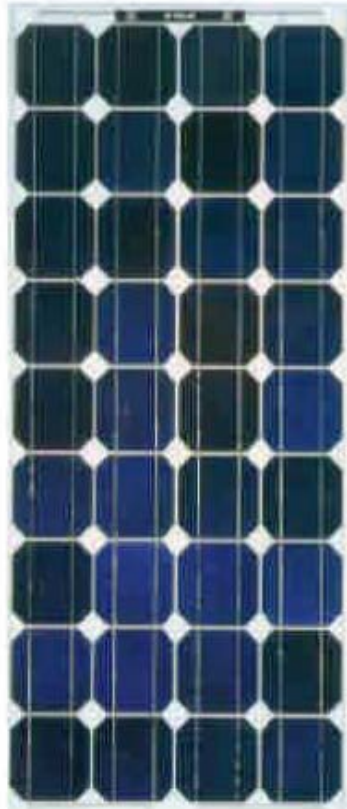


Thin film solar cell: use Si as an example

c-Si (wafer technology)



c-Si solar cell



Si-thickness
200 - 300 μm

solar module
($\eta = 11 - 15 \%$)

a-Si thin film technology

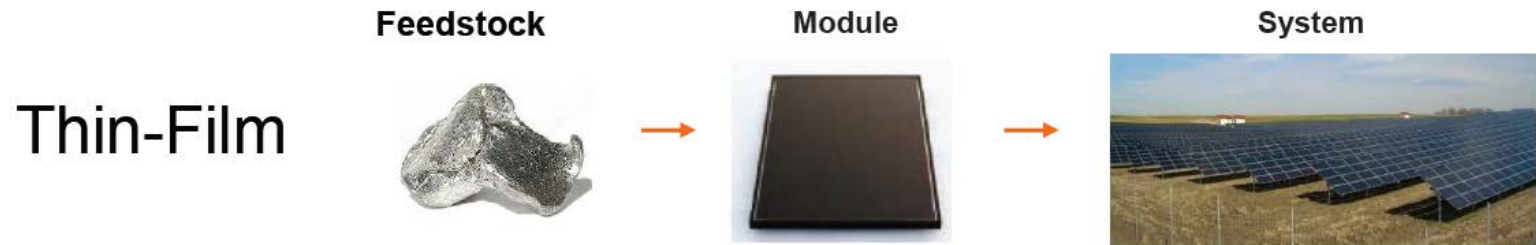
Si-thickness
0.5 μm

solar module
($\eta = 5 - 7 \%$)

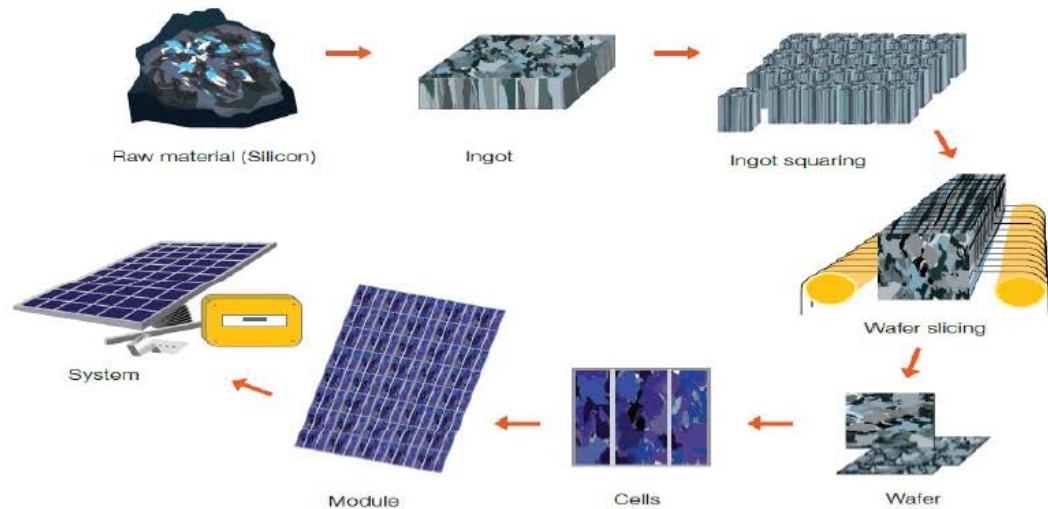


- required thickness of thin film solar cell is around 0.5 μm , 1/500 of that of wafer based solar cell
- material cost is very low

Advantage of Thin-Film



Crystalline Si

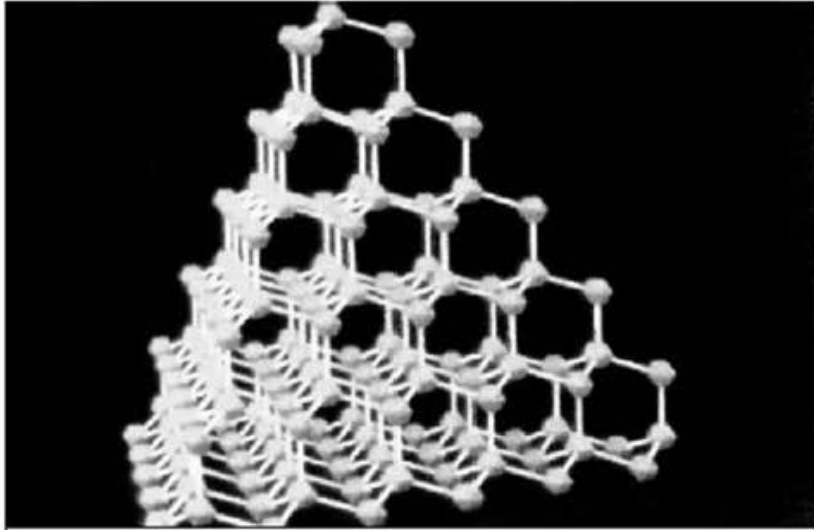


- Thin-film solar cells required a shorter value chain
- Long value chain presents difficulties with reaching grid parity.

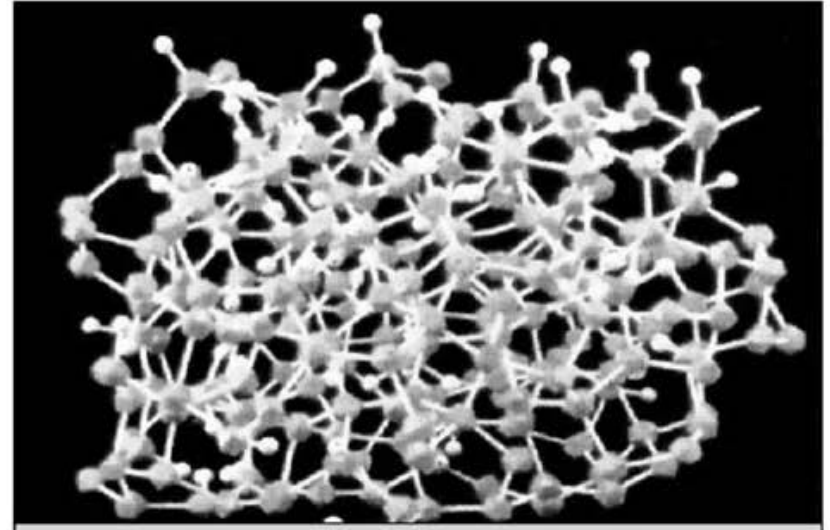
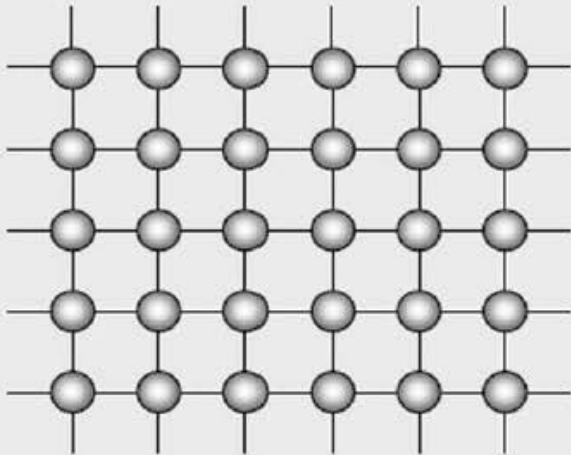
Advantages of thin film solar cells

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)

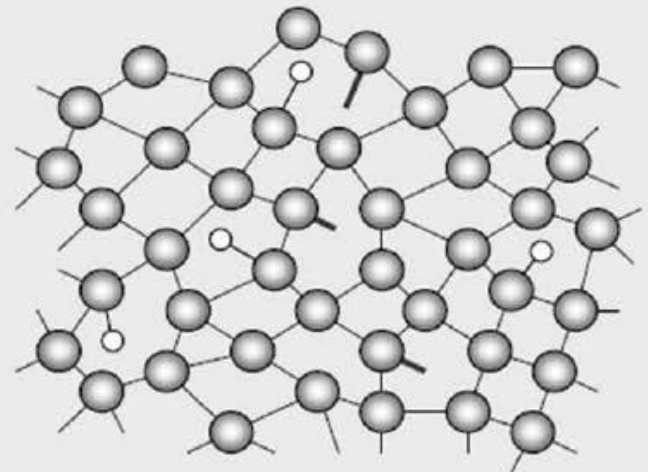
Comparison of Atomic Structure of c-Si and a-Si:H



Single crystal silicon



Hydrogenated amorphous silicon



Device structure of amorphous Si solar cell

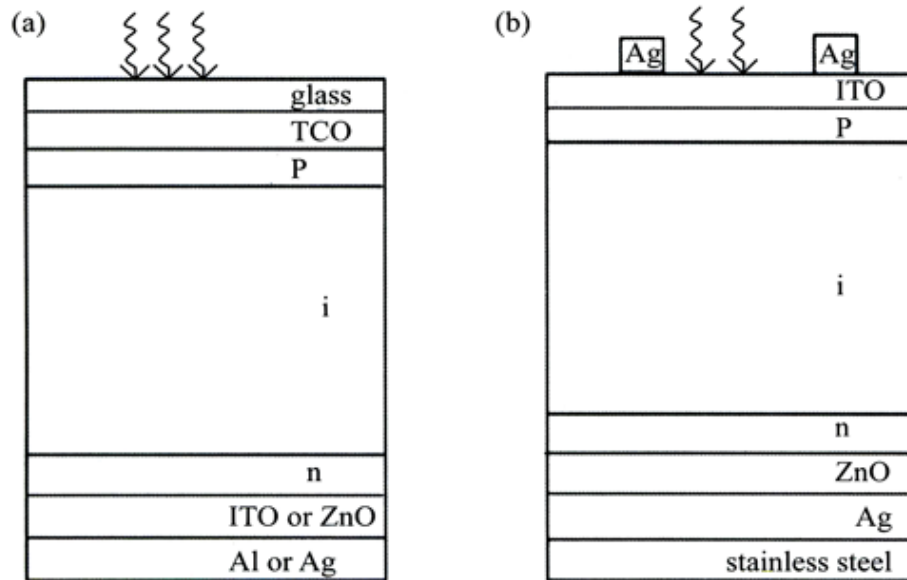
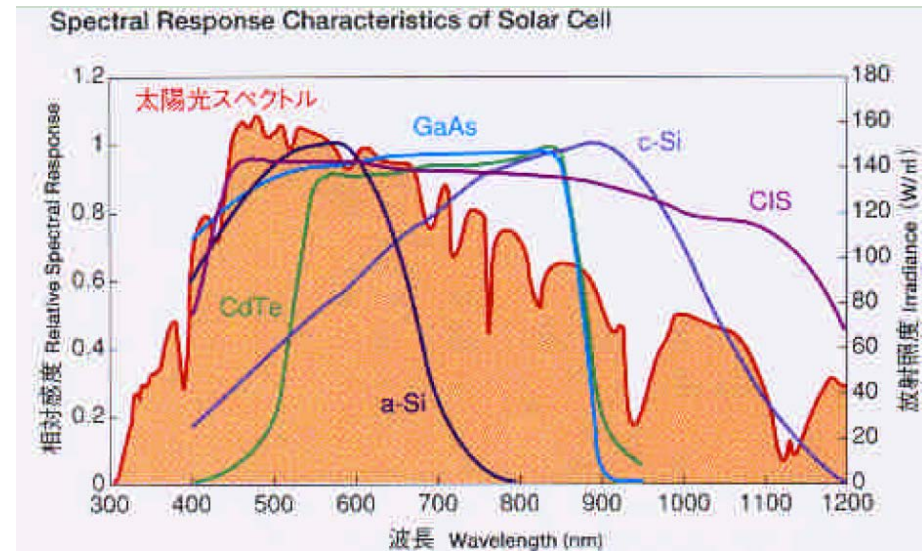


