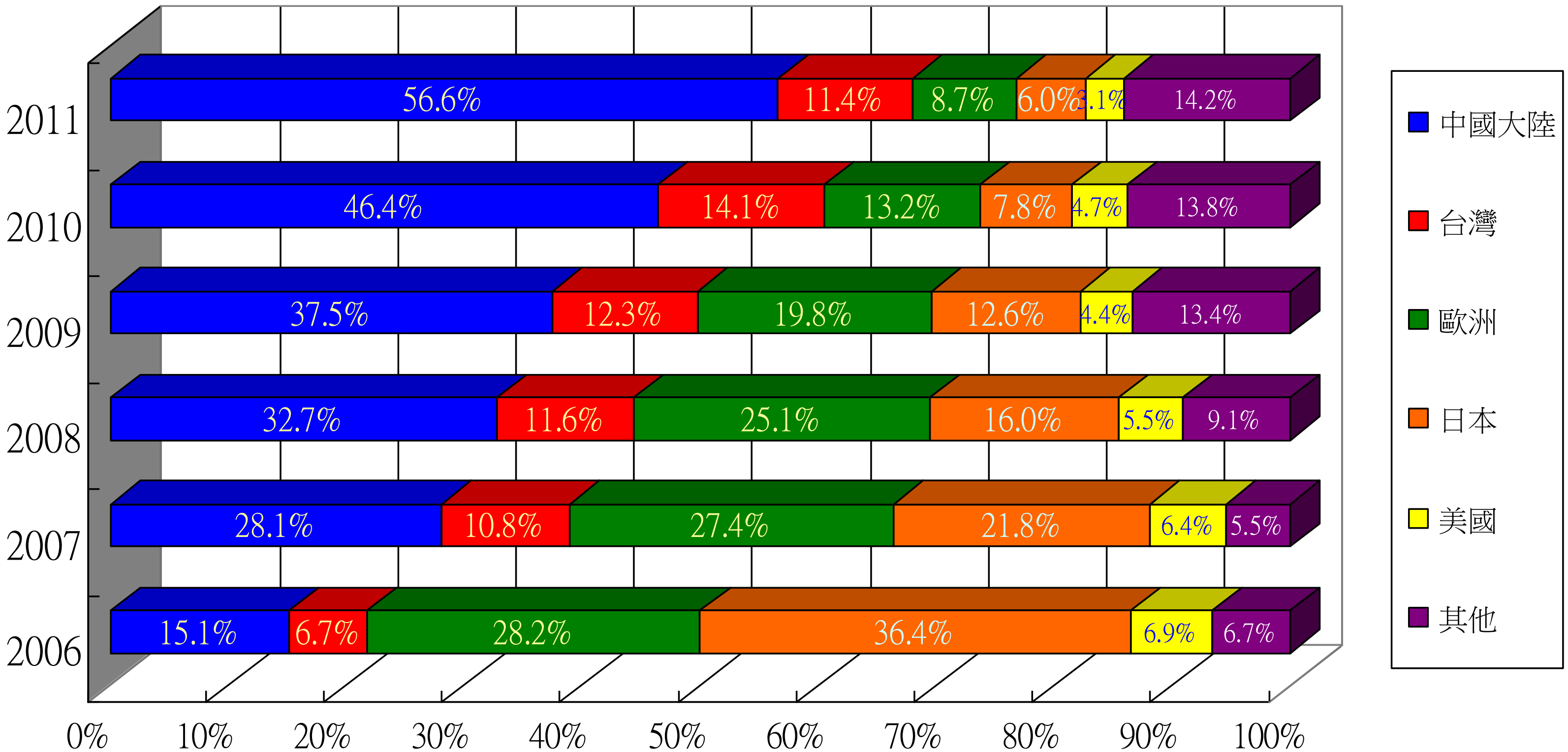
System Parts：台玻、元璋、太美、城東、力鋼、元一、高鋒、法隆、泉鋼、盈正豫順、明碁材料、達方、台虹、碩禾、致嘉、台塑、暘益、台聚、新輝、昇貿、宏致、泰和、建和興、科宥

Equipment：均豪、廣運、欽揚、東遠、志聖、帆宣、北儒、翔勝、致茂、綠色

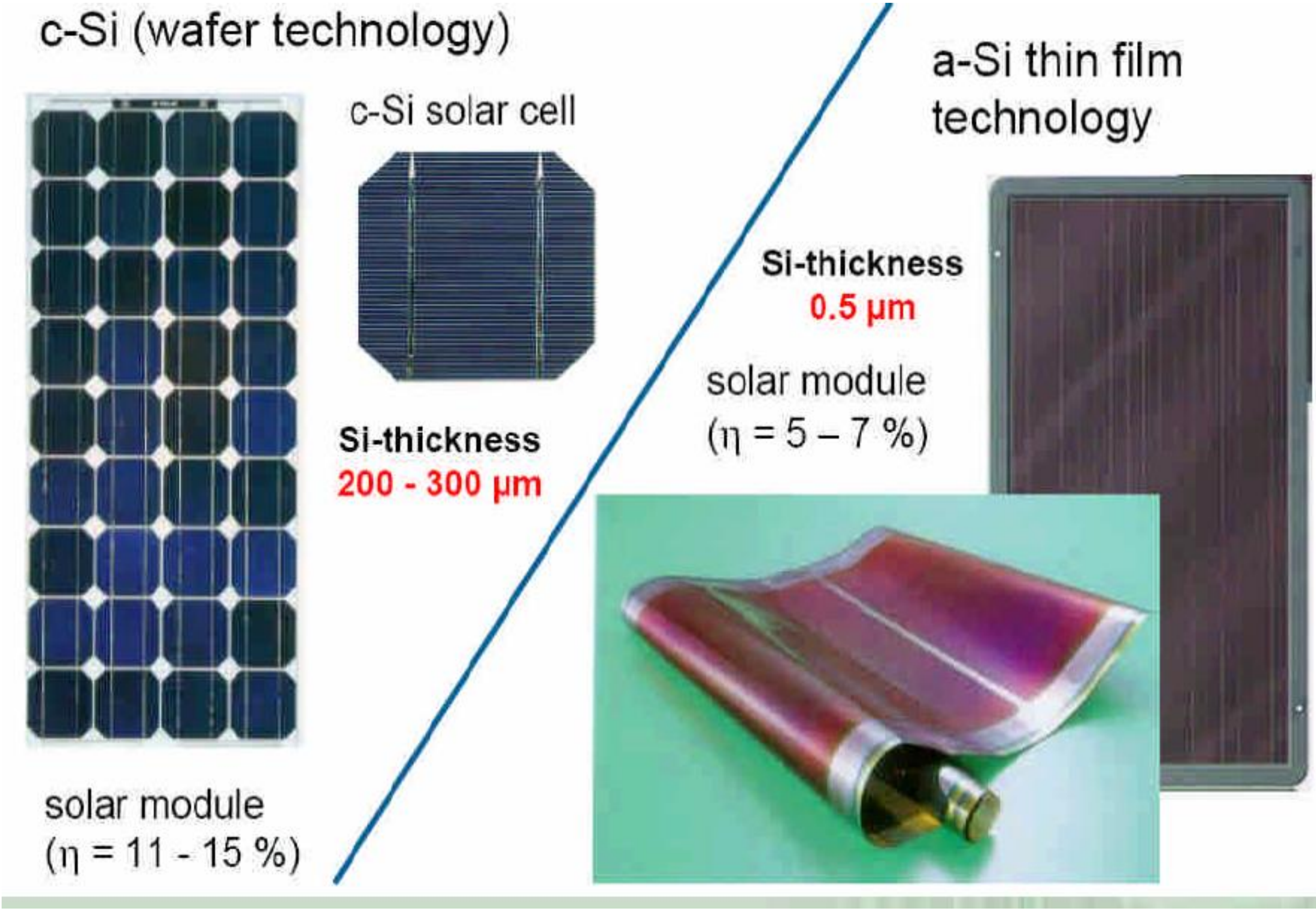
Product：亞通、東城、強而青、鯨威、日光能、茂迪、中國大陸電器、同昱、旭辰、旭邦、科宥、信合、千附、永炬、日曜、宇能、智柏、登陽 、誼成、森富國際、

>100 Companies

- 歐洲與日本之電池產量由**2006**年市占率約**30%**下降至**2011**年的**10%**以下。
- 太陽光電生產基地持續向亞洲移動趨勢不變，中國大陸與臺灣生產比例近全球**70%**。
- 大陸挾其成本優勢與政策支持，成為全球最大製造國，**2011**年產值達**2536**億元人民幣。



