Developing of Silicon thin-film solar cells

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99/11/15

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- 簡介
- 製程控制
- 材料控制
- 元件結構
- 新材料與元件
- 研發與生產現況
- 結論

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簡介

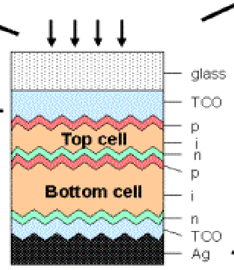
R&D Topics

Silicon thin film solar cells

cell concepts
stacked cells
amorphous / μc
pin/nip
ligth trapping

Solar cell characterization and modelling
efficiency
quantum yield
ligth coupling
degradation

Transparent conductive contact layers (TCOs)
ZnO, ligth coupling



Absorber layers
electr./opt./struct. Properties
a-Si(X):H (X: Ge,O,C,N,...)
μc-Si(X):H (X: Ge,...)

Interfaces
electronic properties
chemical stability

Process technology
process control
rate increase
scaling up to 30x30 cm²
small modules

Cell development
doped function layers
recombination layers
incorporatin of new absorber layers

Institute of Photovoltaics (IPV), Forschungszentrum Juelich GmbH, Germany

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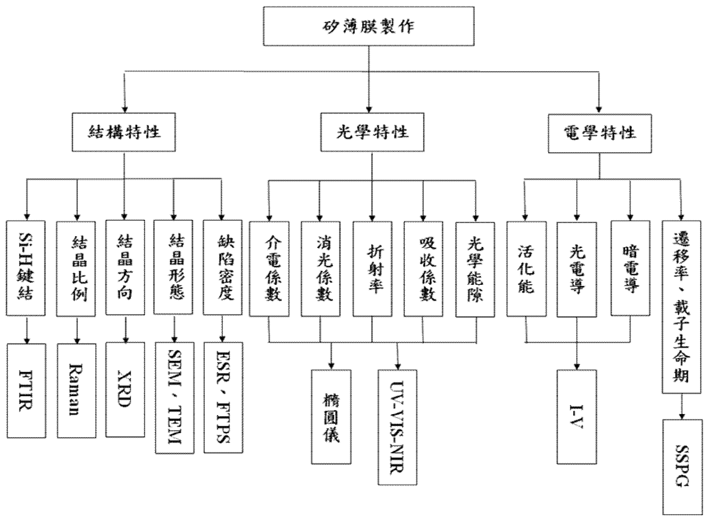
矽薄膜的結構、光學及電學特性分析



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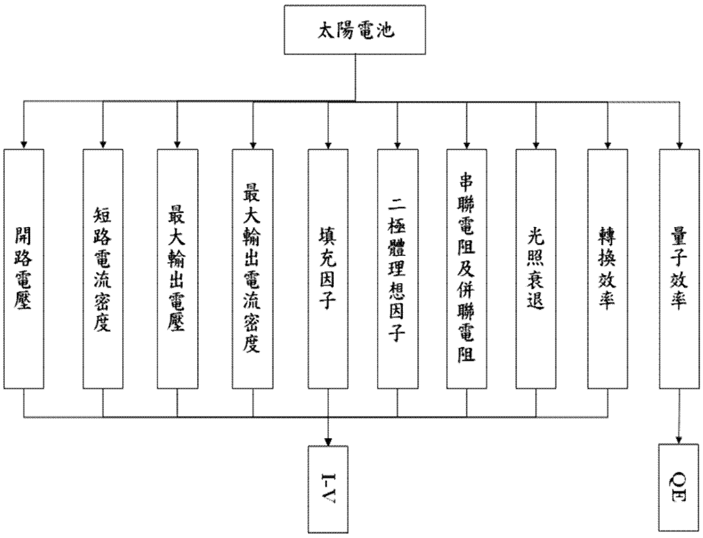
矽薄膜太陽電池電流-電壓及光譜響應性質的分析



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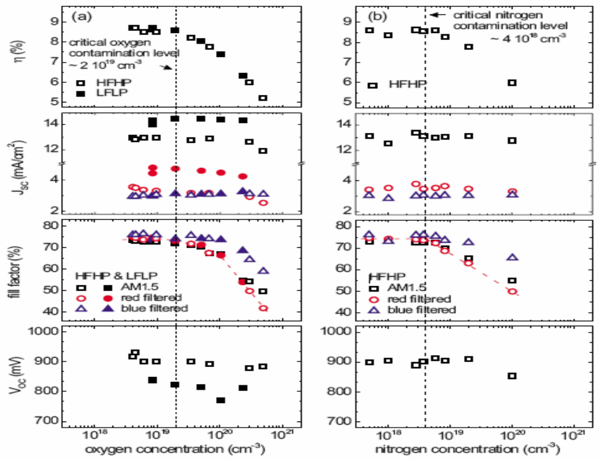
製程控制: 氧及氮汙染



製程方式	SiH_4/H_2 (sccm)	Pressure(torr)
HFHP	7.8/360	10
LFLP	12/100	3

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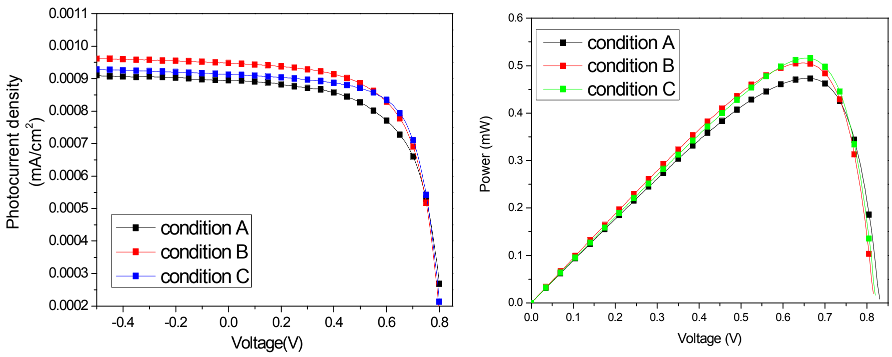
J. Woerdenweber . et.al., JOURNAL OF APPLIED PHYSICS **104, 094507 2008**