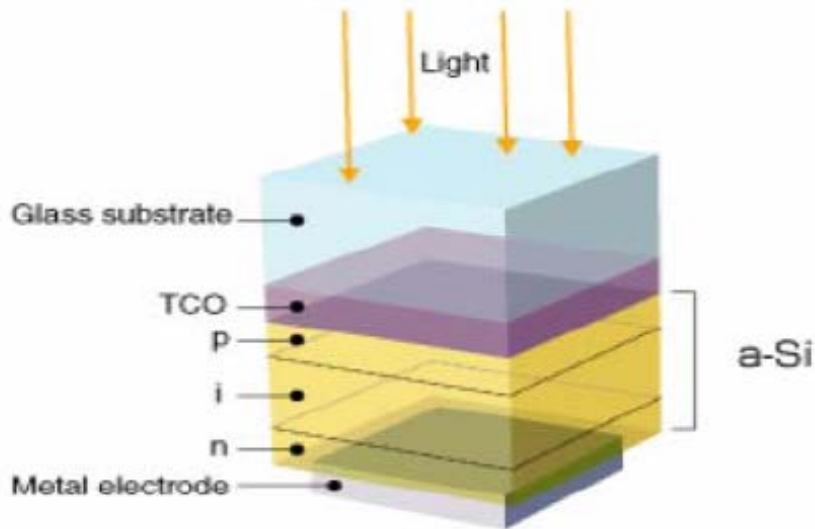
圖 6.7 典型 a-Si:H p-i-n 單界面太陽電池
 (a)superstrate 型式, (b) substrate 型式



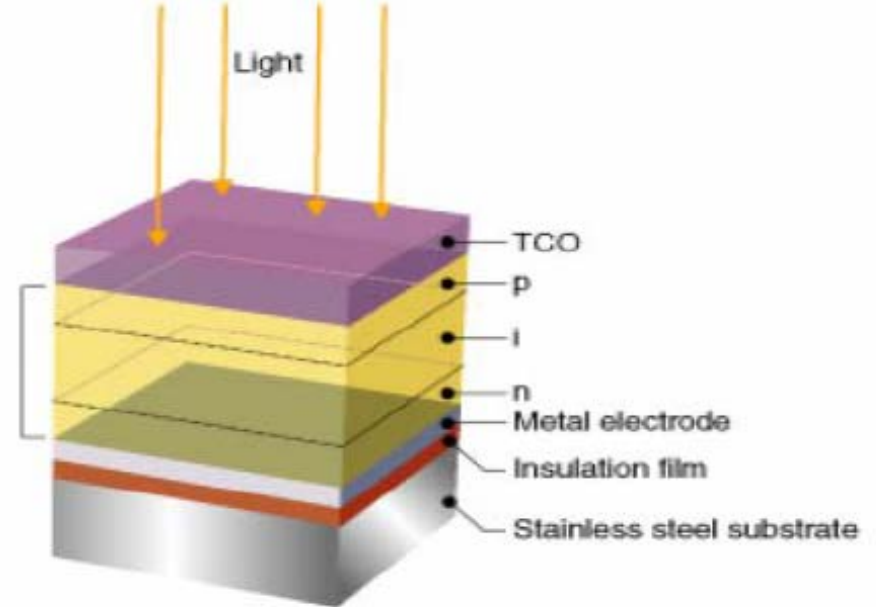
-a-Si's absorption coefficient at visible light is one order of magnitude than c-Si, so **only 10-30 nm** is needed to capture most photon in the visible region
 -thickness of p and n type are around 10-30nm, thickness of i layer is less than 500 nm

Structure of an amorphous Si solar cell

Glass/TCO/p-SiC/i-Si/n-Si/metal



TCO/p-SiC/i-Si/n-Si/metal/IL/SUS



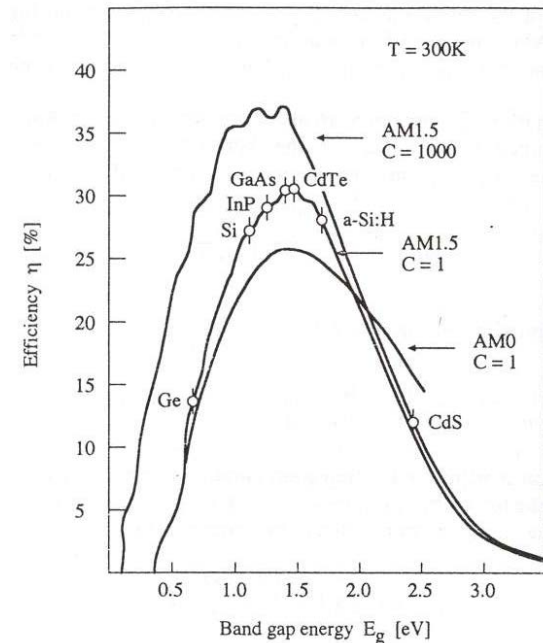
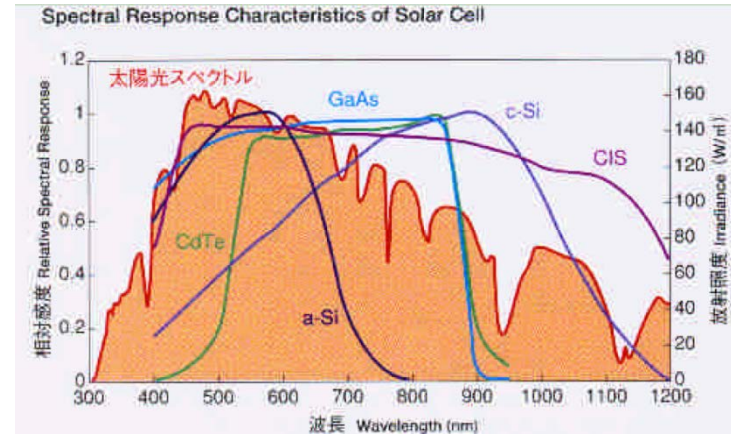
II-VI compound solar cell: CdTe

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.

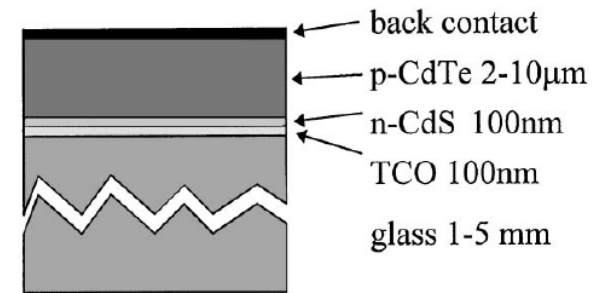
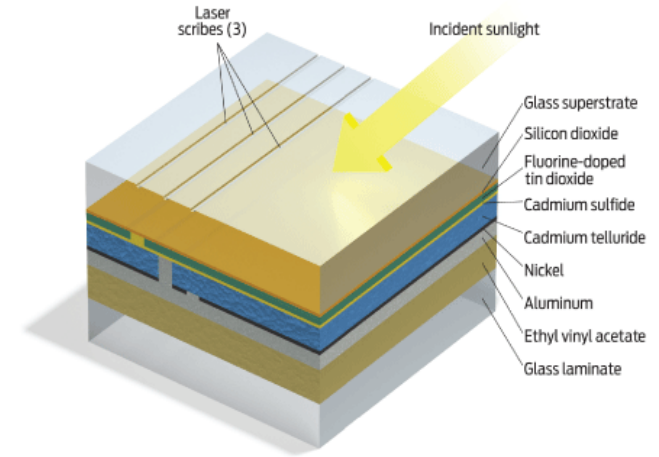
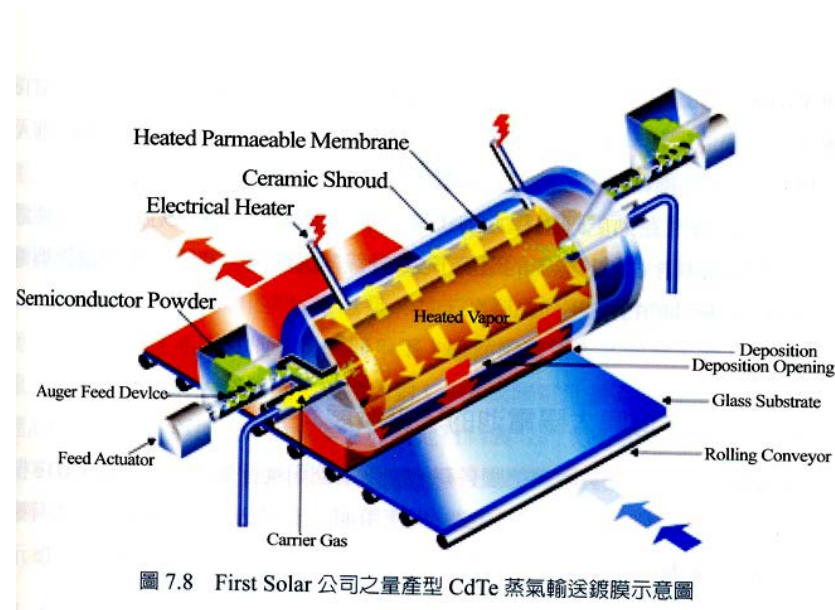


Fig. 1. The 'superstrate' configuration used for CdTe/CdS heterojunction solar cells.