Thin film solar cell: use Si as an example

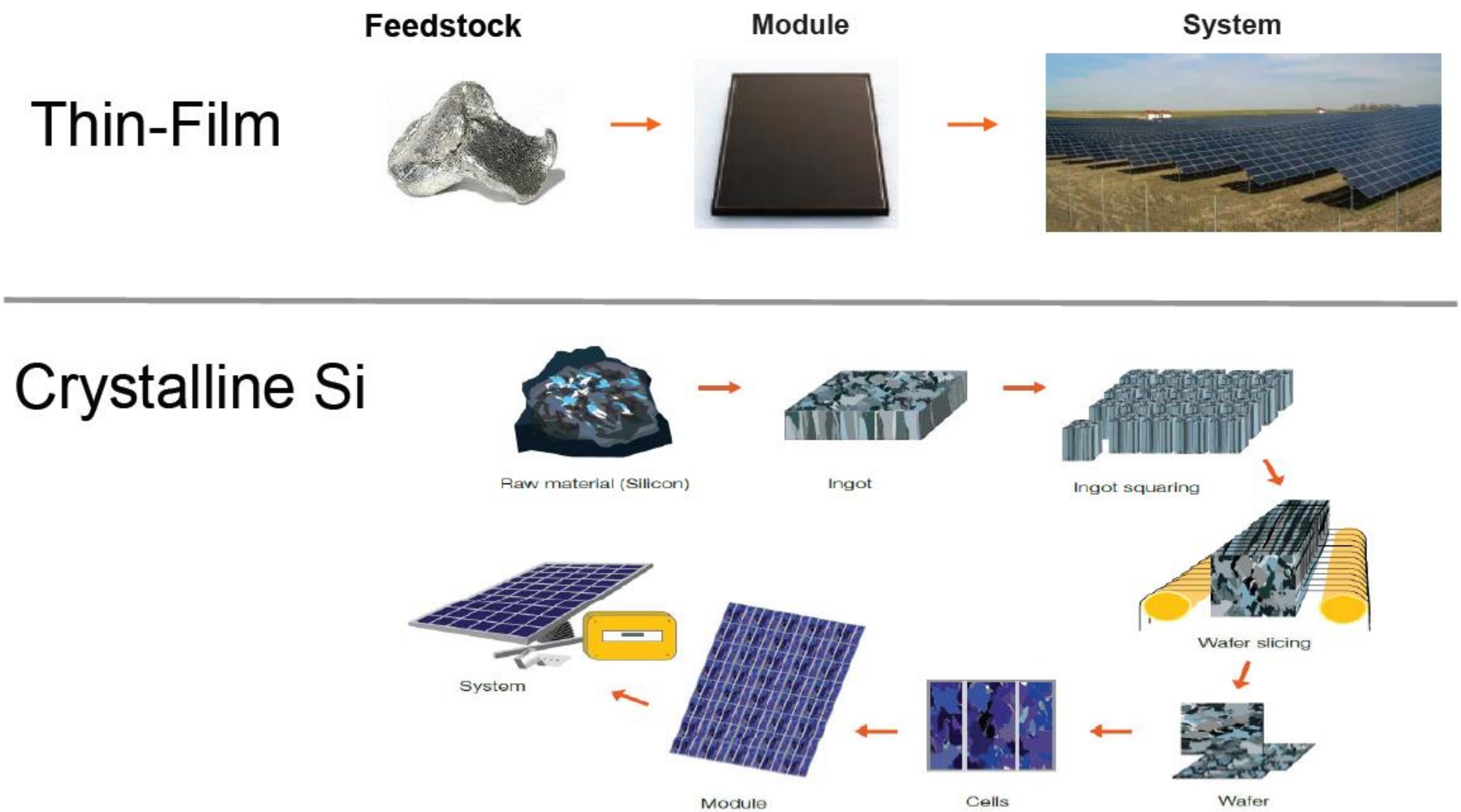


- required thickness of thin film solar cell is around 0.5 µm, 1/500 of that of wafer based solar cell
- material cost is very low

Advantages of thin film solar cells

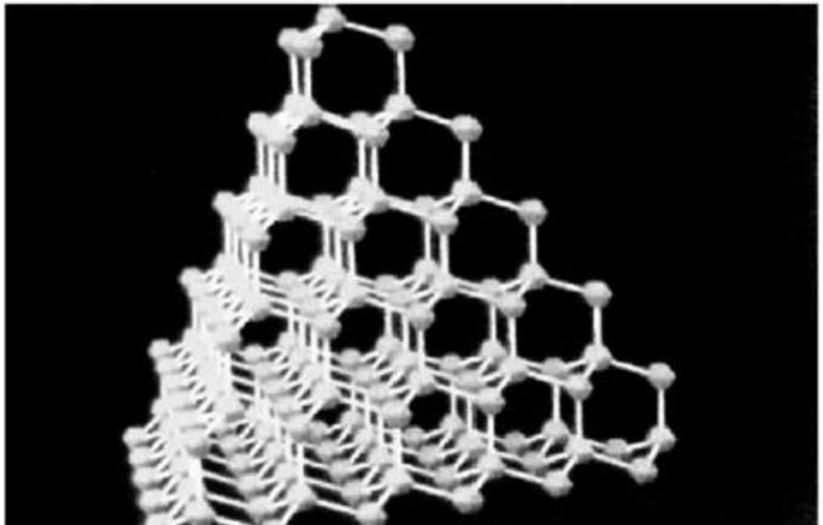
1. low raw materials are required for fabrication
2. light transmission is better
3. more competitive price (CdTe, US$1 per watt ; First Solar, stock price is US$180)
4. frameless design
5. Ideal for BIPV(building integrated photovoltaic)

Advantage of Thin-Film

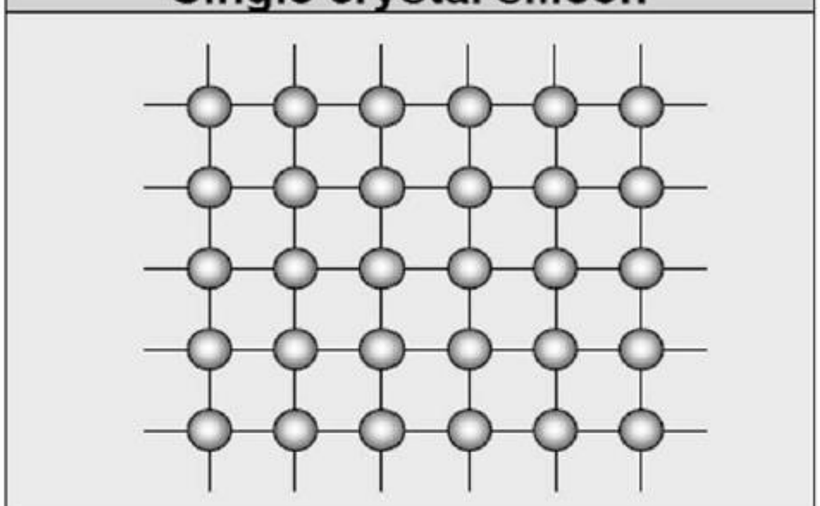


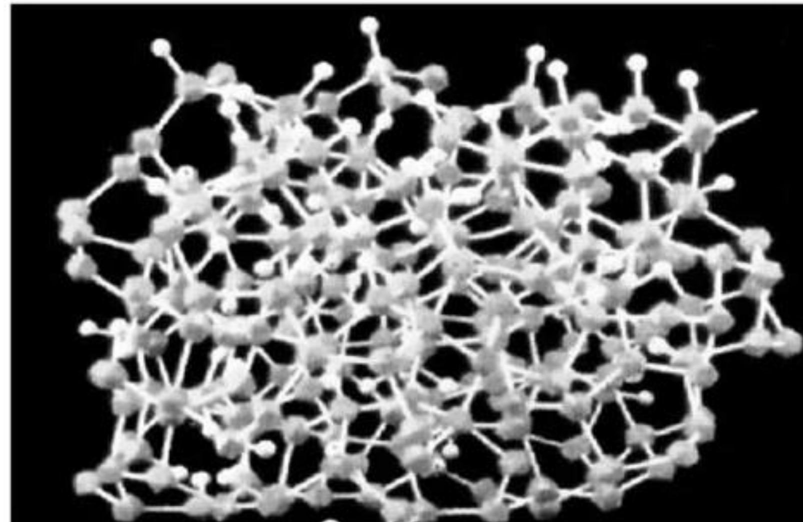
- Thin-film solar cells required a shorter value chain
- Long value chain presents difficulties with reaching grid parity.