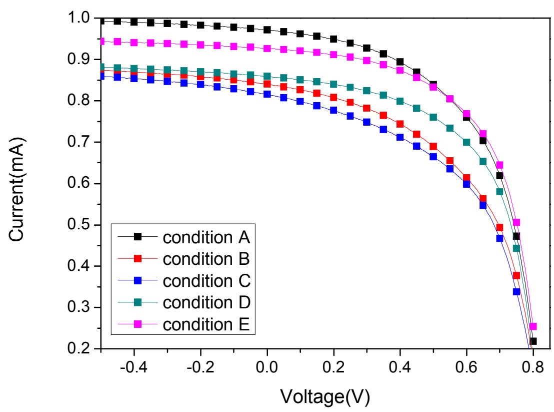
污染控制(1)

(a) (b)



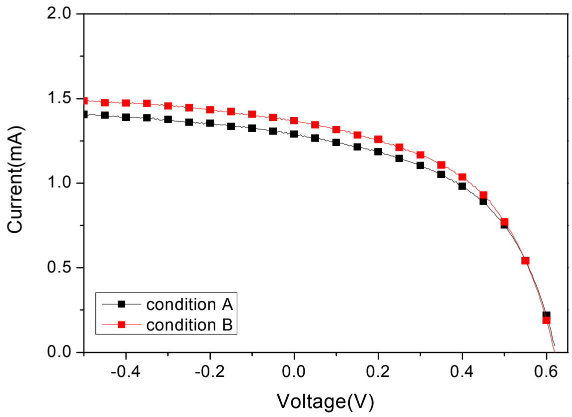
於不同製程壓力下之太陽電池的 (a)*I*-*V*特性曲線與 (b)輸出功率疊圖

污染控制(2)



試片名稱	Voc (V)	Isc(mA)	Jsc(mA/cm^2)	FF (%)	Eff (%)
condition A	0.83	0.97	13.7	56.9	6.49
condition B	0.83	0.84	11.9	53	5.22
condition C	0.83	0.82	11.5	53.2	5.09
condition D	0.82	0.86	12.2	60	6.01
condition E	0.83	0.93	13.1	60.7	6.63

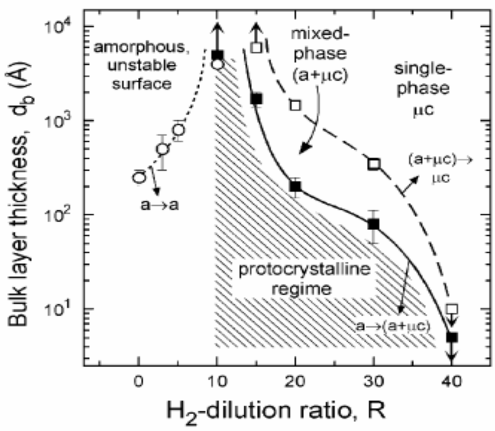
污染控制(3)



試片名稱	Voc(V)	Isc(mA)	Jsc(mA/cm²)	FF(%)	η (%)
condition A	0.625	1.28	18.25	49.92	5.69
condition B	0.62	1.36	19.37	49.68	5.97

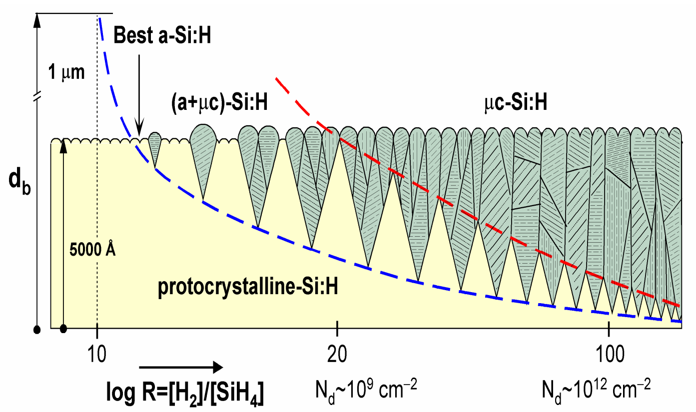
材料控制

Hydrogenated proto-crystalline silicon: pc-Si:H

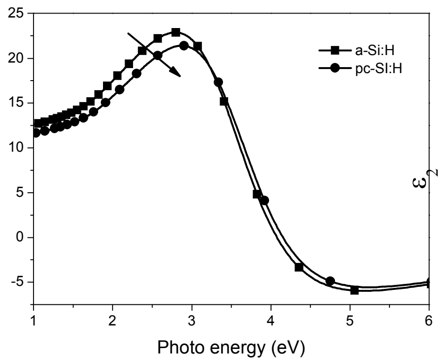


C.R. Wronski *, R.W. Collins, Solar Energy 77 (2004)

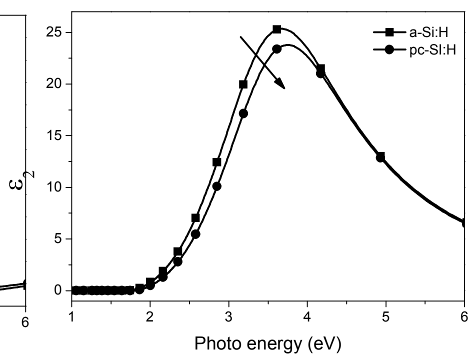
pc-Si:H



a-Si:H與pc-Si:H薄膜的介電係數



介電係數實部(ε 1)