P-type: CdTe
n-type: CdS

First solar



Pallas 綜合外電報導 / SolarExchange

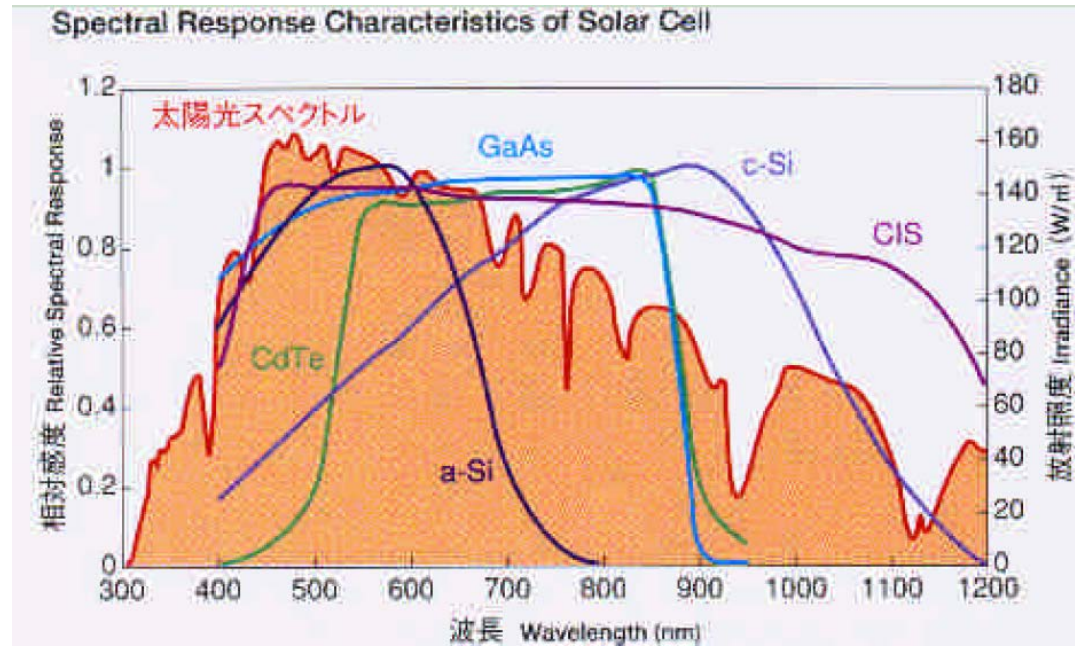
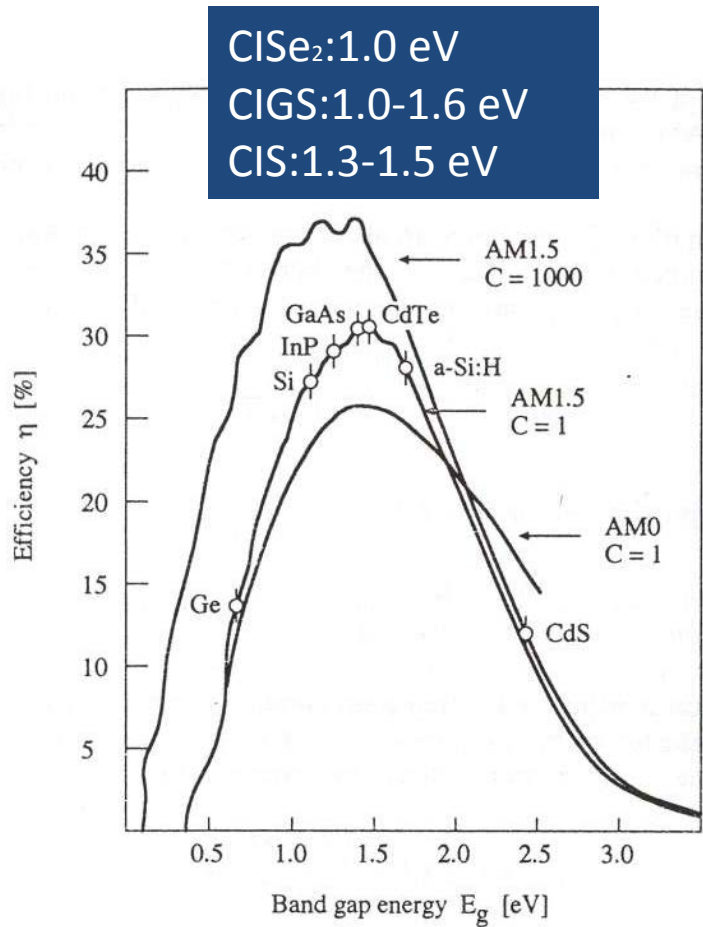
美國太陽能廠商First Solar於去年第四季生產成本降到每瓦0.98美元

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



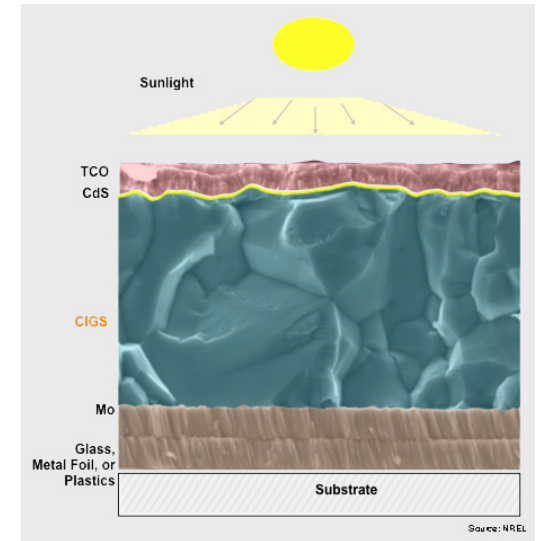
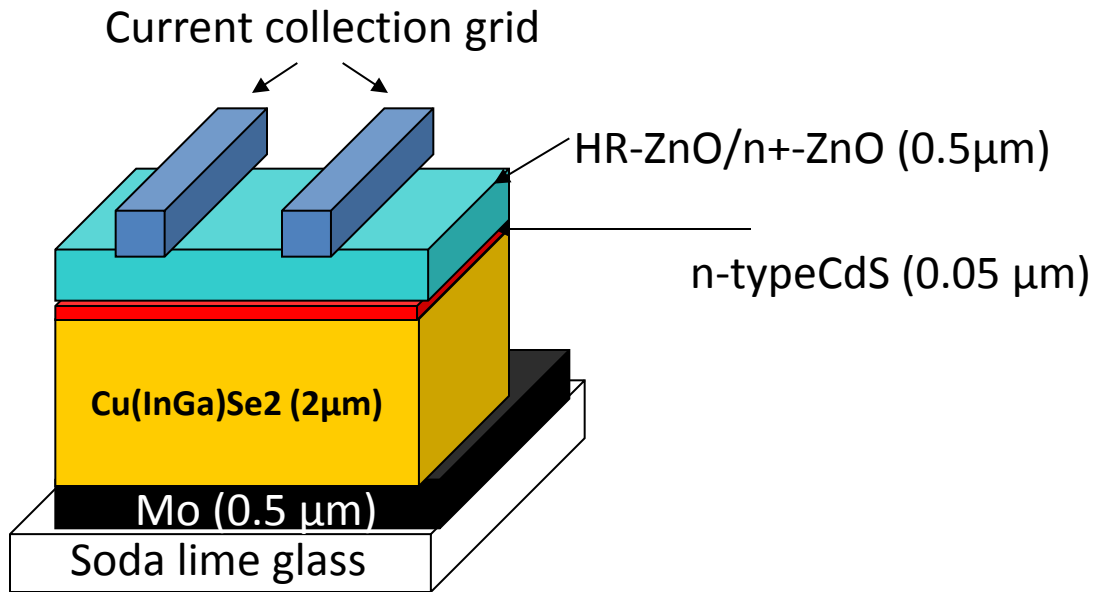
Muller, semiconductor for solar cells, 1993

$$\text{Efficiency} = \frac{FFV_{oc}I_{sc}}{P_{in}}$$

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

I-III-V₂ 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

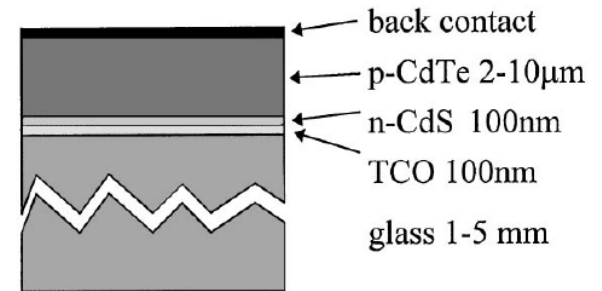
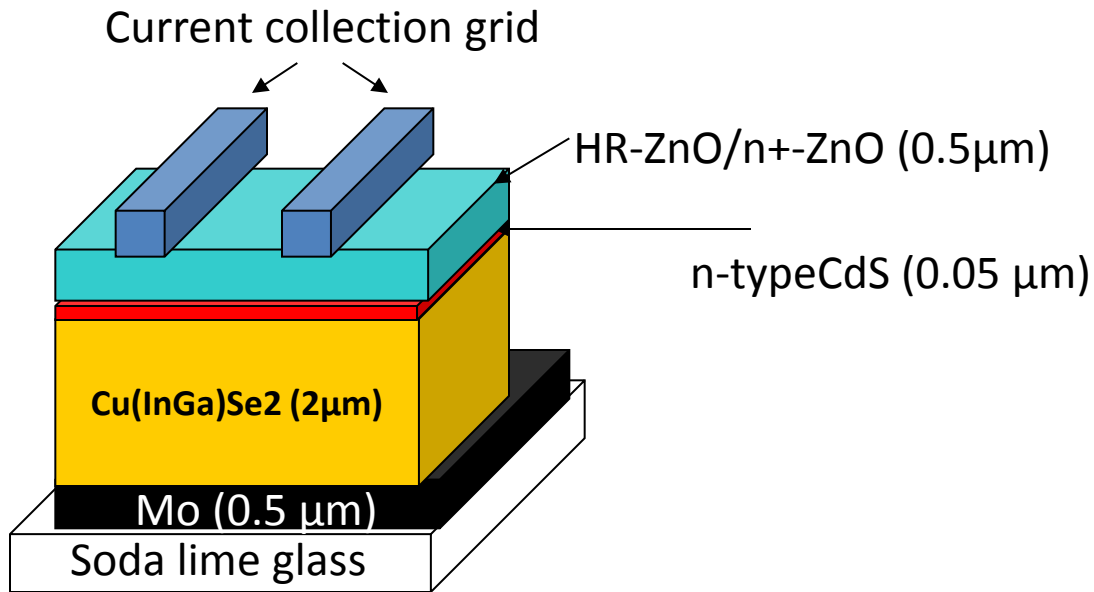
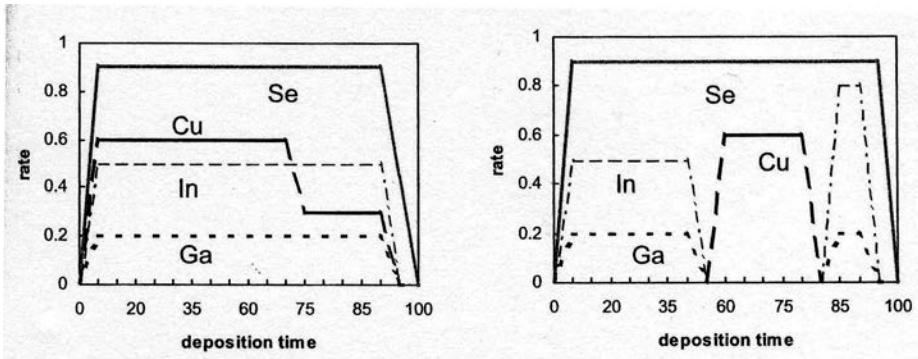
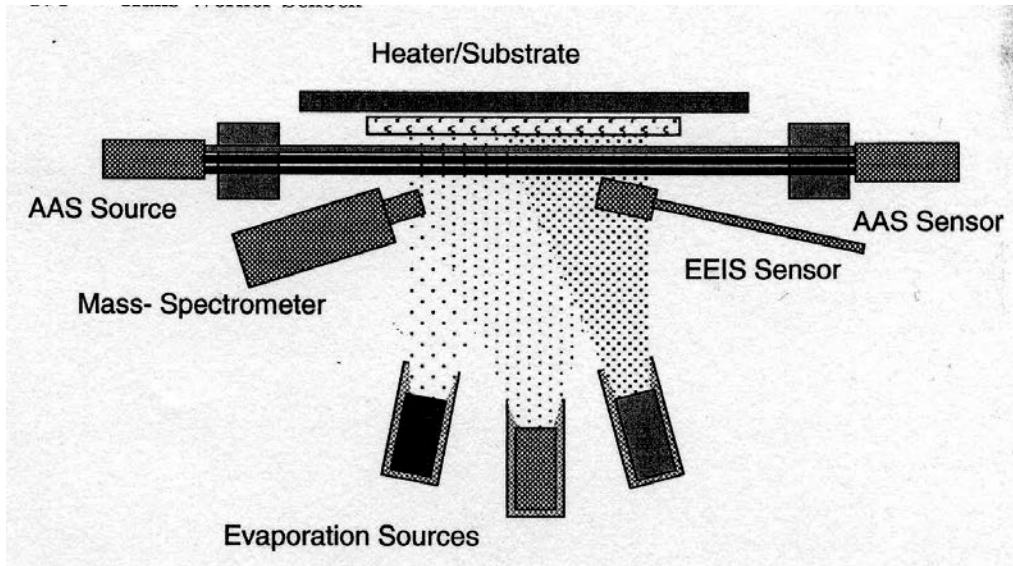


Fig. 1. The 'superstrate' configuration used for CdTe/CdS heterojunction solar cells.