Comparison of Atomic Structure of c-Si and a-Si:H

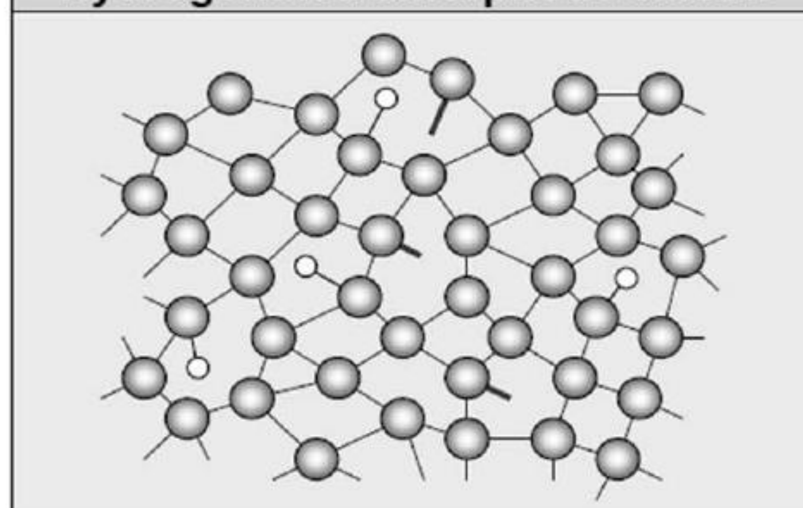


Single crystal silicon





Hydrogenated amorphous silicon



Device structure of amorphous Si solar cell

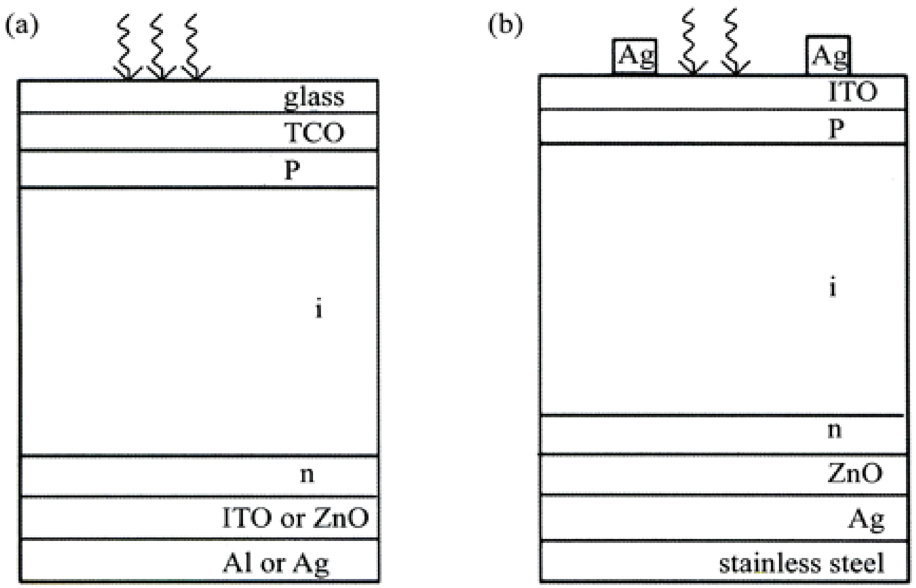
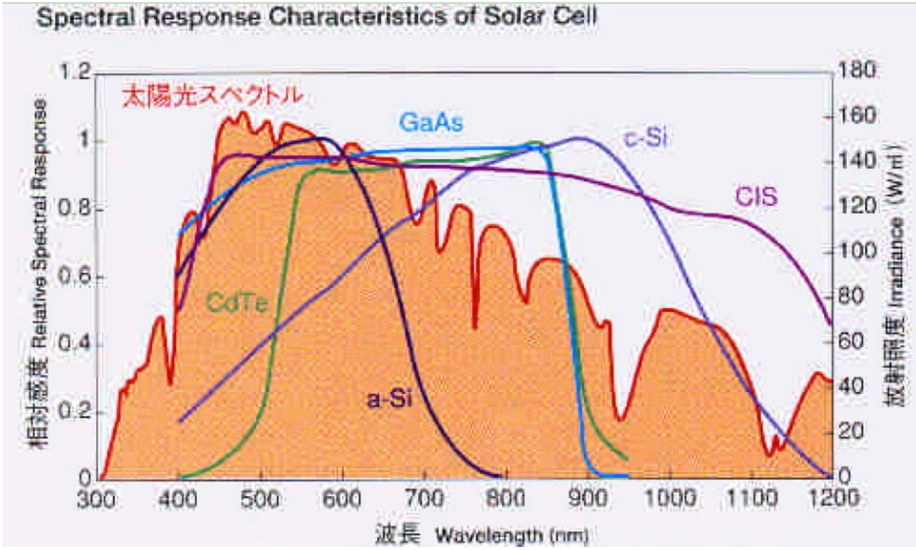


圖 6.7 典型 a-Si:H p-i-n 單接面太陽電池

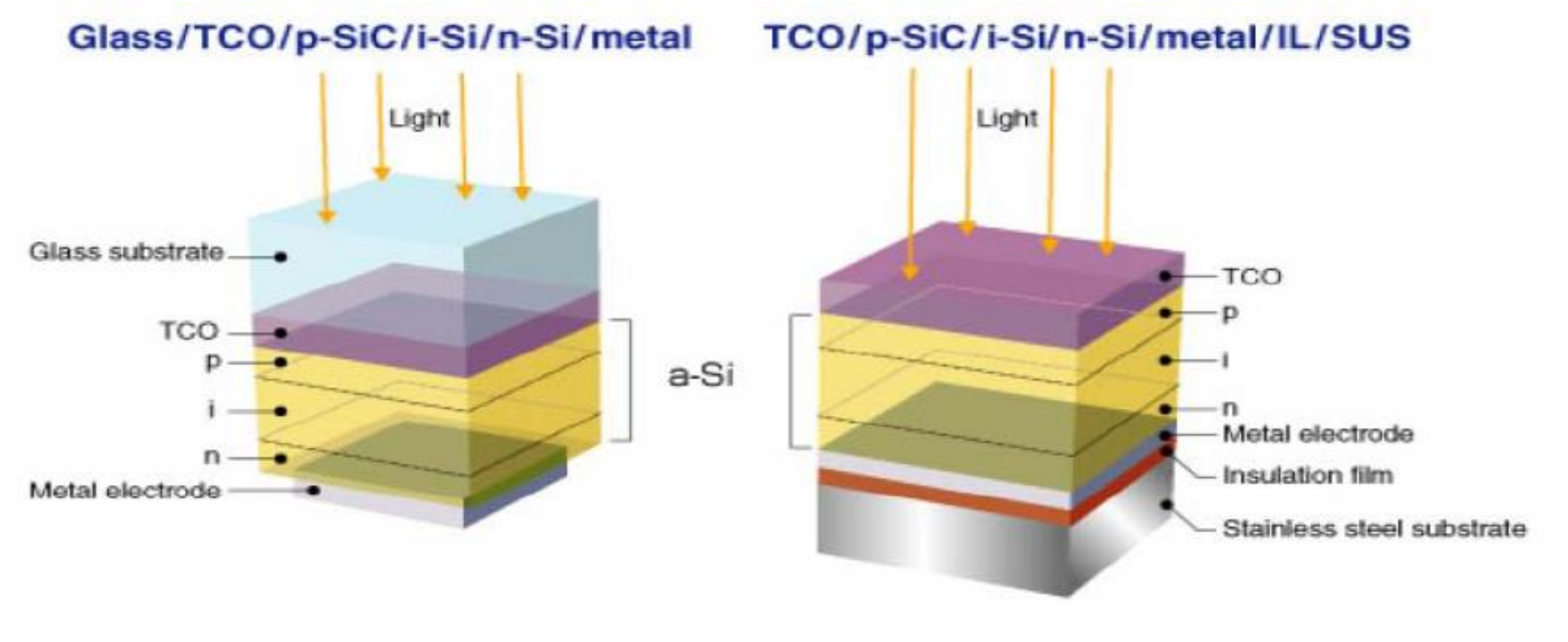
(a)superstrate 型式，(b) substrate 型式



-a-Si's absorption coefficient at visible light is one order of magnitude than c-Si , so only 10-30 nm is needed to capture most photon in the visible region

-thickness of p and n type are around 10-30nm, thickness of i layer is less than 500 nm