介電係數虛部(ε 2)

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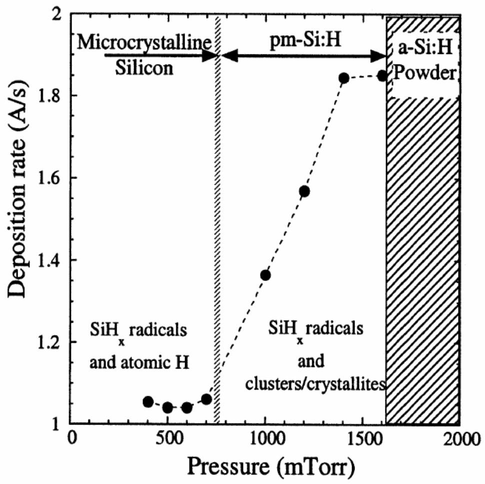
Hydrogenated polymorphous silicon: pm-Si:H



dispersed nanocrystallines embedded in an amorphous network

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C. Longeaud et al. Journal of Non-Crystalline Solids 227–230(1998)96–99

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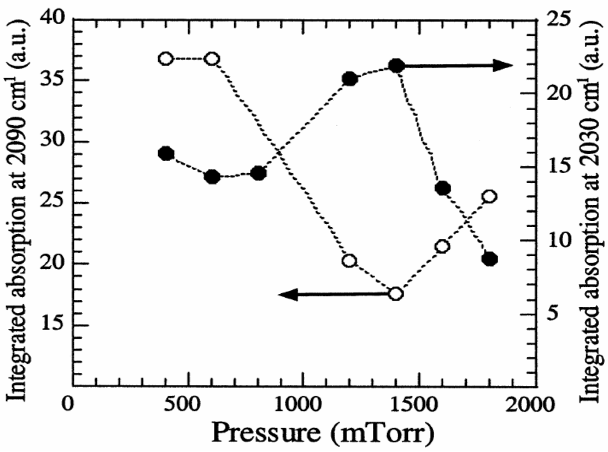
pm-Si:H: Si-H bonds



2002 IUPAC, *Pure and Applied Chemistry 74, 359–367*

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pm-Si:H: Defect absorption

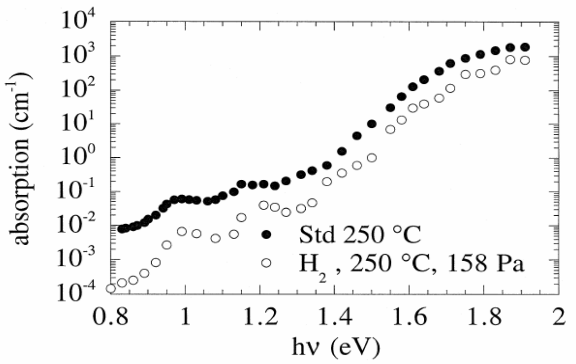
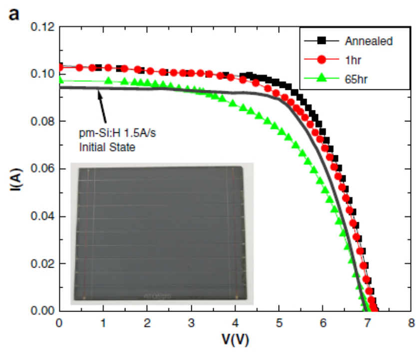


Fig. 3. CPM spectra of a ‘standard’ sample and of the best sample of the H_2 series.

C. Longeaud et al., J. of Non-Crystal. Solids 227–230,1998, 96–99

pm-Si:H 太陽電池

結構	Voc (V)	Jsc (mA/cm^2)	F.F (%)	η (%)	出處
Glass/textured SnO_2:F/p+ a-SiC:H/pm-Si:H /n+ a-Si:H /Al	0.94	13.1	65	7.7	Y.M. Soro, et. al, Journal of Non-Crystalline Solids, v 354, p 2092-2095, January 2008
Glass/SnO_2/p-typea-SiC:H/intrinsic a-SiC:H buffer/pm-Si:H/n-type aSi:H/Al	0.91	14.8	69	9.3	S. Tchakarov, et. al, Journal of Non-Crystalline Solids, v 338-340, p 668-672, 2004



Y.M. Soro, et. al, Journal of Non-Crystalline Solids, v 354, p 2092-2095, January 2008

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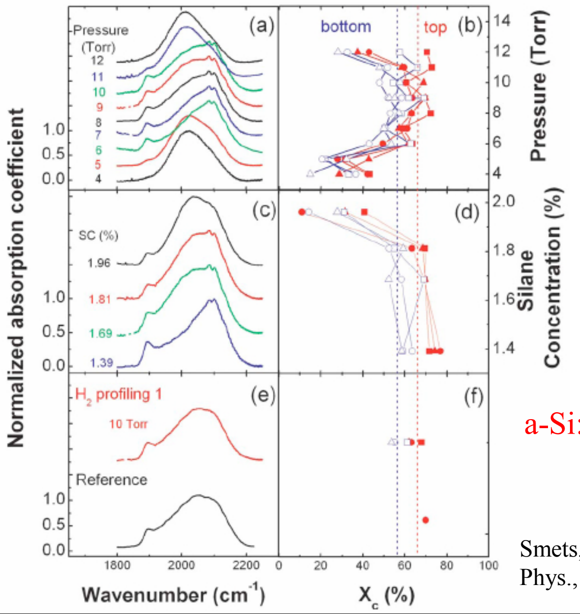
Hydrogenated microcrystalline silicon: μc-Si:H



Pressure(torr) ： 3-12

SiH_4 flow(sccm) ： 12

H_2 flow(sccm) ： 600-850

a-Si:H→μc-Si:H transition

Smets, A.H.M. et.al., J. Appl. Phys., 104, 034508(2008).