Much less Cd required

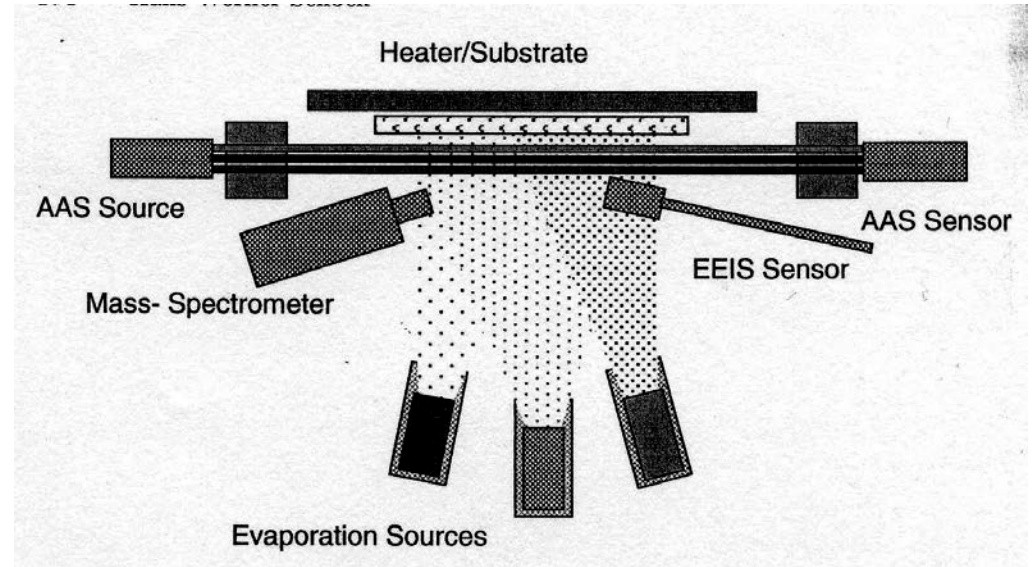
An example of vacuum-based CIGS film deposition



Y. Hamakawa Thin-film solar cells,

Vaccum-based CIGS film deposition

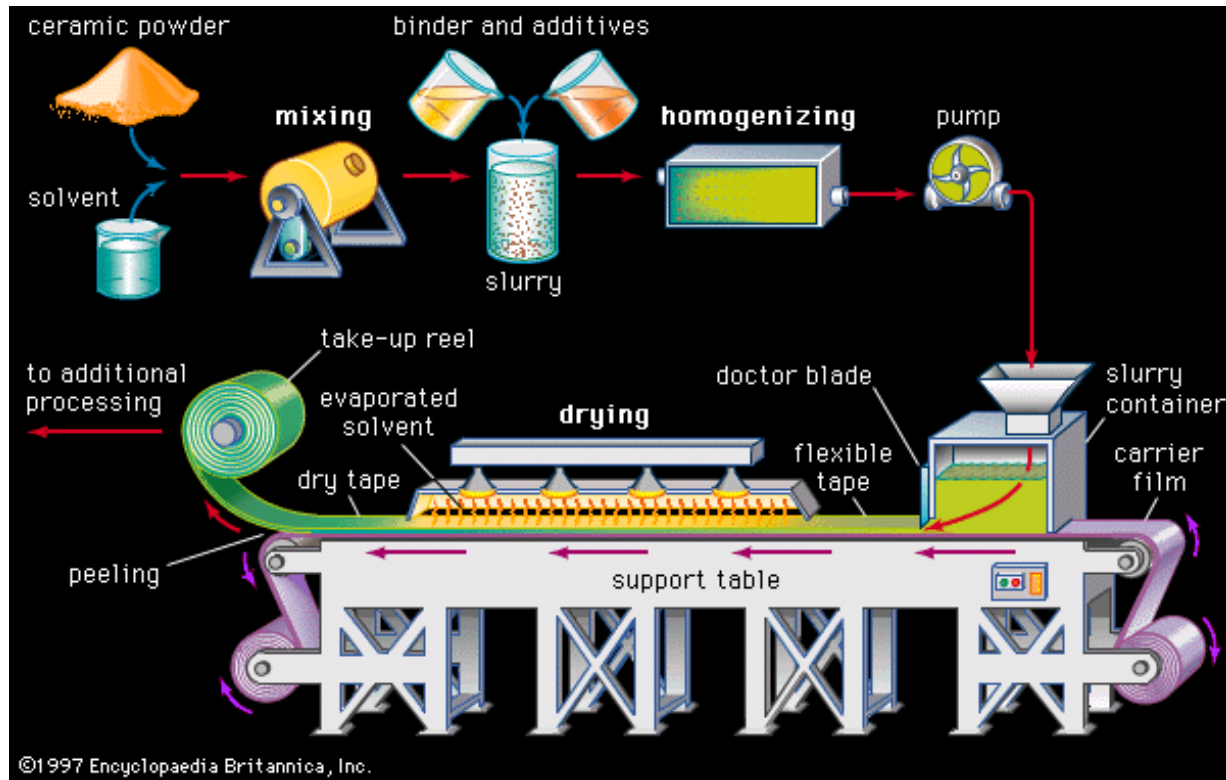
- Highest efficiency (lab scale: 18~20%)
- Usually UHV/MBE
- Cost prohibitive (but <cryst-Si)



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

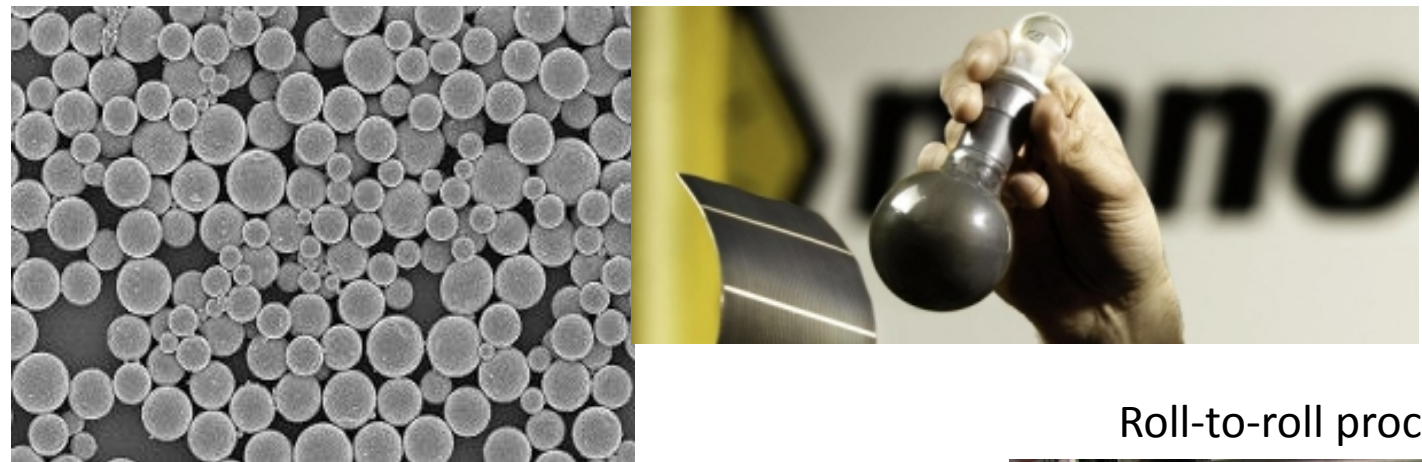
Non-Vacuum Processing



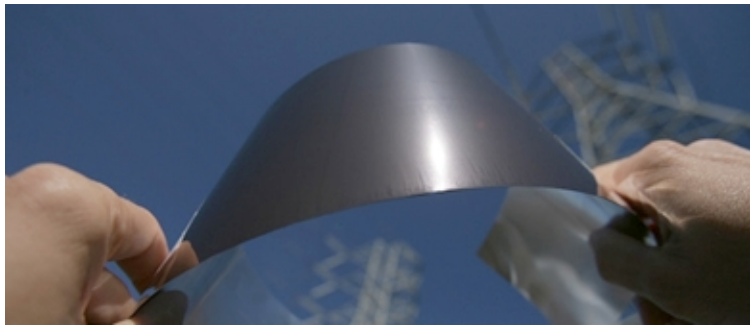
- Synthesize colloidal nanocrystals with controlled CIGS stoichiometry and deposit layer
- Roll-to-roll manufacturing process

Nano solar- Nanoparticle as ink for printable solar cell

CIGS particle ink



Flexible solar cell



Roll-to-roll processing



Add a video

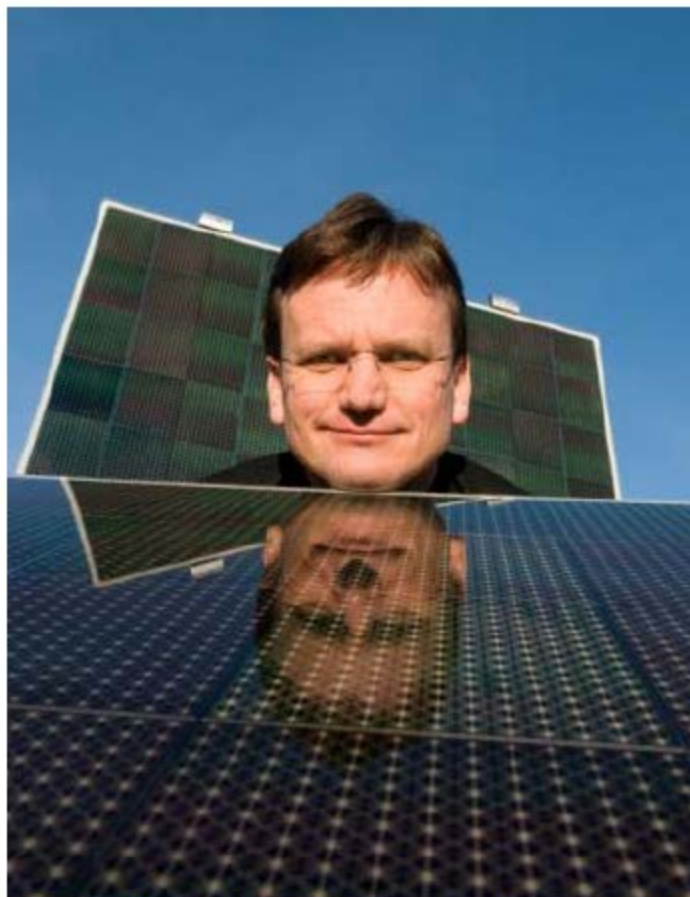
has denonstrated a 1GW coater in a movie¹⁶

1 GW CIGS solar cell fabrication process demonstrated by nanosolar



	Silicon Wafer cells	Vacuum- based thin film	Roll-printed thin film
Process	Si wafer processing	High vacuum deposition	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。

CIGS Rocks!