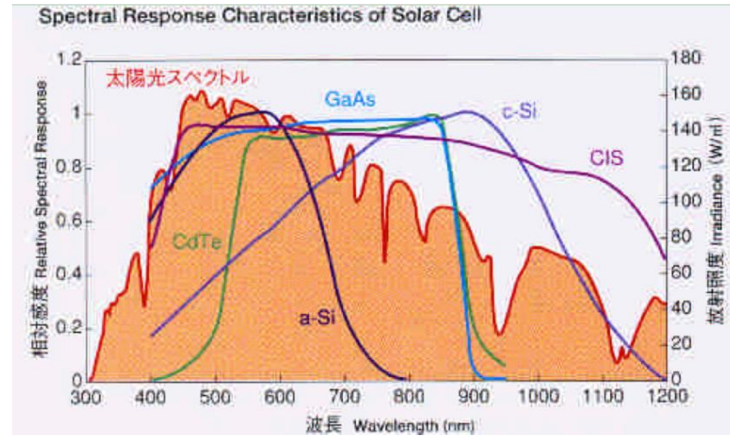
Structure of an amorphous Si solar cell



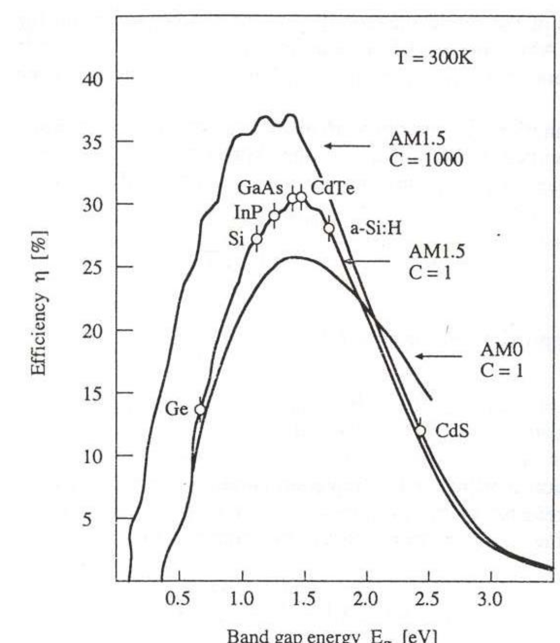
II-VI compound solar cell: CdTe

Abbreviated periodic table

I	II	III	IV	V	VI
		B	C	N	O
		Al	Si	P	S
Cu	Zn	Ga	Ge	As	Se
Ag	Cd	In	Sn	Sb	Te



II-VI group as light harvesting materials



band gap of CdTe : 1.5 eV

Device structure of a CdTe solar cell

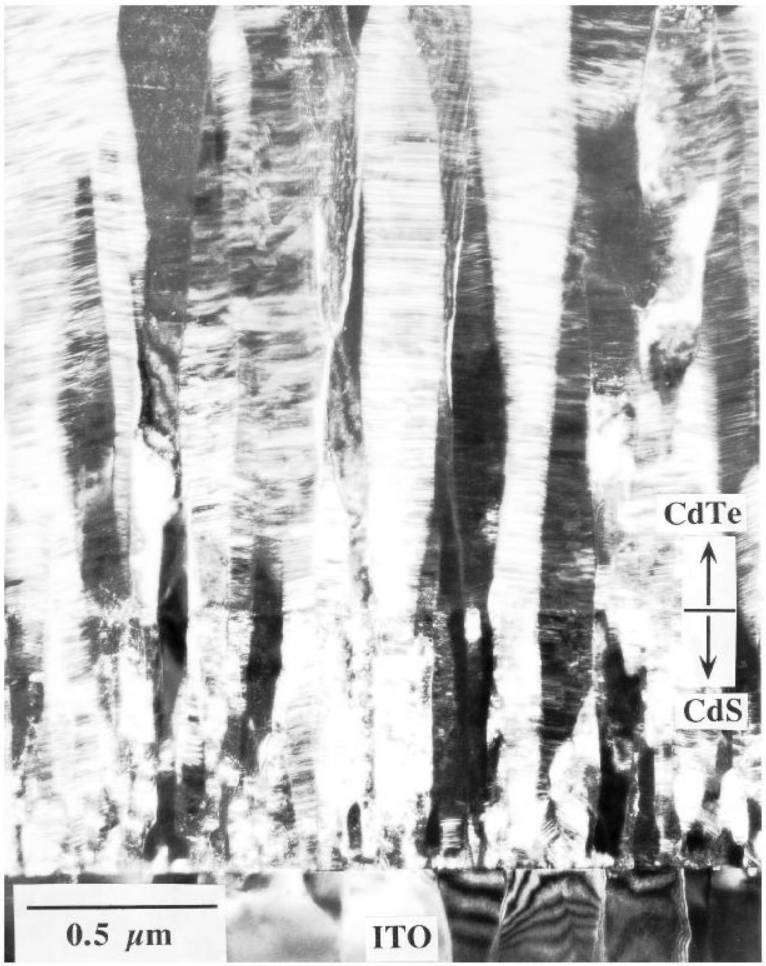
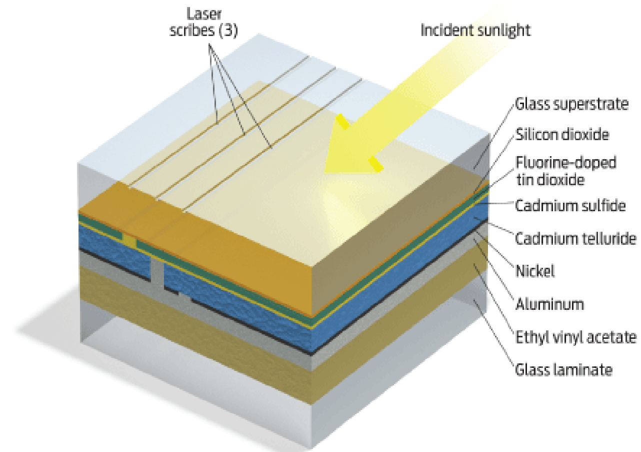


Figure 9 TEM micrograph showing the as deposited cross section of ITO/CdS/CdTe structure. Both CdS and CdTe are vapor deposited from the respective compounds.



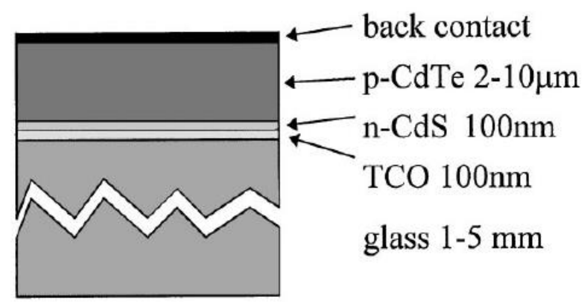


Fig. 1. The 'superstrate' configuration used for CdTe/CdS heterojunction solar cells.

P-type: CdTe

n-type: CdS

First solar

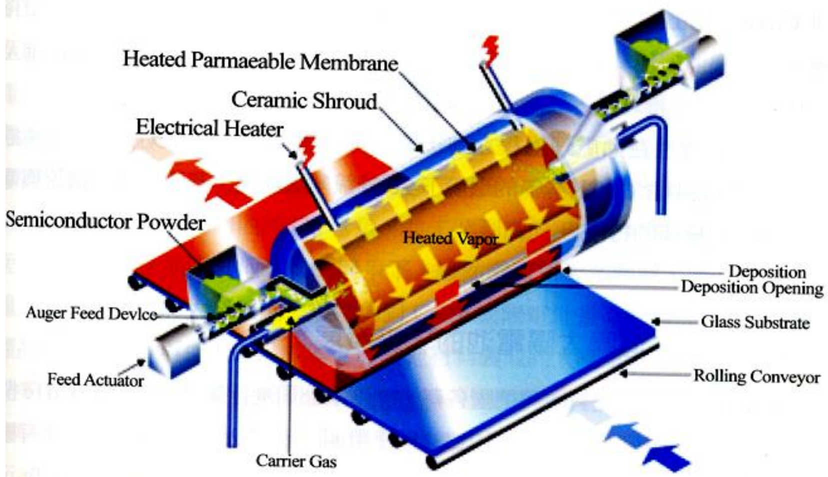


圖 7.8 First Solar 公司之量產型 CdTe 蒸氣輸送鍍膜示意圖

Pallas 綜合外電報導 / SolarExchange

美國太陽能廠商First Solar於去年第四季生產成本降到每瓦0.98美元

美國太陽能模組製造商First Solar（Nasdaq: FSLR）於24日宣布，2008年第四季平均生產成本降到每瓦0.98美元，成為首家低於每瓦1美元的太陽能廠商。

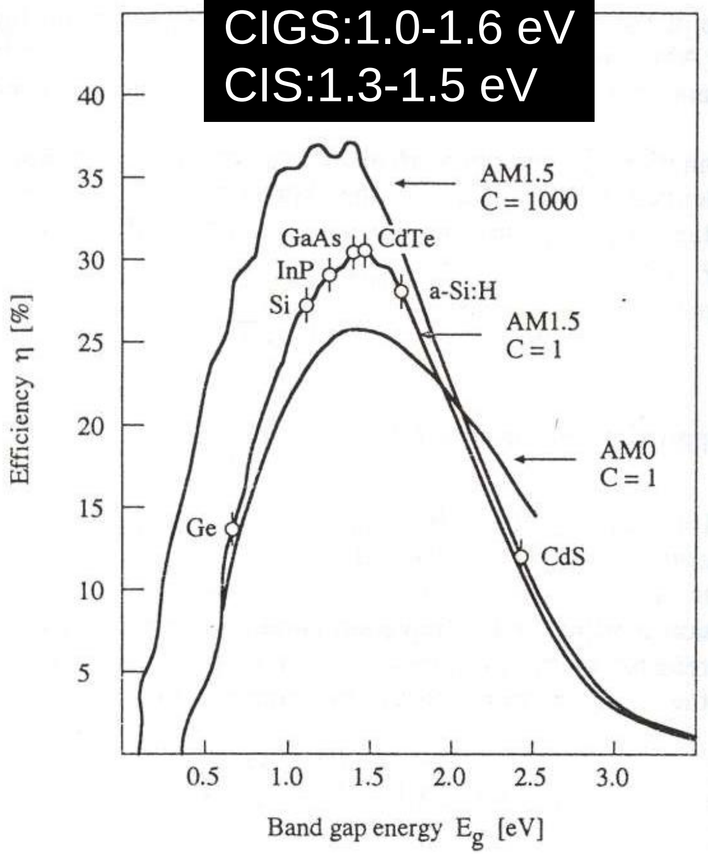
美國太陽能模組製造商First Solar（Nasdaq: FSLR）於24日宣布，2008年第四季平均生產成本降到每瓦0.98美元，成為首家低於每瓦1美元的太陽能廠商。