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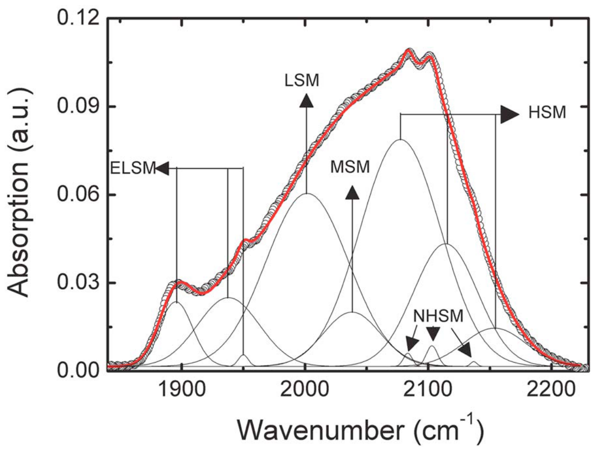
μc-Si:H薄膜伸張模吸收峰特徵



Smets, A.H.M. et.al., J. Appl. Phys., 104, 034508(2008).

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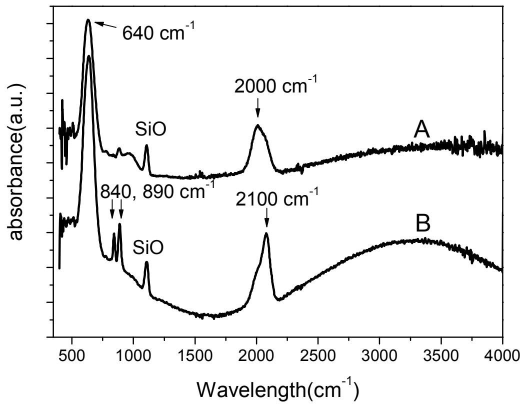
controlling of plasma chemistry



以短脈衝(A)及長脈衝(B)開關時間製作的a-Si:H 薄膜之FTIR吸收光譜

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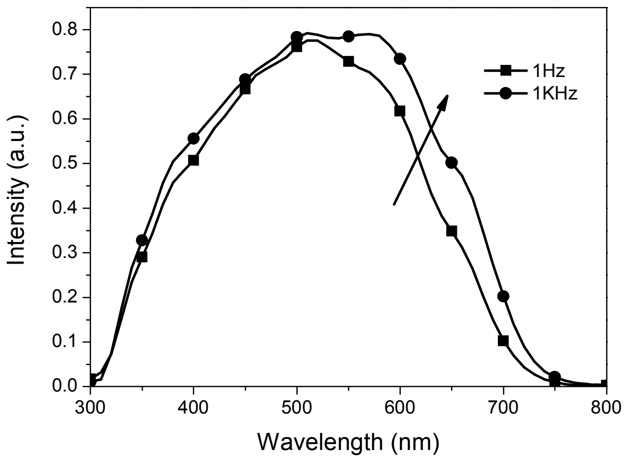
controlling of plasma chemistry



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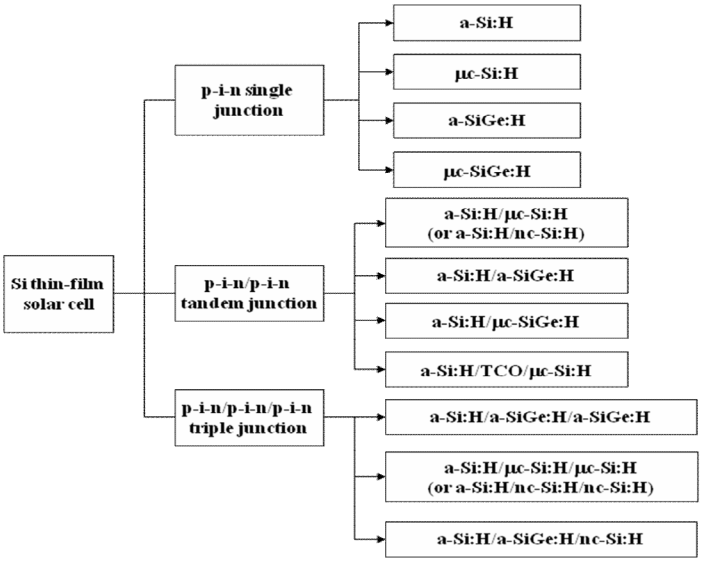
以脈波電漿頻率1 Hz及1 kHz製作的a-Si:H薄膜太陽電池QE曲線

矽薄膜太陽電池元件結構



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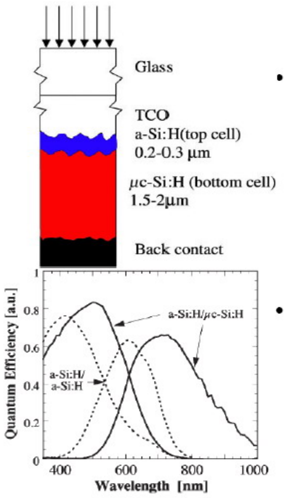
a-Si:H/μc-Si:H tandem cell: micromorph cell



- IMT pioneered in 1994
  the **μc-Si:H/a-Si:H**
  or « **micromorph** » tandem
- In such a micromorph tandem,
  the solar spectrum is ideally shared
  between **top (a-Si:H)** and
  bottom (μc-Si:H) cell.