2012

【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。

CIGS Rock!

June 2013, 在CIGS太陽能電池領域，台積電是模組轉換率冠軍，2013年1月，台積電就已經以15.1%的轉換率拿下世界第一寶座，不過台積電精益求精，6月18日，台積電宣布轉換率又提升0.6%，來到15.7%，同時也改善溫度係數至-0.26%/°C

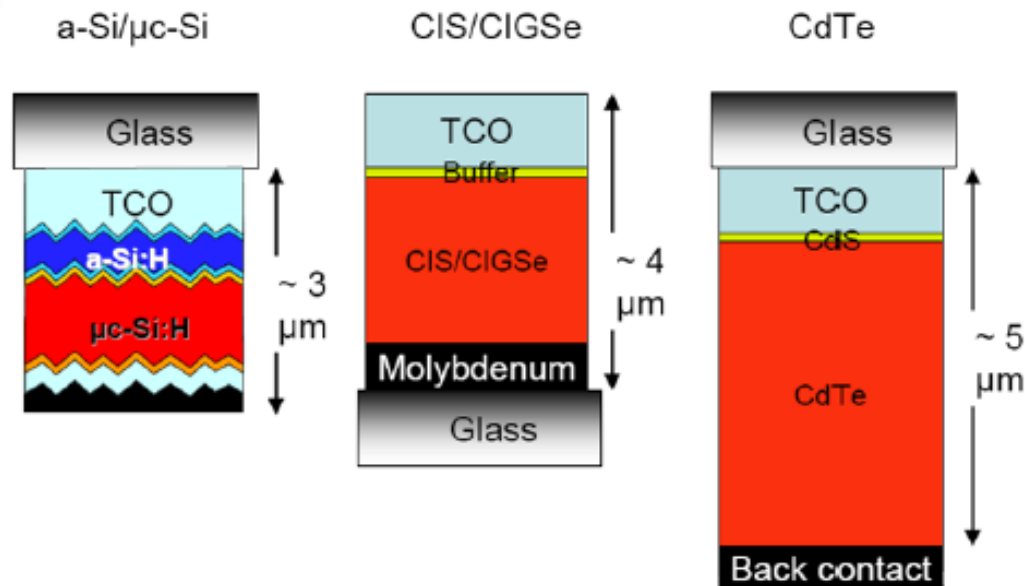
July, 2013 台積電轉換率提升的腳步可說相當快，2012年9月，台積電CIGS太陽能電池模組轉換率14.2%，5個多月後已到15.1%，4個多月後又來到15.7%，相較之下，競爭對手如日本Solar Frontier，6月18日也宣布其日本宮崎縣國富町廠的最佳產品已達到14.6%轉換率，Solar Frontier沾沾自喜表示此數據已經達到量產型多晶矽太陽能電池的水準，不過台積電還比他們更勝一籌。

基於歐盟委員會對中國大陸製造太陽能產品6月6日起至8月6日徵收反傾銷稅初步稅率11.8%並預定公告磋商結果，外界關注台積電CIGS太陽能模組實際銷售量產規模與價格，則僅表示，「合理利潤報酬」與「穩定出貨」原則，售價絕對不是落入PVsights等機構調查所謂的低檔區間。

台積電CIGS模組目標轉換效率方面預定在2014年產線上單片效率17%；廠區量產效率16%持續用開solar frontier等競爭者並稱將挑戰單晶與多晶模組效率。

台積電CIGS太陽能模組量產良率達95% 產能全開800MW

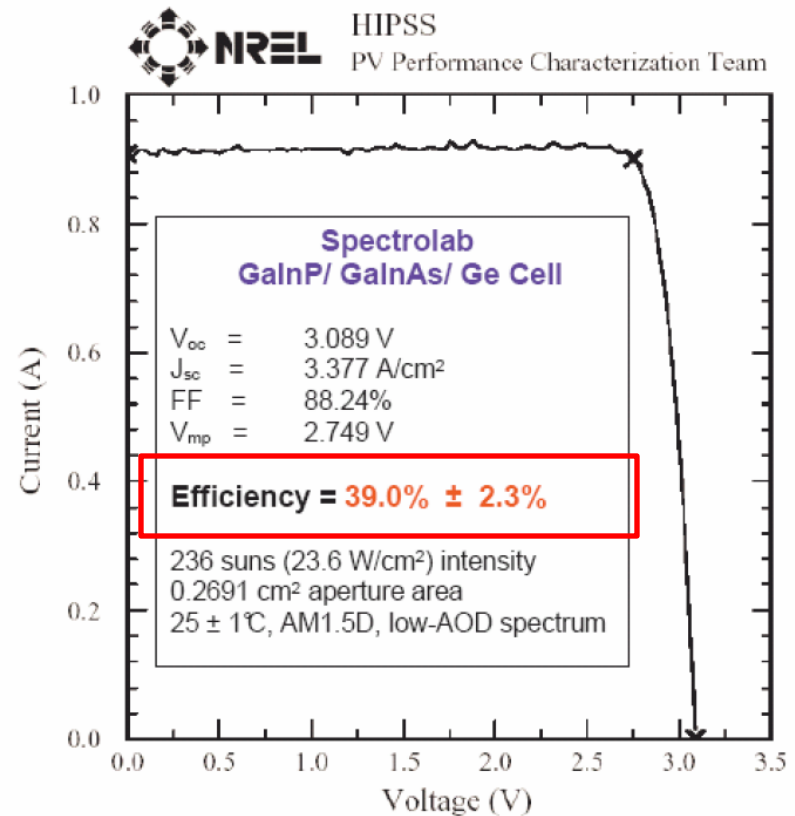
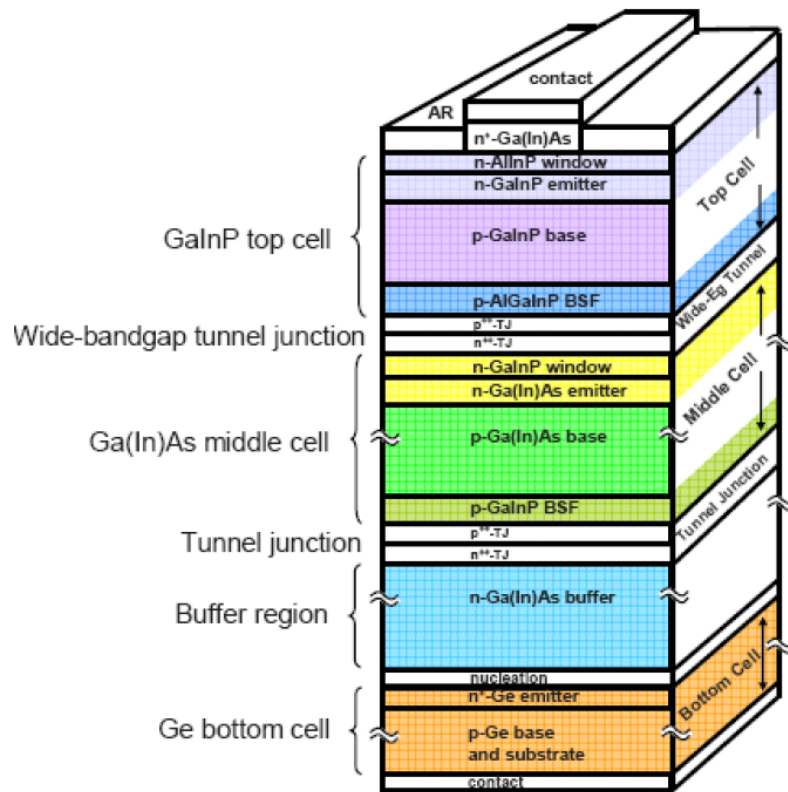
Comparison of three thin film solar cells



	a-Si/ μ c-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)

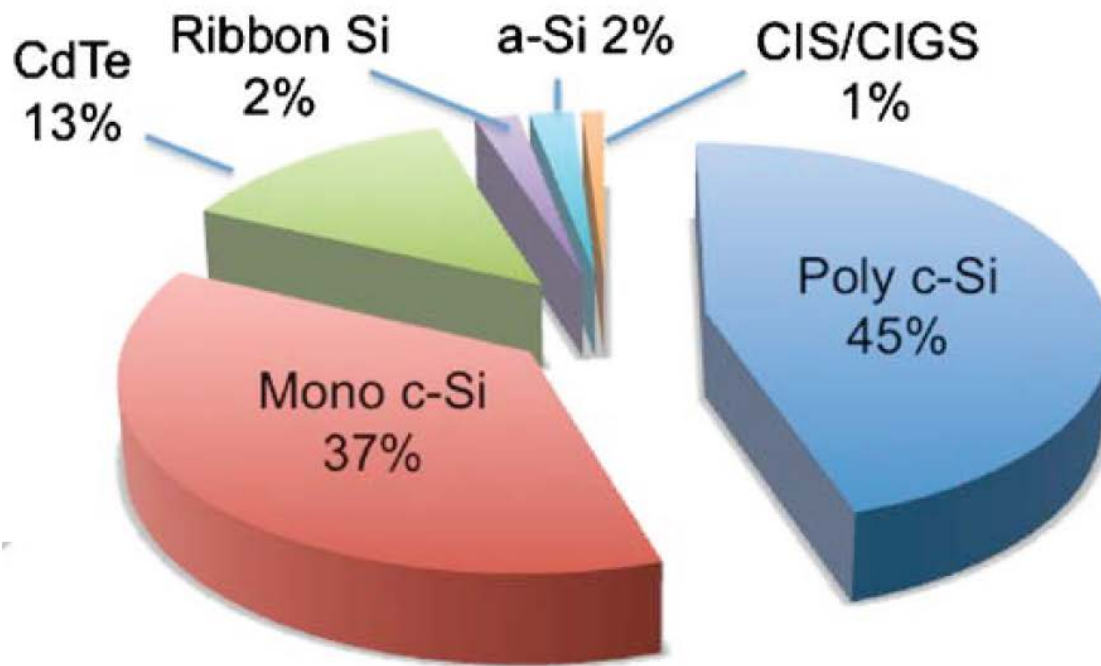
Tandem Junction Solar cells

GalnP/GaAs/Ge Triple Junction Cell



Video

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.