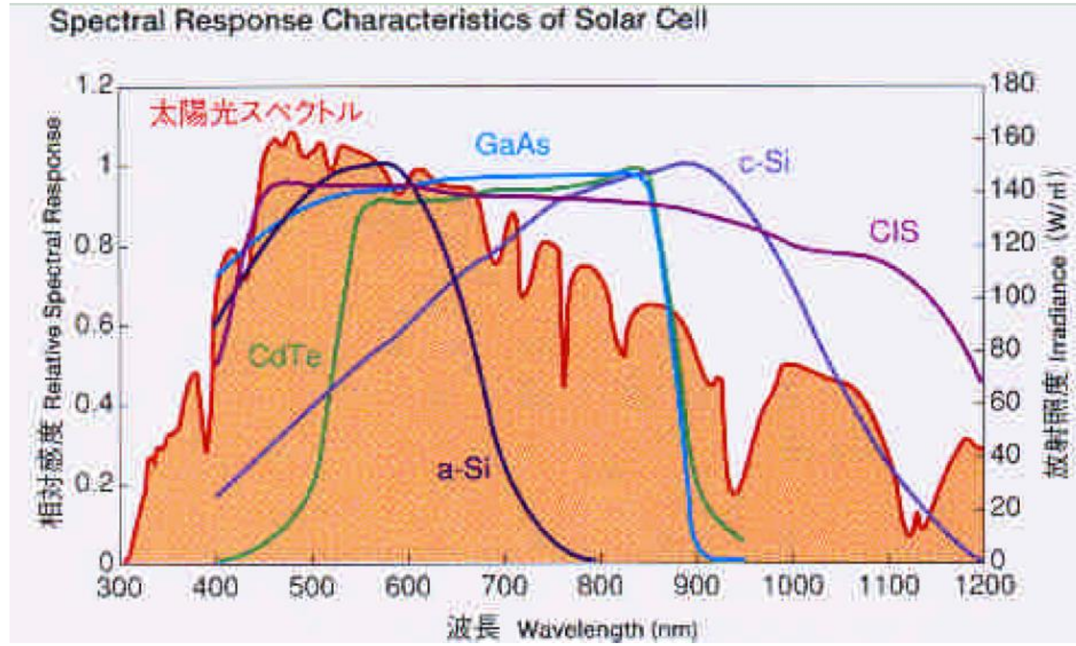
First Solar於2004年開始商業化生產以來，2008年產能成長約2500 % 達到500 MW。2009年產能將再增加一倍，達到1GW。這相當於一般核電廠的規模。這些成長率隨著成本迅速降低而提高。生產成本自2004年以來降了超過三分之二，從每瓦3美元降到每瓦1美元不到。First Solar有信心能基於First Solar未用盡的技術和製程的潛力，進一步再將成本降至更低。

Current production
Cost of crystalline
Solar cell is around
US 2/Wp

Band gap and optical absorption of CIGS

$CISe_2$:1.0 eV
CIGS:1.0-1.6 eV
CIS:1.3-1.5 eV





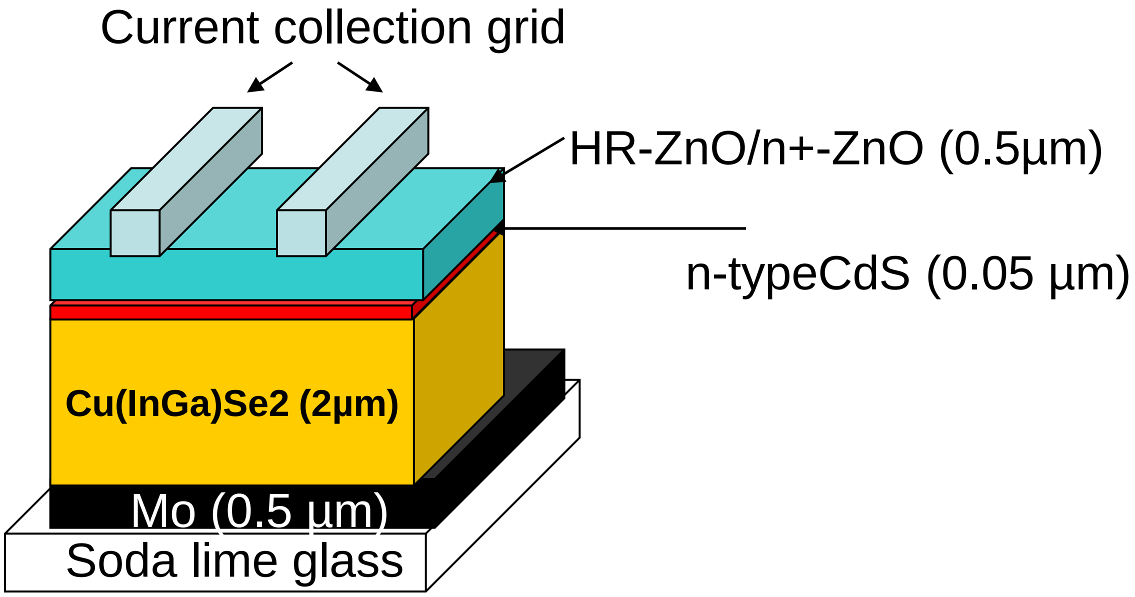
Muller, semiconductor for solar cells, 1993

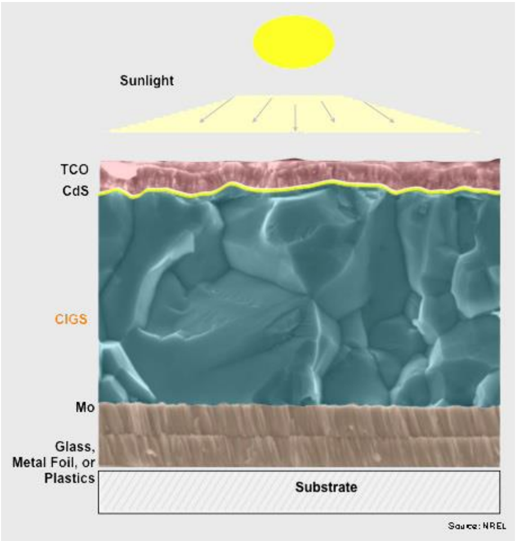
$$\text{Efficiency} = \frac{FFVocIsc}{Pin}$$

-CIGS's band gap is in the range of 1.1 to 1.5 ev

I-III-V_2 compound solar cell: (CIGS)

Schematic picture

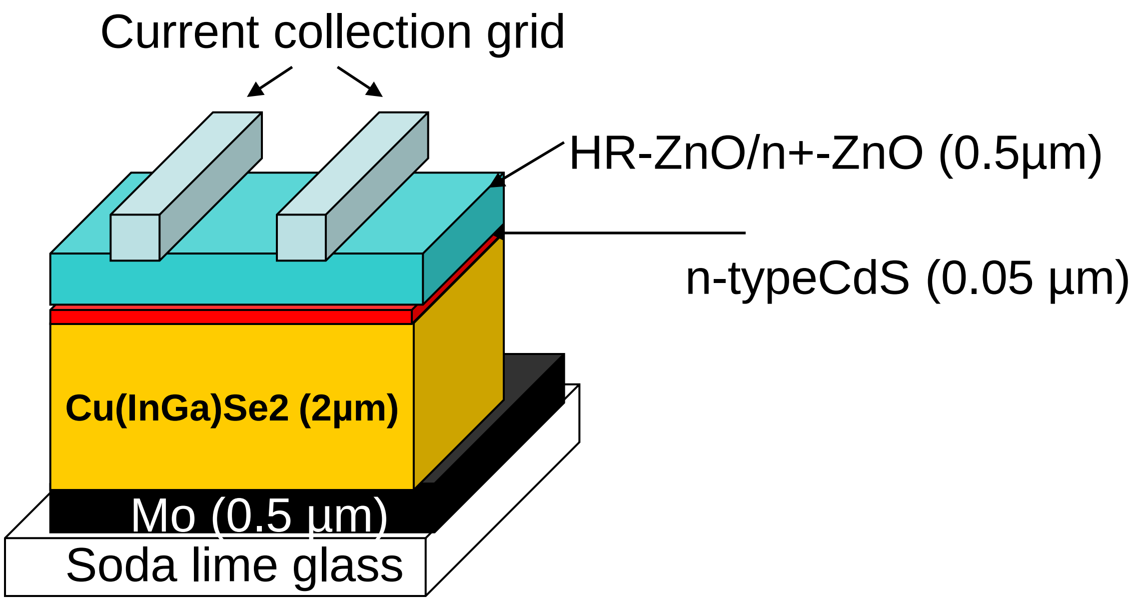




total device thickness less than 5 µm (Crystalline Si module~200 µm)