[A. Shah et al., Prog. Photovolt: Res. Appl. 12 (2004) 113-142]

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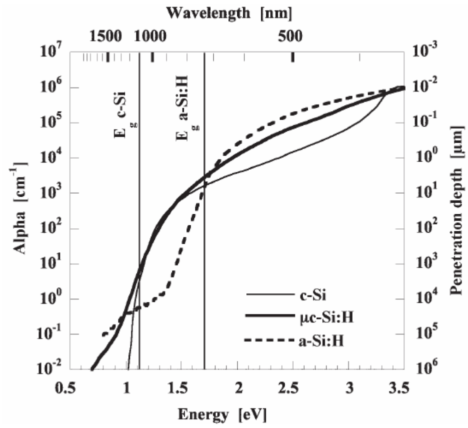
a-Si:H及μc-Si:H 的吸收係數與光能量關係曲線



Shah, A.V. et.al., J, prog. photovolt: Res. Appl., 12, 113~142(2004).

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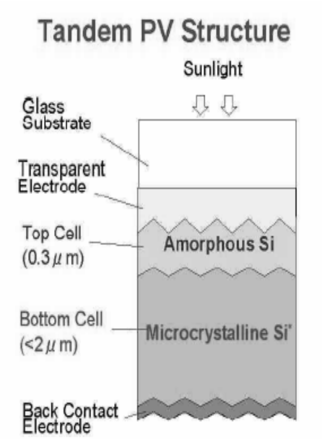
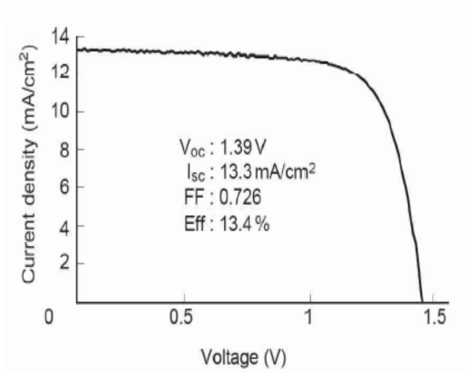
a-Si:H/μc-Si:H tandem solar cell (MHI)





Takatsuka, H.et.al.,IEEE, 2, 2028-2033(2007).

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ULVAC: CCV-1400 and CIM-1400

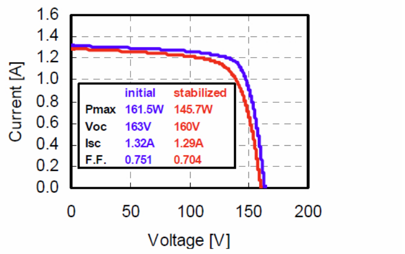

Figure 5: Characteristic of a-Si/mc-Si tandem junction module

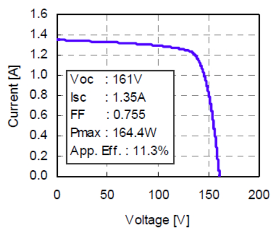

Figure 8: Initial characteristics of a-Si/mc-Si tandem module with increased thickness of absorbers.

Top cell: 250 nm
Bottom cell: 1,800 nm
Degradation: 10%
Stab. Eff.: 10%

Top cell: 280 nm
Bottom cell: 2,000 nm

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Y. Ue, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

Oerlikon Solar: KAI systems

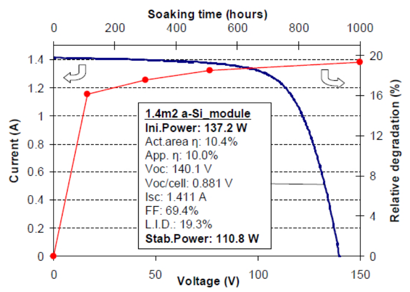

Figure 3: I(V) characteristic and parameters of a 1.4 m^2 a-Si:H single junction module comprising the absorber3 layer with a thickness of 220 nm. On the secondary axis the relative light induced degradation of corresponding cells is shown. A stabilized module power of 110.8 W is achieved.

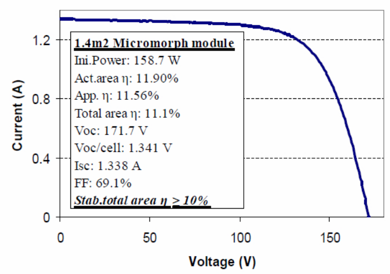

Figure 6: I(V) curve and parameters of a typical Micromorph module that includes the latest processes developed in the Oerlikon Solar pilot line. The low relative degradation due to the new top cell allows for stabilized total area efficiency over 10%.

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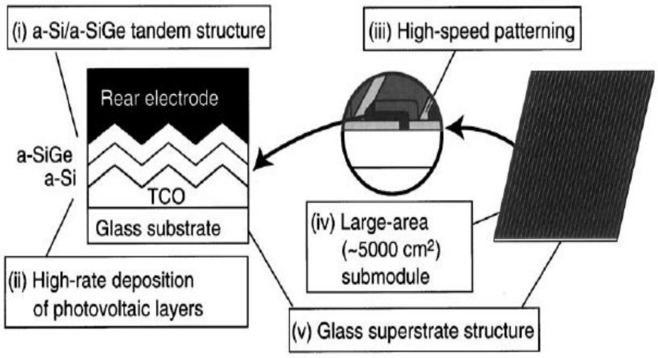
M. Fecioru-Morariu, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

a-Si:H/a-SiGe:H tandem cell



Maruyama et al., Solar Energy Materials & Solar cells 74 (2002)