能源科技與環境概論

電池的簡介

Hsing-Yu Tuan (段興宇)

Department of Chemical Engineering, National Tsing-Hua University

Batteries



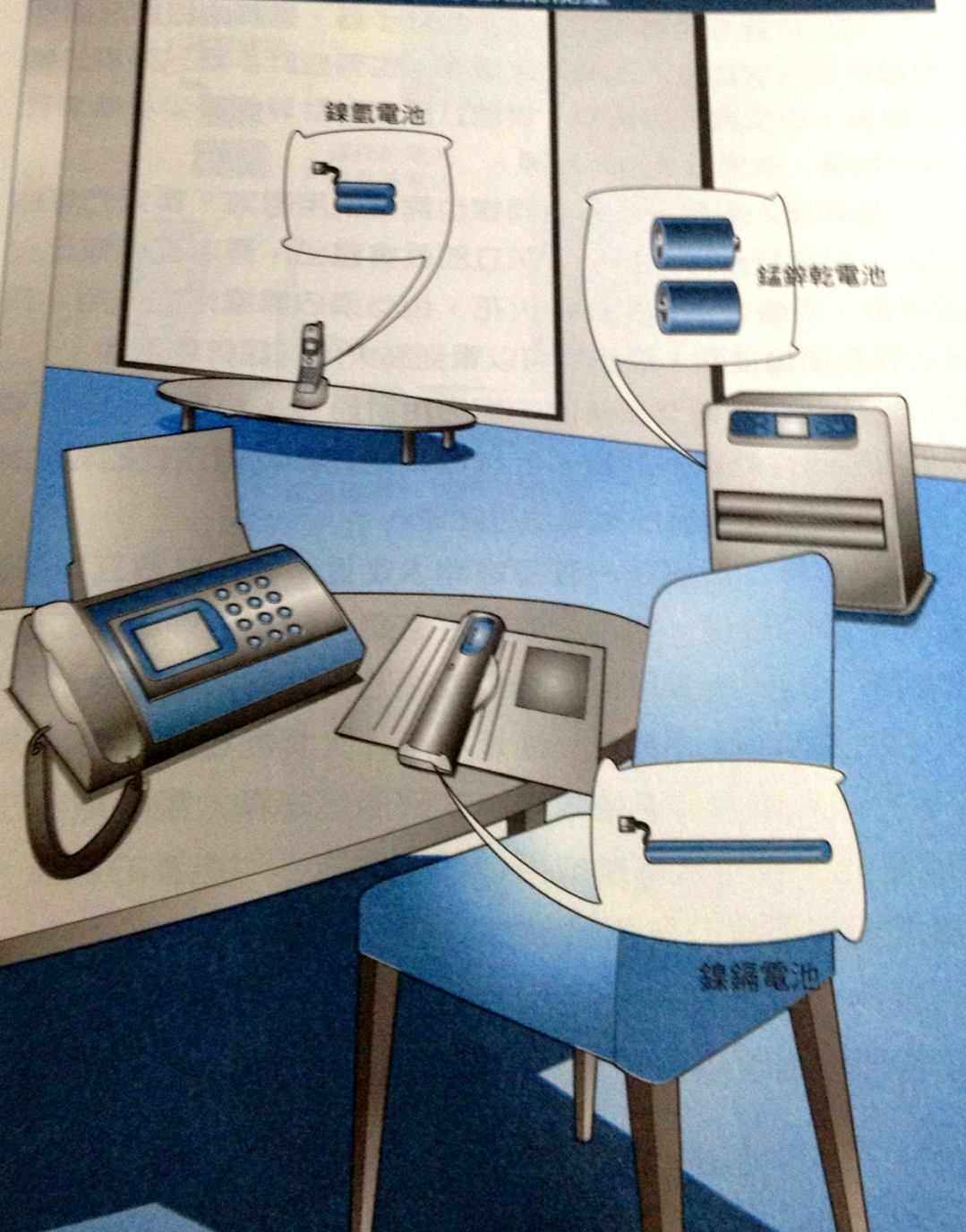
- Definition: devices that transform chemical energy into electricity
- Every battery has two terminals:
positive cathode (+) and the negative anode(-)
- Procedure to produce electricity

Device plug in → chemical reaction started
→ electron produced → electron travel from (-)
to (+) → electrical work is produced