Compared to CdTe solar cells

Schematic picture



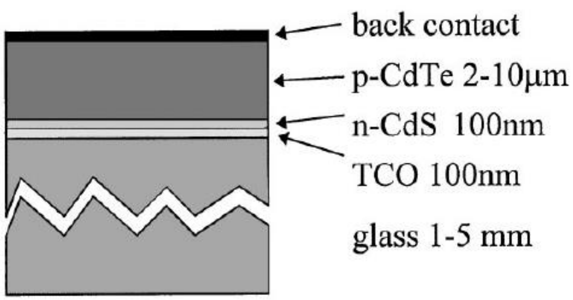
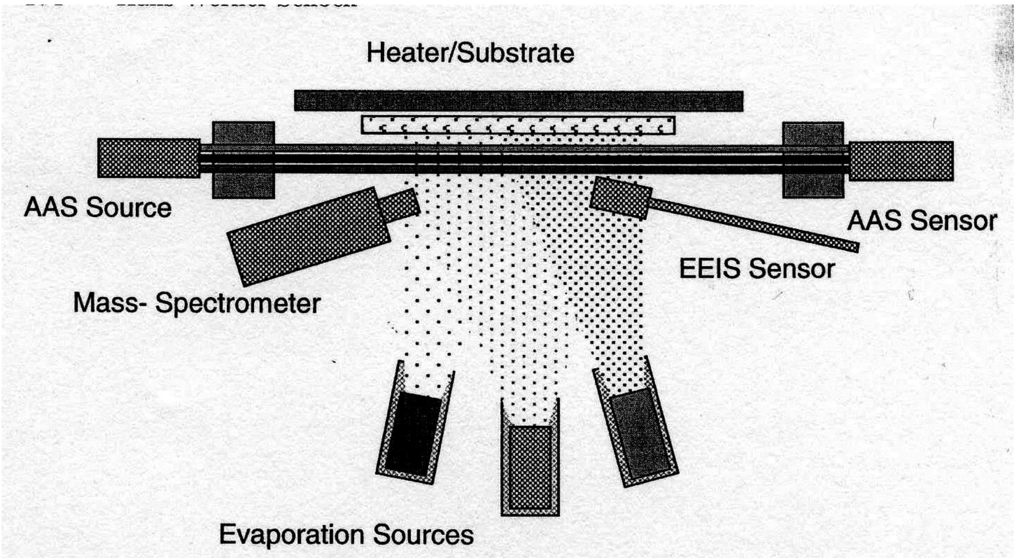
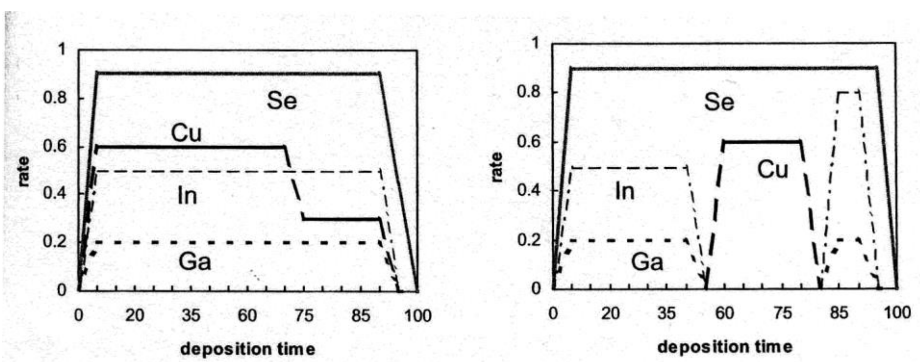


Fig. 1. The 'superstrate' configuration used for CdTe/CdS heterojunction solar cells.

Much less Cd required

An example of vaccum-based CIGS film deposition

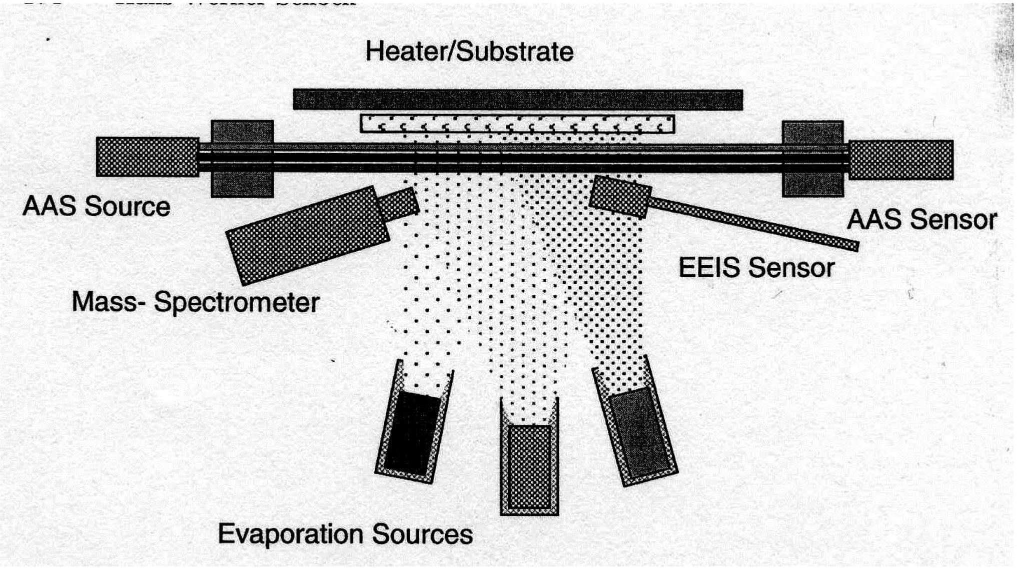




Y. Hamakawa Thin-film solar cells,

Vaccum-based CIGS film deposition

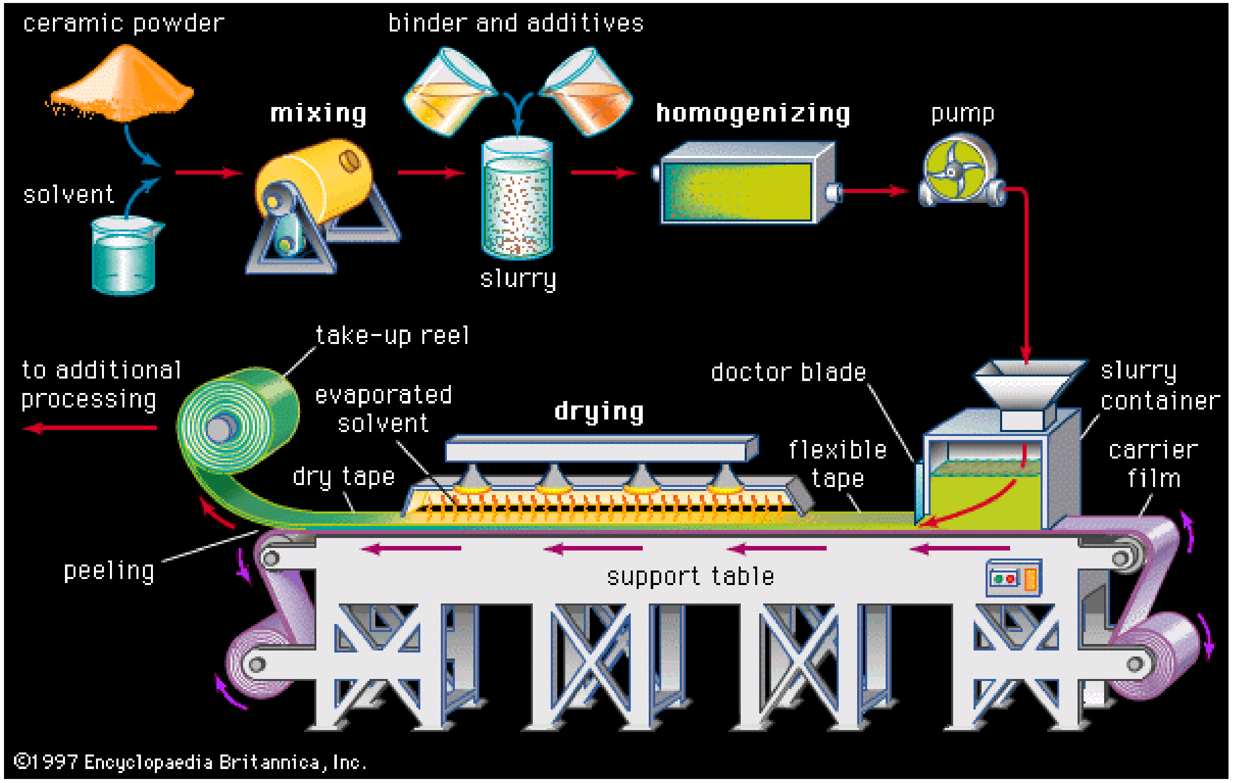
-Highest efficiency (lab scale: 18~20
-Usually UHV/MBE
-Cost prohibitive (but <cryst-Si)



General drawbacks:

-Difficult to achieve controlled-stoichiometry over large device areas
-Manufacturing equipment is “very” expensive (> NT 0.1 billion)
-The deposition process is time-consuming
-Poor materials utilization (30-50%)
-Low throughput

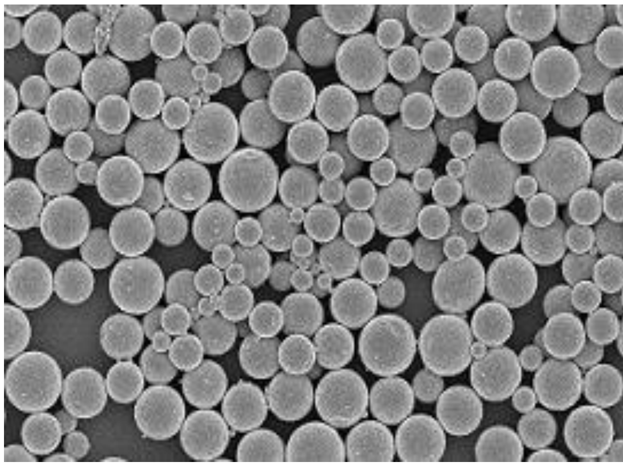
Non-Vacuum Processing



-Synthesize colloidal nanocrystals with controlled CIGS stoichiometry and deposit layer
-Roll-to-roll manufractruing process