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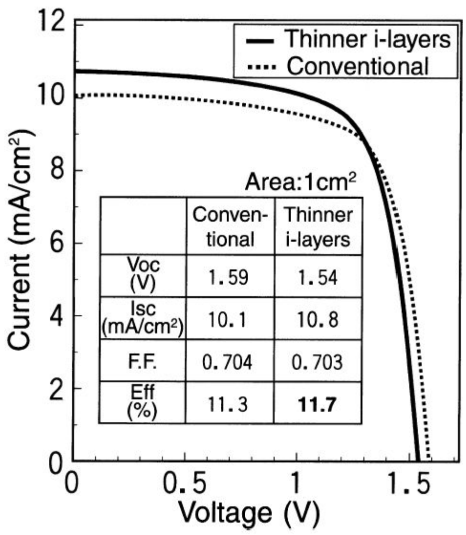

	Conven-tional	Thinner i-layers
Voc (V)	1.59	1.54
Isc (mA/cm²)	10.1	10.8
F.F.	0.704	0.703
Eff (%)	11.3	**11.7**

Conventional :
a-Si (150 nm)/a-SiGe (150 nm)
thinner i-layers
a-Si (130 nm)/a-SiGe (100 nm)

Maruyama et al., Solar Energy Materials & Solar cells 74 (2002)

USO: a-SiGe:H and nc-Si:H based multi-junction solar cells

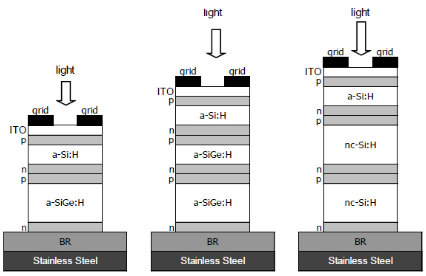

Figure 1: Schematic of three a-SiGe:H and nc-Si:H based multi-junction cell structures investigated in this study.

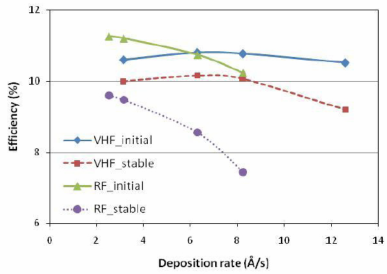

Figure 2: Initial and stable a-Si:H/a-SiGe:H double-junction cell efficiency as a function of a-SiGe:H layer deposition rate. The active-area cell size is 0.25 cm^2.

X. Xu, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

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USO: a-SiGe:H and nc-Si:H based multi-junction solar cells

Table II: J-V characteristics comparison between large-area encapsulated a-Si:H/a-SiGe:H double-junction and a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells. The cell aperture area is ~464 cm^2. Light soaking was performed under one-sun light intensity, open circuit, and at 50 ˚C for 1000 hours.

Sample #	Cell Structure	State	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
9542	Si/SiGe/SiGe triple	Initial	2.29	7.25	0.66	11.0
	Si/SiGe/SiGe triple	Stable	2.18	7.20	0.64	10.0
9179	Si/SiGe/SiGe triple	Initial	2.33	7.10	0.67	11.1
	Si/SiGe/SiGe triple	Stable	2.22	7.05	0.63	10.0
		Stable ave.	2.20	7.13	0.64	10.0
9030	Si/SiGe double	Initial	1.69	9.61	0.66	10.8
	Si/SiGe double	Stable	1.64	9.55	0.62	9.7
9035	Si/SiGe double	Initial	1.69	9.57	0.66	10.7
	Si/SiGe double	Stable	1.64	9.52	0.62	9.7
		Stable ave.	1.64	9.53	0.62	9.7
Triple/Double		Stable average	1.35	0.75	1.03	1.03

X. Xu, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

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USO: a-SiGe:H and nc-Si:H based multi-junction solar cells

Table IV: Comparison of Light-induced degradation for encapsulated, 1 cm^2, a-Si:H/a-SiGe:H/a-SiGe:H and a-Si:H/nc-Si:H/nc-Si:H triple-junction cells. .

Sample	State	V_{oc} (V)	FF	QE_{Top} (mA/cm^2)	QE_{Middle} (mA/cm^2)	QE_{Bottom} (mA/cm^2)	Efficiency (%)
a-SiGe	Initial	2.32	0.75	6.60	7.42	7.69	11.4
	Stable	2.24	0.72	6.52	7.08	7.35	10.4
	Degradation (%)	3.4%	4.2%	1.2%	4.6%	4.4%	**8.6%**
nc-Si	Initial	1.89	0.74	9.17	9.03	8.80	12.2
	Stable	1.88	0.71	8.87	8.96	8.75	11.7
	Degradation (%)	0.8%	2.9%	3.3%	0.8%	0.6%	**4.2%**

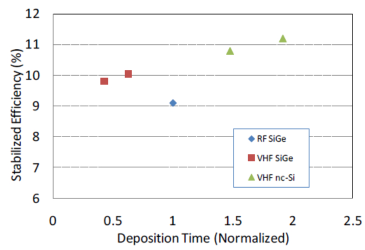

Figure 5: Best stabilized efficiency of large-area encapsulated cell, with aperture area of ~400 cm^2, as a function of deposition time, normalized to the current RF manufacturing time at USO.

X. Xu, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

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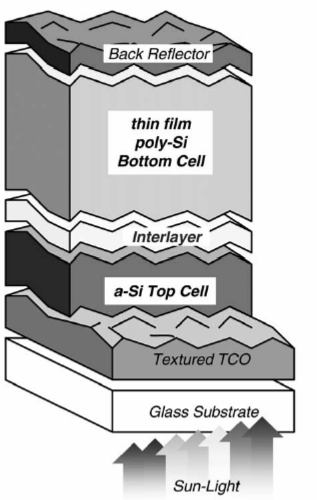
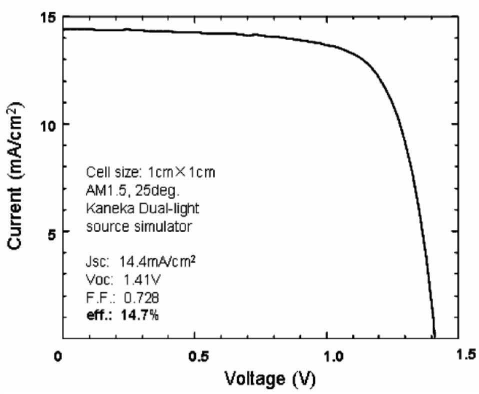
a-Si:H/μc-Si:H tandem solar cell (Kaneka)





Yamamoto, K. et.al., Solar Energy, 77, 939-949(2004).