客廳

家用電話和暖爐設備都同樣利用電池的能量



家用電話 和暖爐設備



洗臉台等場所使用的電池設備

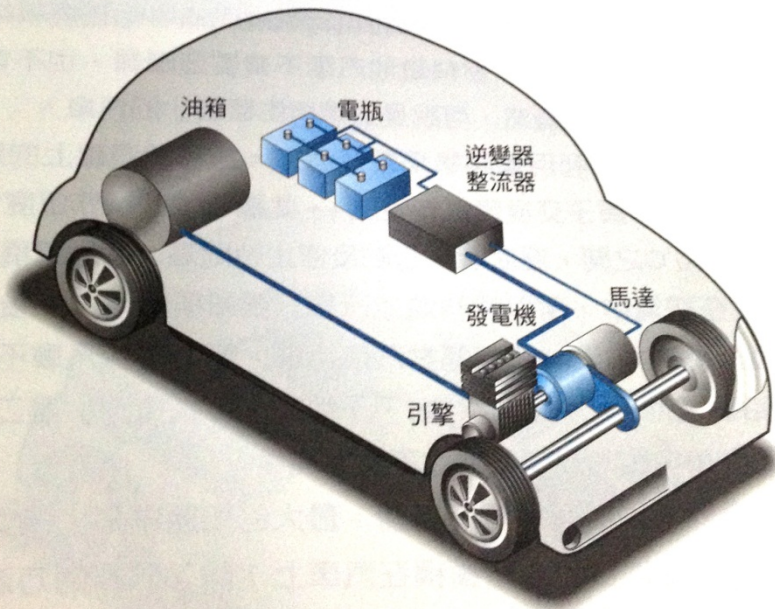
Mobile

- Mostly Lithium-ion batteries

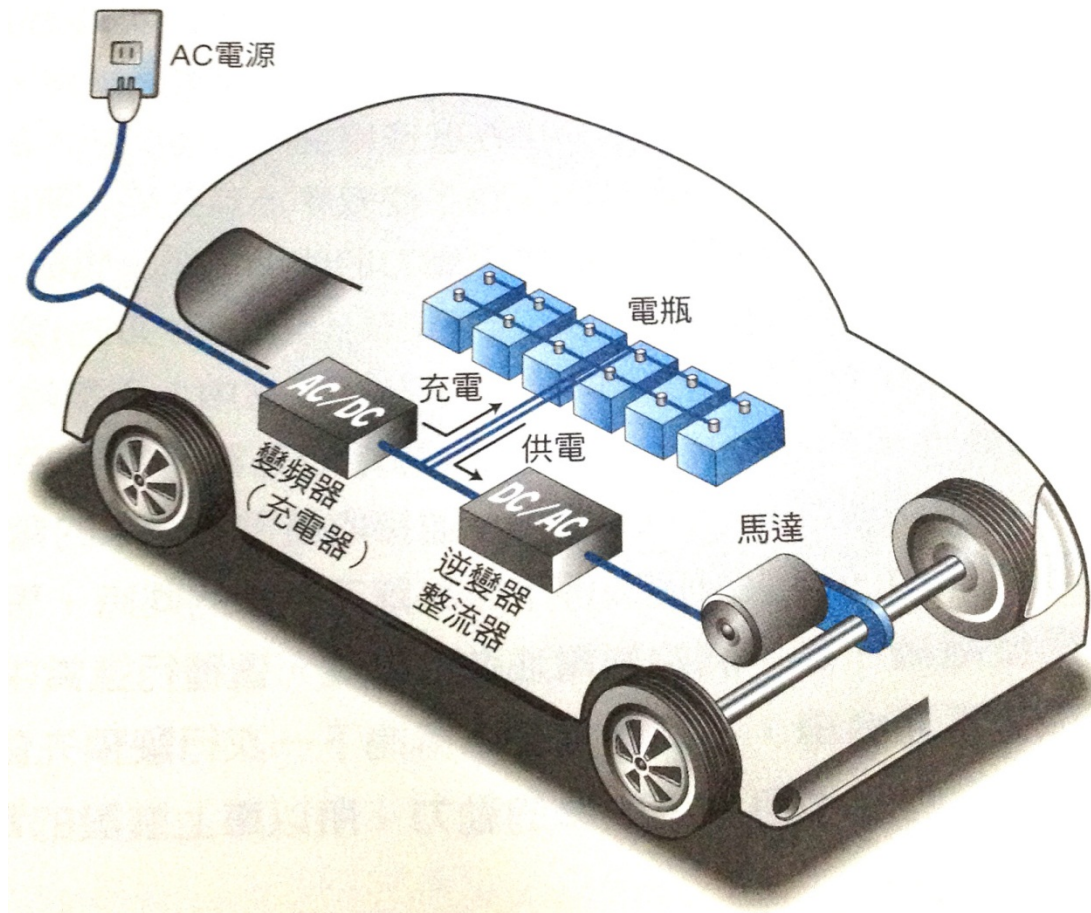


Hybrid car

- 行進過程，引擎本身附有大型發電機，除了驅動汽車，也會產生電力，為電池充電。

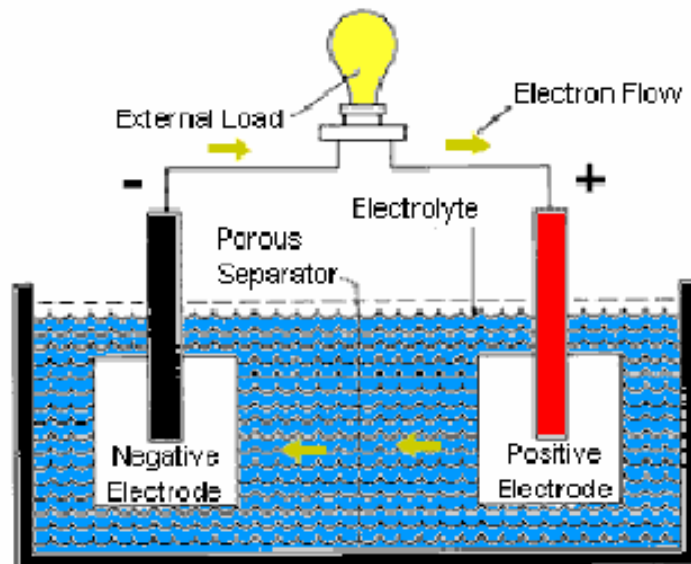


Electrical car



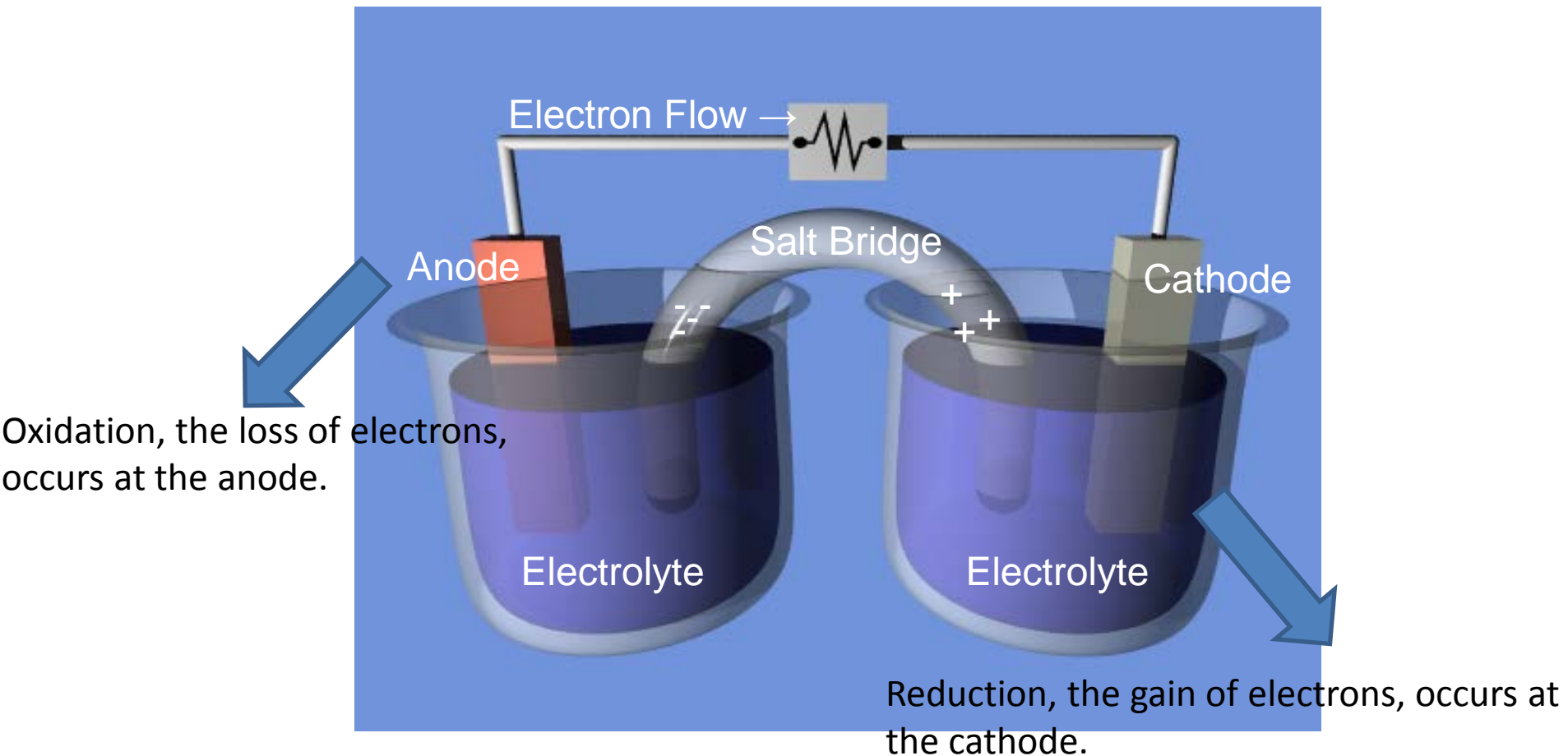
Electrochemical Cell

- An electrochemical cell :
 - a negative electrode to which anions (-) migrate – donates electrons to the external circuit as the cell discharge (anode)
 - A positive electrode to which cations migrate (cathode)
 - Electrolyte solution containing dissociated salts, which enable ion transfer between the two electrodes, providing a mechanism for charge to flow between positive and negative electrodes.
 - A separator which electrically isolates the positive and negative electrodes.




How Electrochemical Batteries Work

- REDOX Reaction



The Periodic Table: choose the electrode

Periodic Table of the Elements



- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

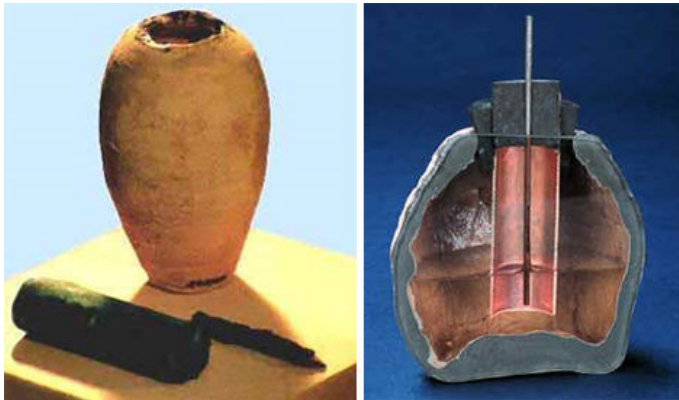
1 H																	2 He																												
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne																												
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar																												
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr																												
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe																												
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn																												
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Uun																																				
<table border="1" style="width: 100%; border-collapse: collapse; text-align: center; background-color: gray;"> <tr> <td>58 Ce</td><td>59 Pr</td><td>60 Nd</td><td>61 Pm</td><td>62 Sm</td><td>63 Eu</td><td>64 Gd</td><td>65 Tb</td><td>66 Dy</td><td>67 Ho</td><td>68 Er</td><td>69 Tm</td><td>70 Yb</td><td>71 Lu</td> </tr> <tr> <td>90 Th</td><td>91 Pa</td><td>92 U</td><td>93 Np</td><td>94 Pu</td><td>95 Am</td><td>96 Cm</td><td>97 Bk</td><td>98 Cf</td><td>99 Es</td><td>100 Fm</td><td>101 Md</td><td>102 No</td><td>103 Lr</td> </tr> </table>																		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu																																
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr																																

Combination of electrodes to make a variety types of batteries:
 lithium ion battery 、 nickel-zinc 、 zinc air 、 Nickel cadmium 、 Ni iron 、 Silver zinc 、 Mercury cell

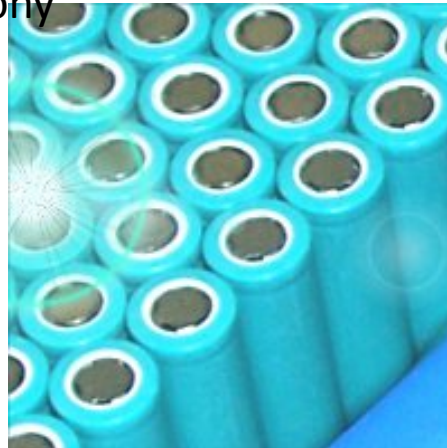
The History of Battery

Volta piles

Baghdad battery



Lithium ion battery -sony



Time	Event	Name
200 B.C.	Baghdad battery	??
1791	Frog leg experiment	Galvani
1800	Voltaic piles	Volta
1802	Mass produced battery	Cruikshank
1812	Giant battery (2,000 cells)	Davy
1820	Electricity from magnetism	Ampere
1827	Ohm's law	Ohm
1833	Ionic mobility in Ag ₂ S	Faraday
1836	Cu/CuSO ₄ , ZnSO ₄ /Zn	Daniell
1839	Principle of the air cell	Grove
1859	Lead acid battery	Planté
1868	Zn/NH₄Cl/C wet battery	Leclanché
1874	Telegraph	Edison
1878	Air Cell	Maiché
1880	High capacity lead/acid	Faure
1881	Zn/NH₄Cl/C encapsulated	Thiebault
1885	Zinc-bromine	Bradley
1887	Zn/NH₄Cl/C dry battery	Gassner
1891	Thermodynamics of dry cells	Nernst
1899	Nickel cadmium battery	Jungner
1900	Ni Storage batteries	Edison
1905	Ni iron batteries	Edison
1911	Automobile self-starter	Kettering
1927	Silver zinc	Andre
1930	Nickel-zinc battery	Drumm
1943	Cuprous chloride battery	Adams
1945	Mercury cell	Ruben
1950	Sealed mercury Cell	Ruben
1956	Alkaline fuel cell	Bacon
1959	Alkaline primary cell	Urry
1983	Lithium metal rechargeable	Moli
1991	Commercial lithium ion	Sony
1992	Reusable alkaline	Kordesch
1995+	Recent developments	..

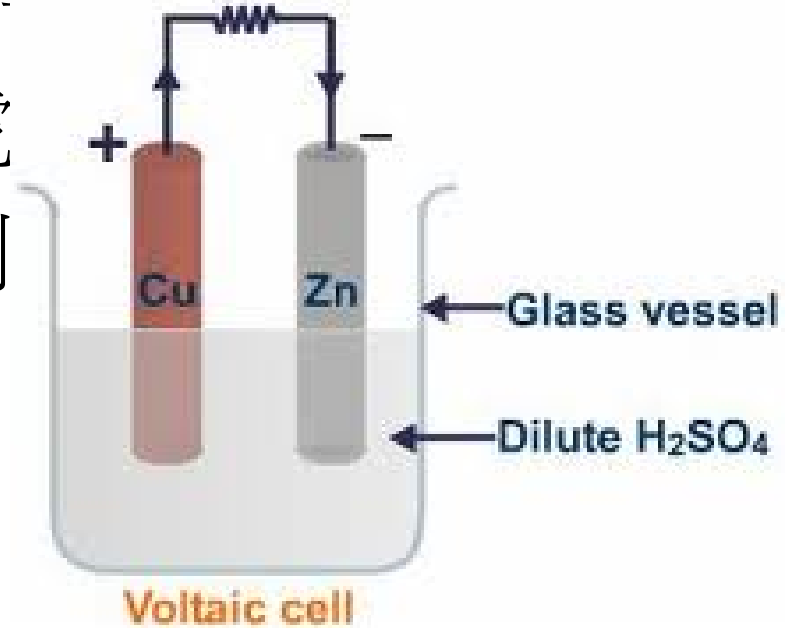


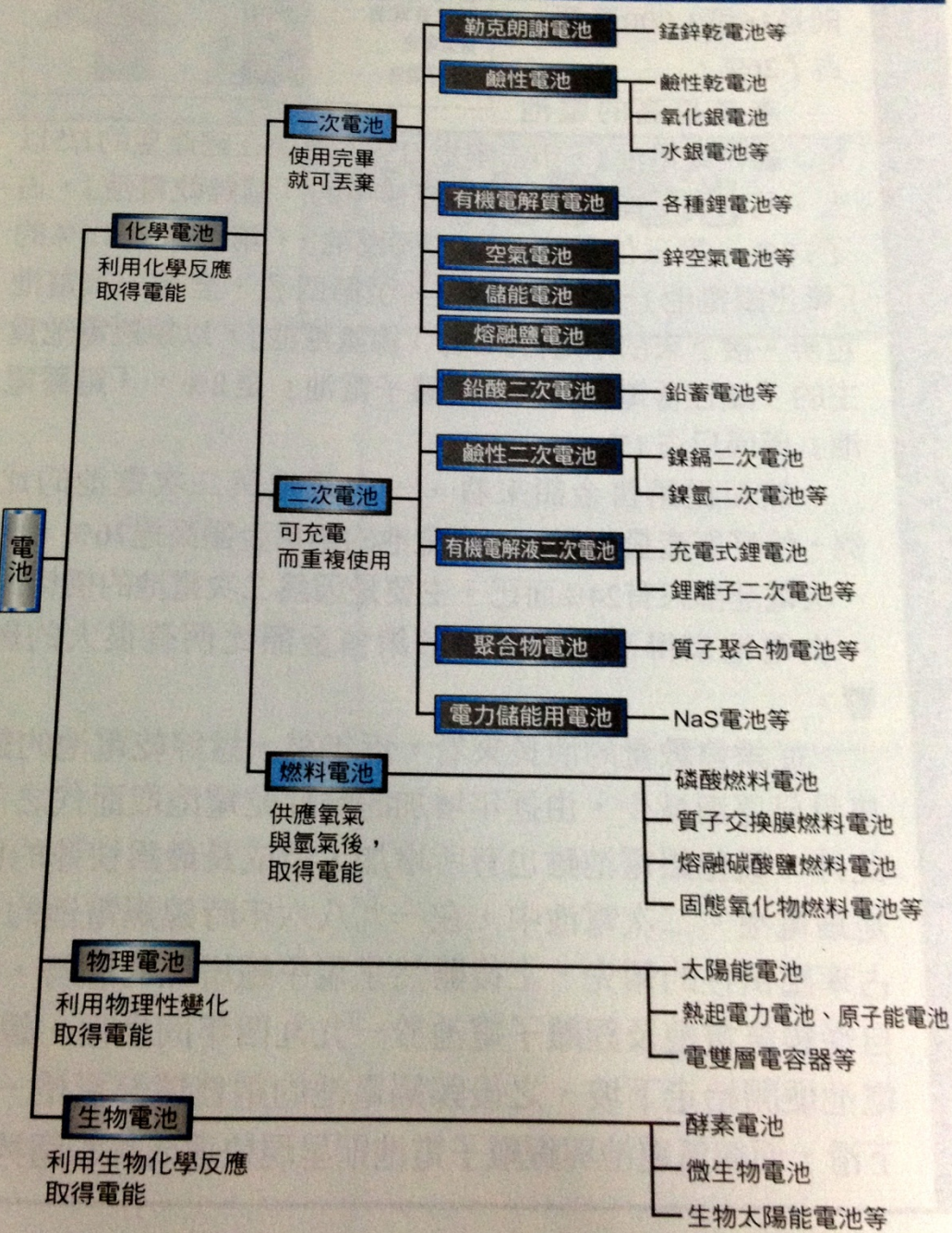
Electrochemical Battery History Cont'd

- The Nickel-Cadmium Battery
 - Invented in 1899 by Waldmar Jungner.
- The common Alkaline Battery
 - Invented in 1955 by Lewis Urry
- The Nickel Metal-Hydrid Battery
 - NiMH batteries for smaller applications started to be on the market in 1989.
- Lithium and Lithium-ion Batteries
 - First lithium batteries sold in the 1970s
 - First lithium-ion batteries sold in 1991 → portable electronic devices
 - First lithium-ion polymer batteries released in 1996