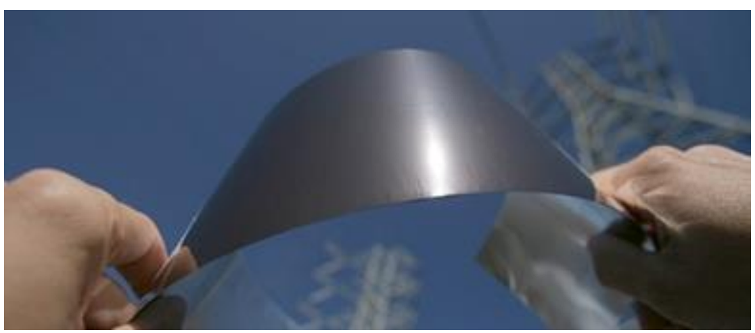
Nano solar- Nanoparticle as ink for printable solar cell

CIGS particle ink



Roll-to-roll processing

Flexible solar cell

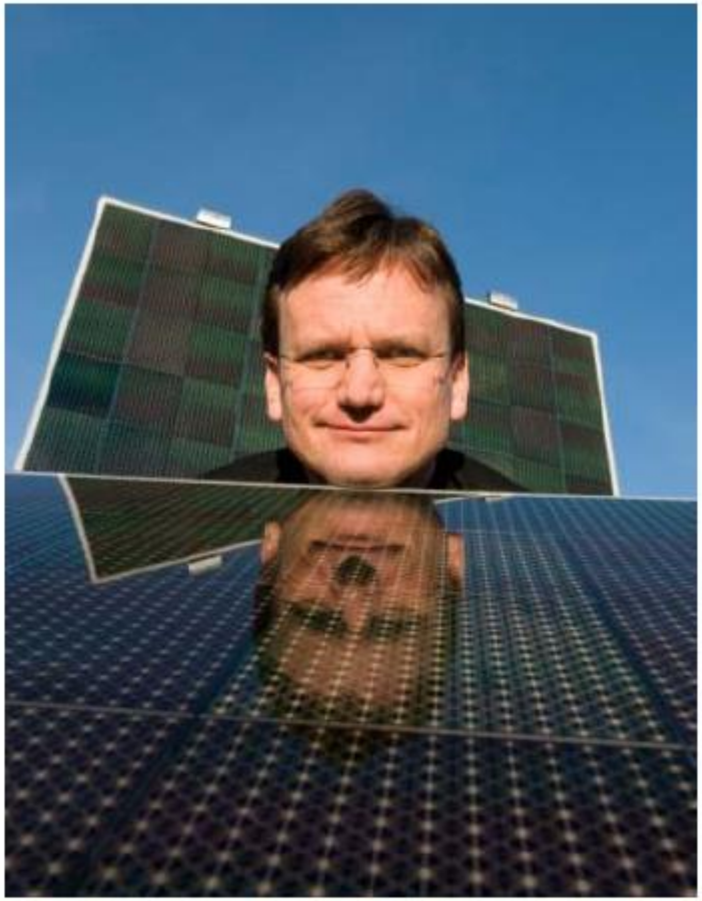


Add a video

has denmostrated a 1GW coater in a movie

	Silicon Wafer cells	Vacuum-based thin film	Roll-printed thin film
Process	Si wafer processing	High vacuum depositon	Roll-to-roll printing
Process Yield	Robust	Fragile	Robust
Materials Utilization	30%	30-60%	Over 97%
Throughput	1	2-5	10-25

Nanosolar Ships First Panels - Dec. 18,2007



Martin Roscheisen,
CEO

首批的三片量產太陽能板一片將掛在公司裡做「精神堡壘」，一片捐贈給聖荷西的科技博物館，一片拿到 eBay 上拍賣，起價 0.99 美元，3天後叫價到13,000美元。

Nanosolar, Thin-Film Solar Hype Firm, Officially Dead

U.S. CIGS solar assets are being auctioned off after more than $400 million in VC investment.

by Eric Wesoff

July 12, 2013

CIGS Rocks! 2010/July

【時報記者沈培華台北報導】台積電 (2330) 新事業總經理蔡力行表示，
台積電將以CIGS薄膜產品進軍太陽能產業，以五年期間朝全球前五大廠邁進，
產能規模將達1GW規模，並看好此事業對台積電是有獲利與高成長潛力的新事業。
台積電今天舉行先進薄膜太陽能技術研發中心暨先期量產廠房動土典禮。
新事業總經理蔡力行表示，全球太陽能電池市場將持續成長，預期2009年至
2015年全球太陽能電池市場年複合成長率可望達23%；其中，銅銦鎵硒(CIGS)
因具有薄膜的低成本價格等優勢，成長率將最高，年複合成長率將達115%。
台積電因此將以CIGS薄膜產品為主力，進軍太陽能產業。
台積電先進薄膜太陽能廠第一期將投資約79.2億，預計2012年量產200百萬瓦(MW)
，終期產能為700百萬瓦(MW)。台積電董事長張忠謀並預估，2015年太陽能佔
台積電營收比重可望達10%。蔡力行表示，台積電三年內CIGS薄膜太陽能電池
模組轉換效率將達14%，產能規模將約300至500百萬瓦，預期3至5年轉換效率
將進一步提升至16%，產能規模將達1GW規模。

薄膜太陽能翻身　台積電產能衝3倍　全球龍頭廠轉盈　產業前景漸撥雲見日 2014/Feb

台積電旗下銅銦鎵硒(CIGS)薄膜太陽能廠目前年產能為40百萬瓦(MWp)，隨著整體市況轉佳、訂單滿載且技術獲得重大突破，台積電第4季CIGS年產能將擴增到120MWp，達到3倍規模，太陽能業者透露，以台積電在太陽能領域穩紮穩打風格來看，這次產能出現大躍進，凸顯CIGS接單情況明顯轉佳，業界紛預期台積電太陽能事業可望邁向獲利。不過，台積電發言體系表示，目前針對財務部分不予置評。

全球最具代表性的CIGS薄膜太陽能龍頭大廠是日本昭和殼牌石油旗下子公司Solar Frontier，年產能規模達900MWp，近年來一直陷入虧損困境翻不了身，然近期財報終於首度轉虧為盈，2013年旗下產能全數滿載，年營收暴增8成，並計劃在日本東北(Tohoku)擴增150MWp產能的CIGS新廠，預計2015年投產。

台積太陽能步上關廠 業界:成本難敵矽晶 2015/08/25 16:36

（中央社記者張建中新竹25日電）台積電100%持股子公司台積太陽能將於8月底結束工廠營運。業界人士認為，薄膜太陽能電池成本難敵矽晶太陽能電池，是迫使台積太陽能走向關廠的主因。

台積電新事業發展接連遭逢重大挫敗，旗下台積固態照明因較晚進入發光二極體（LED）產業，業界專利障礙與通路開發不易，考量短期難以轉盈，台積電今年初決定將台積固態照明全部股份賣予晶電。

台積電今天又宣布，旗下台積太陽能因是市場後進者，缺乏經濟規模，雖然轉換效率具領先優勢，但在成本上不具競爭力，即便執行最精進的成本減抑計畫，也將難以逆轉成本劣勢，將於8月底結束工廠營運。

台積電是於2009年成立新事業部，並陸續成立台積固態照明與台積太陽能，分別投入LED與太陽能產業，由前總執行長蔡力行領軍。隨著蔡力行轉往中華電信擔任董事長，台積固態照明與台積太陽能董事長由左大川接任。

台積太陽能成立之初，蔡力行曾表示，台積太陽能將以技術領先為主要策略。

碩禾電子材料 太陽能電池導電膠

碩禾 **(3691)** 股價560.0

碩禾導電漿在全球產業地位

項目	全球市占(%)	台灣市占(%)	挑戰目標(%)	產業地位	主要競爭者
背鋁	35	90	40	全球前2名	中國儒興
背銀	25~30	60	40	全球前3名	杜邦、中國中型廠
正銀	1	3~4	5	起步中	杜邦、賀利氏