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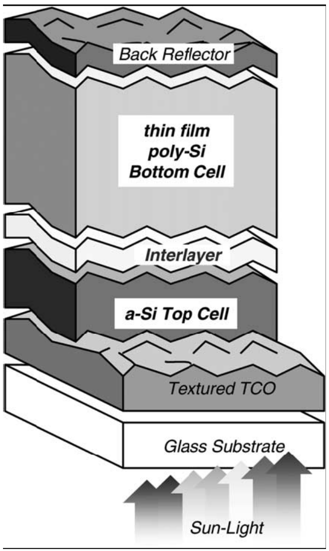
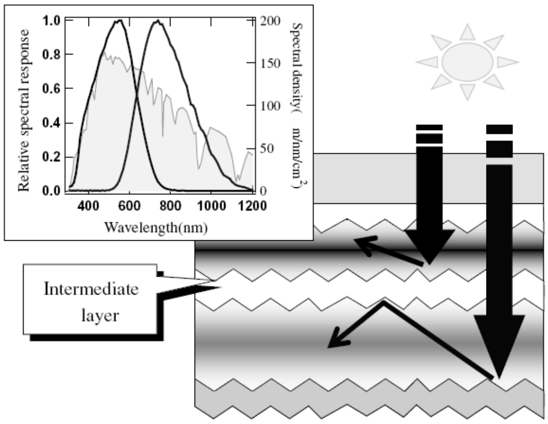
a-Si:H/interlayer/μc-Si:H tandem cell





Yamamoto et al.,Solar energy 77 (2004)

Kaneka, η = 15%, 2006

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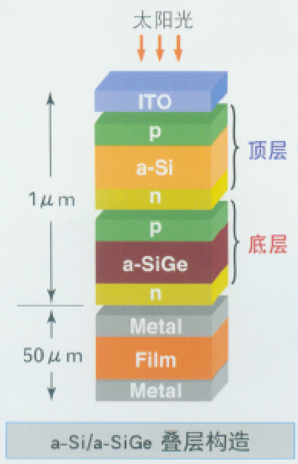
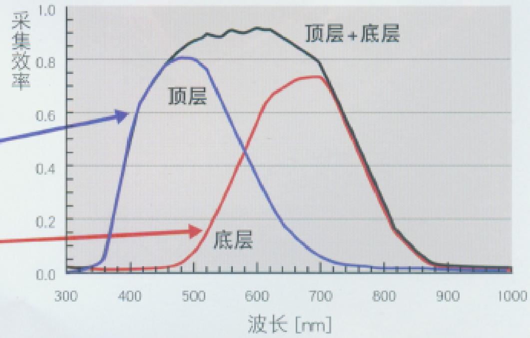
Fuji: a-Si:H/a-SiGe:H (roll-to-roll)





先进的卷进卷出工艺实现了
大批量生产的高流水化和低成本化

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新材料與元件

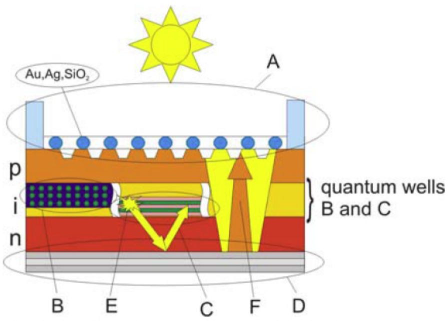
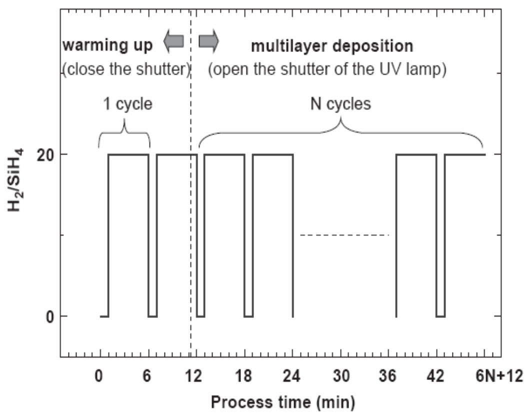


Fig. 1. An idea of proposed solar cell structure,
A- Nanostructured front electrode
B- Silicon thin film with homogenous nanocrystallites
C- a-Si:H/a-Ge:H or a-Si:H/μc-Si:H Quantum Wells
D- Combination of Bragg Mirror and Lambertian Surface in the form of the back electrode
E- Photon from the radiative recombination reflected by this "D" electrode
F- Not absorbed photons reflected by this "D" electrode.