伏特電池的原理

- 在稀硫酸中插入銅板和鋅版兩種電極
 - 鋅金屬變成鋅離子溶出 Zn^{+2} 鋅變成負電
 - 銅板不會融化，但因電⁻被 H^+ 帶走帶著一點正電
- 以導線連接鋅版和銅板則產生電流，直到鋅版耗盡。





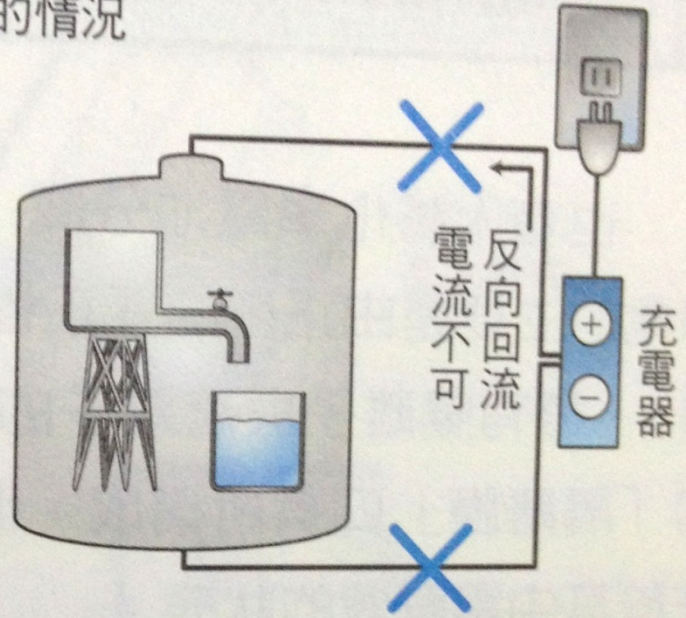
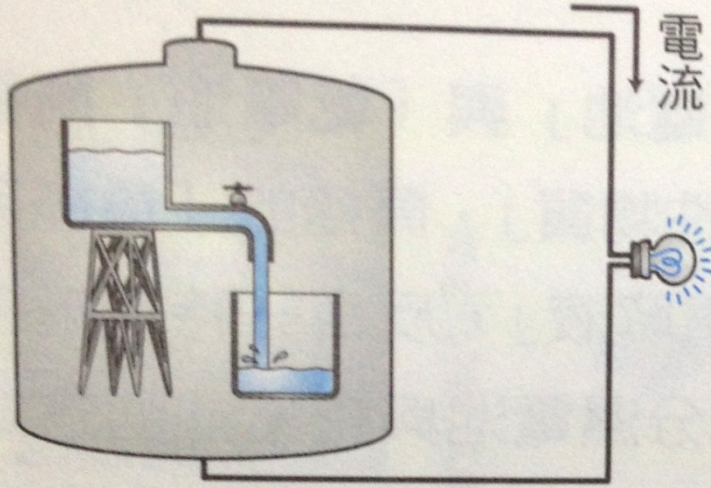
Various
kinds of batteries

Primary vs. Secondary Batteries

- Primary batteries are disposable : their electrochemical reaction cannot be reversed.
- Secondary batteries are rechargeable, because their electrochemical reaction can be reversed by applying a certain voltage to the battery in the opposite direction of the discharge.

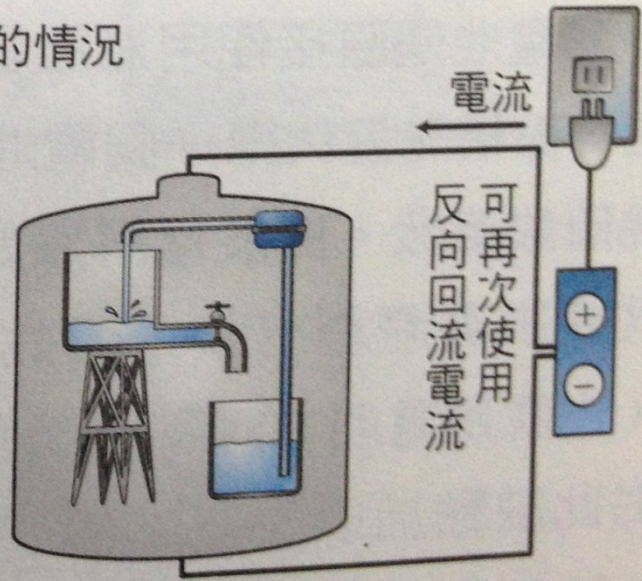
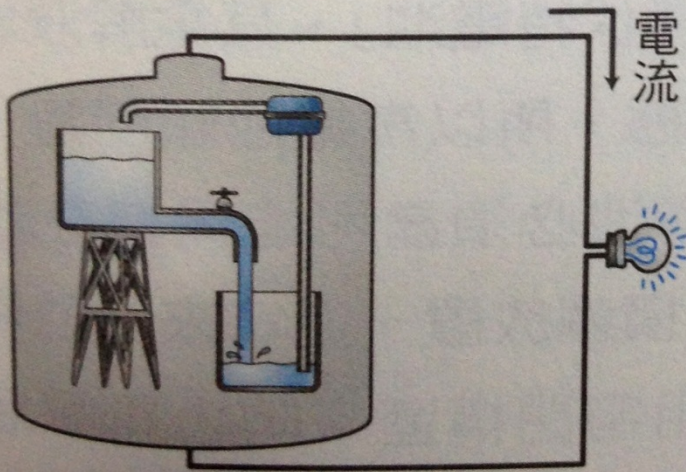
不可逆反應

一次電池的情況



可逆反應

二次電池的情況

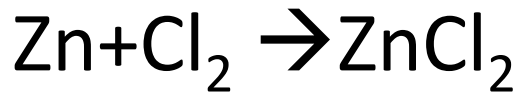


Terminology and Units

- Primary Batteries – Disposable
- Secondary Batteries – Rechargeable
- emf – Electromotive force, voltage
- Ampere·hour (Ah) = 3600 coulombs, a measure of electric charge
- Watt ·hour (Wh) = 3600 joules, a measure of energy
- $Ah = (Wh) / emf$

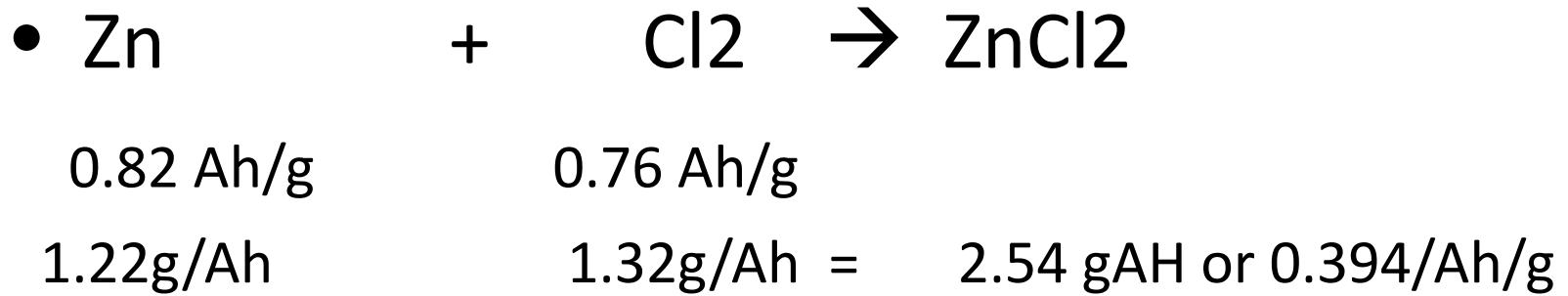
Theoretical Cell voltage

- Anode (oxidation potential)+ cathode (reduction potential)=standard cell potential



$$E^\circ = 2.12 \text{ V} \rightarrow \text{theoretical voltage}$$

Theoretical capacity



Primary Alkaline Batteries

- Can lose 8 – 20% charge every year at room temperature.
- Discharge performance drops at low temperatures.



	AAA	AA	9V	C	D
Capacity (Ah)	1.250	2.890	0.625	8.350	20.500
Voltage	1.5	1.5	9	1.5	1.5
Energy (Wh)	1.875	4.275	5.625	12.525	30.75

Secondary Alkaline Batteries

- Self-discharge more quickly than primary batteries

	Low-Capacity NiMH (1700-2000 mAh)	High-Capacity NiMH (2500+ mAh)	NiCd
Charge Cycles	1000	500	1000

- Must not overcharge because that will damage the batteries. Quick charges will also damage the batteries.
- Must not over-discharge.
- NiCd has “memory effect.”
- NiCd is better for applications where current draw is less than the battery’s own self-discharge rate.
- NiMH have a higher capacity, are cheaper, and are less toxic than NiCd.

Recharge-ability & the “memory effect”

- Recharge-ability: basically, when the direction of electron discharge (negative to positive) is reversed, restoring power.
- the Memory Effect:
 - The battery appears to "remember" the smaller capacity
 - the term 'memory' came from an aerospace nickel-cadmium application in which the cells were repeatedly discharged to 25% of available capacity by exacting computer control, then recharged to 100% capacity **without overcharge**. This long-term, repetitive cycle regime, with no provision for overcharge, resulted in a loss of capacity beyond the 25% discharge point. Hence the birth of a "memory" phenomenon, whereby nickel-cadmium batteries purportedly lose capacity if repeatedly discharged to a specific level of capacity.

Types of Batteries

- Zinc-Carbon: used in all inexpensive AA, C, and D dry-cell batteries. The electrodes are zinc and carbon, with an acidic paste between them serve as the electrolyte (disposable)



- Alkaline: Duracell or Energizer cell batteries. The electrodes are zinc and manganese-oxide, with an alkaline electrolyte (disposable)



Modern batteries

- Lead-Acid: used in cars: the electrodes are lead and lead-oxide, with an acidic electrolyte (rechargeable)



- Lithium-ion batteries
 - rechargeable and no memory effect



- Fuel cells



碳鋅電池

- 電壓：1.5V
- 正極：二氧化錳
- 負極：鋅
- 電解液：NH₄Cl、ZnCl₂

Battery Aspects

- Energy Density: total amount of energy that can be stored per unit mass or volume → how long will your laptop run by a fully-charged cell.
- Power Density: Maximum rate of energy discharge per unit mass or volume. Low power: laptop, ipod high power car
- Safety: could sustain at high temperatures
- Life: stability of energy density and power density with repeated cycling is needed for the long life required in many applications.
- Cost: Must compete with other energy storage technologies