註：背鋁及背銀目標為中期目標，為期2到3年；正銀目標為今年

資料來源：碩禾　簡永祥／製表

碩禾相關權證

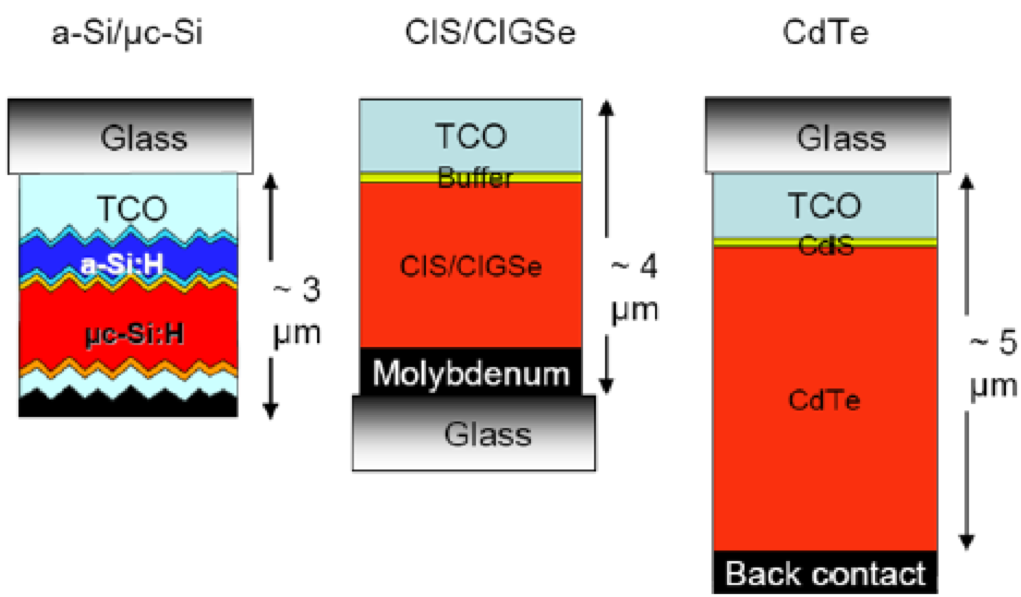
標的證券	權證代號	權證名稱	價內外(%)	權證單價(元)	剩餘天數	標的上漲1%、權證相對漲跌幅(%)
碩禾	706875	群益TK	內11.48	2.43	132	3.57

群益金鼎證券／製表

清大化工系友在光電業界的發展

三大上游材料，都是清大幫天下—清大幫創業公司表
公司名：晶電代表人物：董事長李秉傑畢業系級：1985年化工博士公司地位：台灣第一大LED磊晶廠
公司名：璨圓代表人物：董事長簡奉任畢業系級：1985年化工系公司地位：台灣第二大LED磊晶廠
公司名：上緯代表人物：董事長蔡朝陽畢業系級：1987年化工碩士公司地位：高性能樹脂材料大廠
公司名：碩禾代表人物：蔡禮全 化學工程
公司地位：太陽能導電膠大廠 副總經理

Comparison of three thin film solar cells

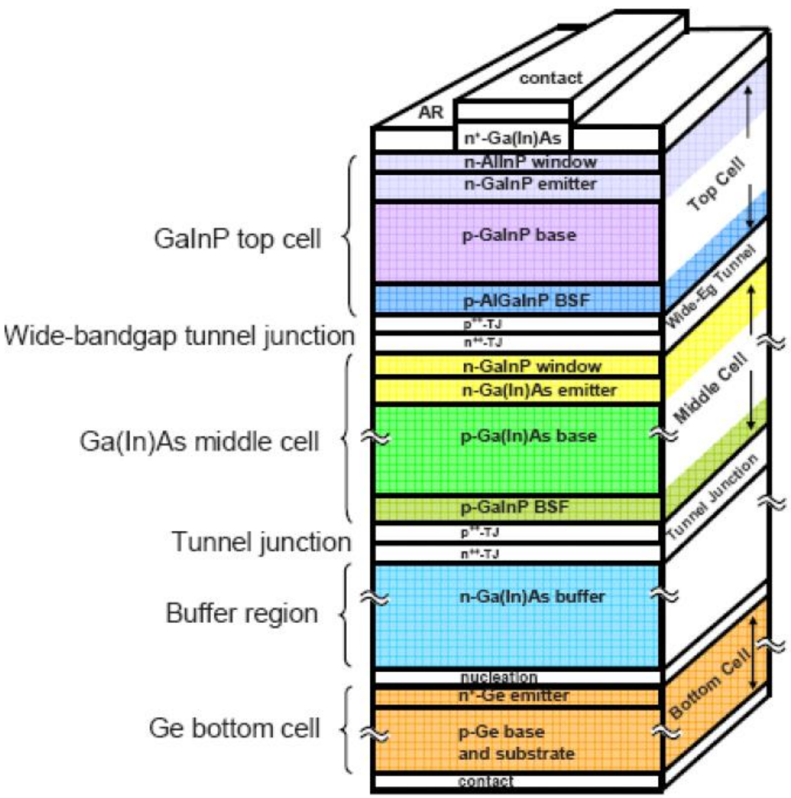


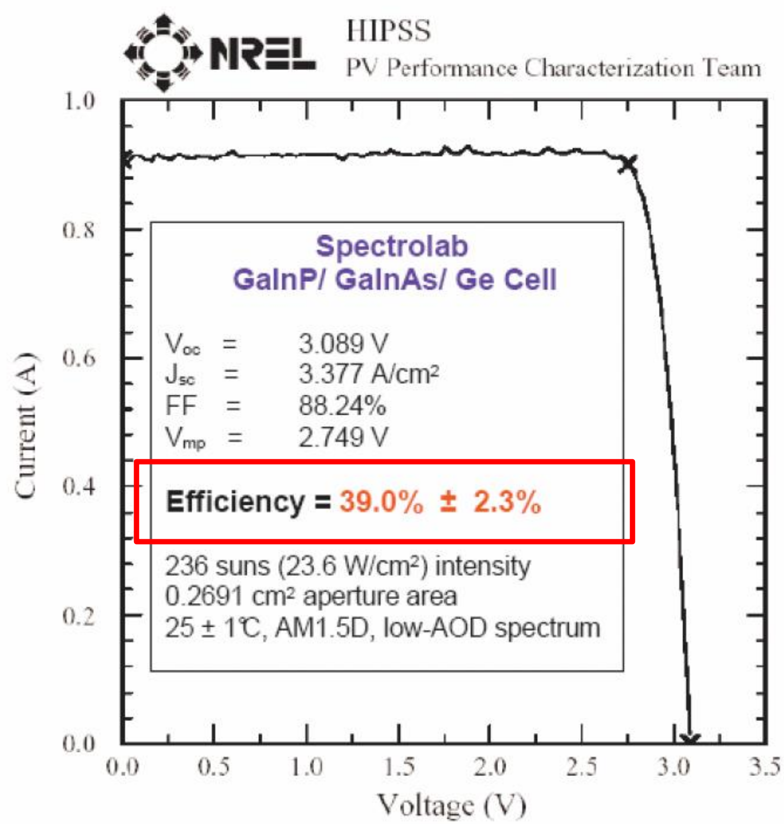
	a-Si/µc-Si	CIGS	CdTe
Junction	p/i/n, Si	p/n, CIGS/CdS	p/n, CdTe/CdS
Absorber	i-Si	P-CIGS.	P-CdTe
TCO	Textured FTO, AZO,	AZO	FTO, ITO
Eff. % in prod. (Lab)	~8.5 (~13)	10~11.5 (19.9)	8.5~10 (16.5)

Semiconductor Taiwan 2008

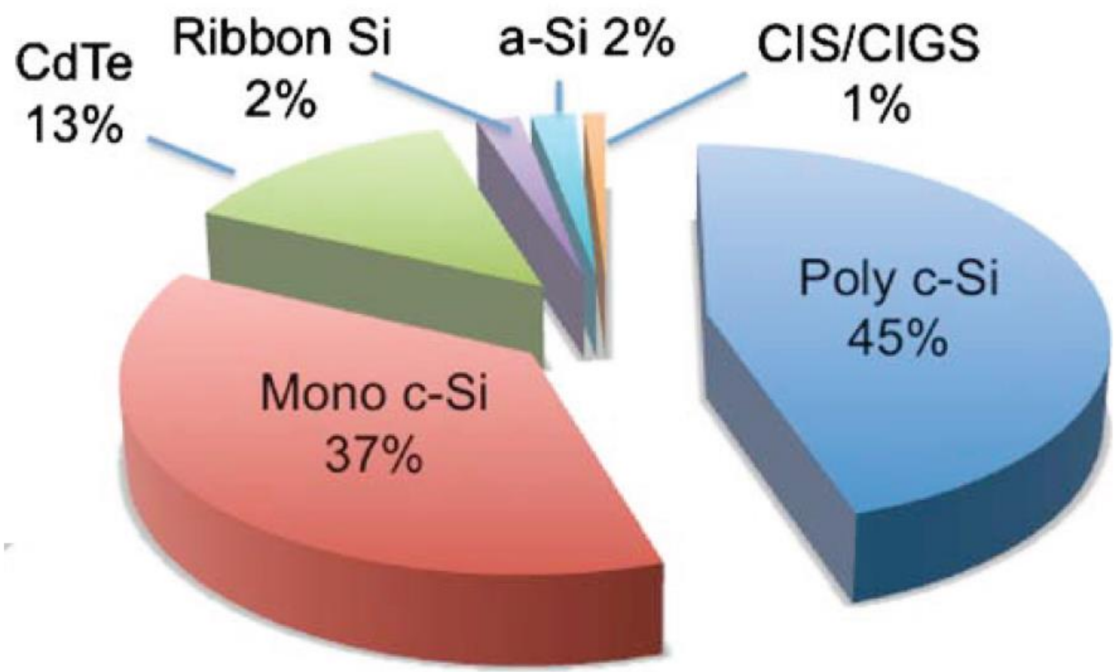
Tandom Junction Solar cells

GaInP/GaAs/Ge Triple Junction Cell





Market distribution in 2009



Total of 7.86 GW

- Both poly-Si and mono-Si combined a total 82%
- First Solar's CdTe was the first company to exceed 1GW/yr production, captured 13% market share.
- CIS/CIGS only has 1% market share.