A. Kolodziej, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

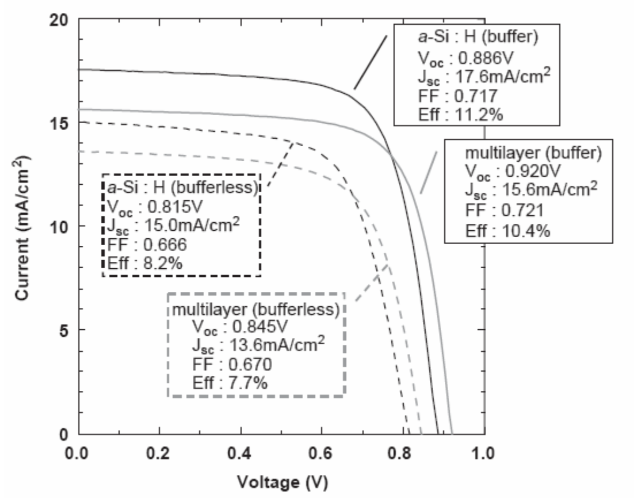
pc-Si:H/a-Si:H multilayer 太陽電池



Schematic diagram of alternated hydrogen dilution for an i–pc-Si:H multilayer deposition

S.Y. Myong et al. / Solar Energy Materials & Solar Cells 85 (2005) 133–140

pc-Si:H/a-Si:H multilayer 太陽電池



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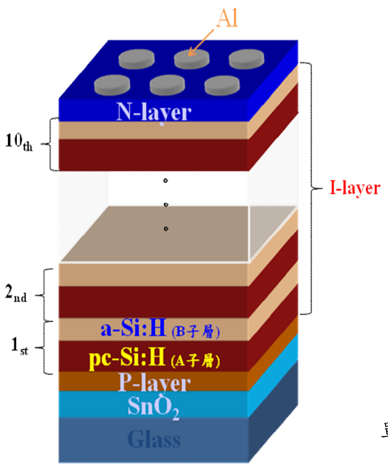
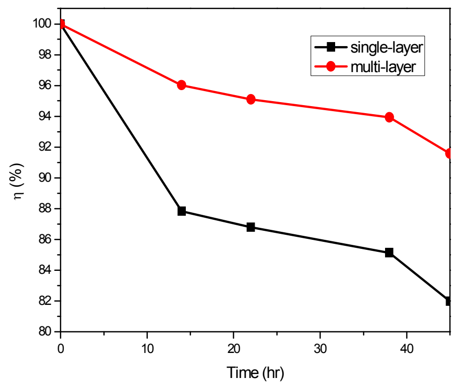
S.Y. Myong et al. / Solar Energy Materials & Solar Cells 85 (2005) 133–140

pc-Si:H/a-Si:H multilayer solar cell





單層膜與多層膜太陽電池照光衰退效率比較圖

pc-Si:H/a-Si:H 多層膜太陽電池結構示意圖

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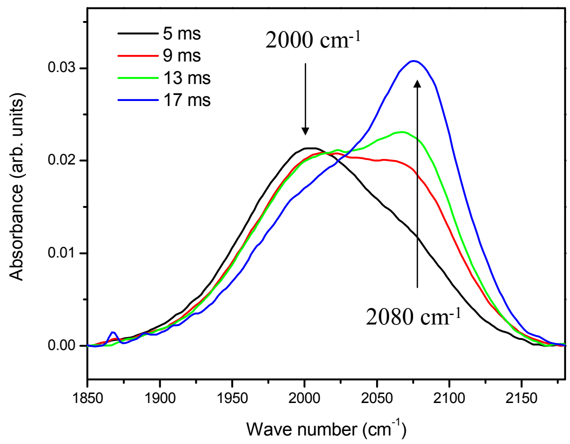
國立中興大學 National ChungHsing University 尖端光電元件實驗室

a-Si:Hx/a-Si:Hy超晶格結構

FTIR: stretching bands (2000-2080 cm^{-1})



SiH bonds: 2000 cm^{-1}

SiH_2 bonds: 2080 cm^{-1}

microstructure: R_S

$$R_S = \frac{I_{2080}}{I_{2000} + I_{2080}}$$

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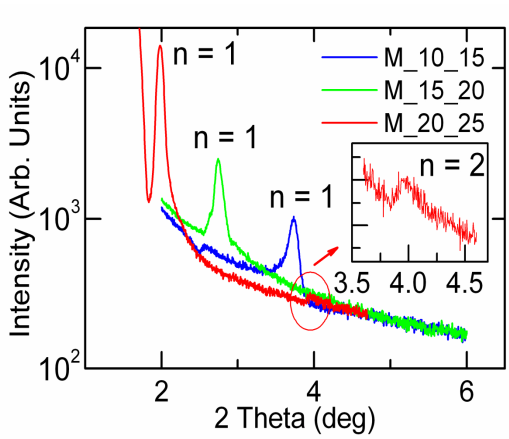
a-Si:H_x/a-Si:H_y超晶格結構之θ–2θ X光繞射



M_AA_BB

AA: A sublayer thickness (Å)

BB: B sublayer thickness (Å)

Period

Blue line: 25 Å

Green line: 35 Å

Red line: 45 Å

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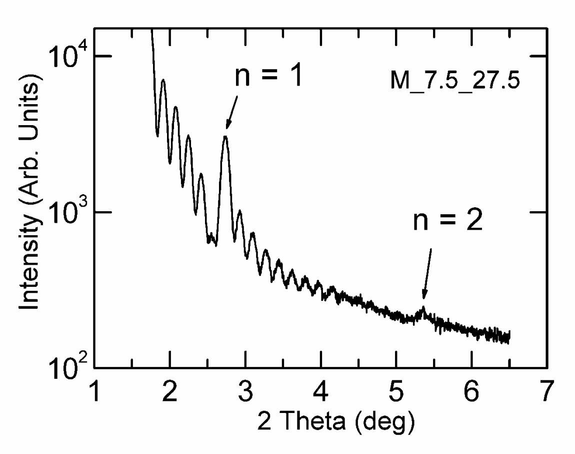
Jiang, Y.L.; Shih, P.T.; Kuo, T.C, Appl. Phys. Lett., 92, 101915(2008).

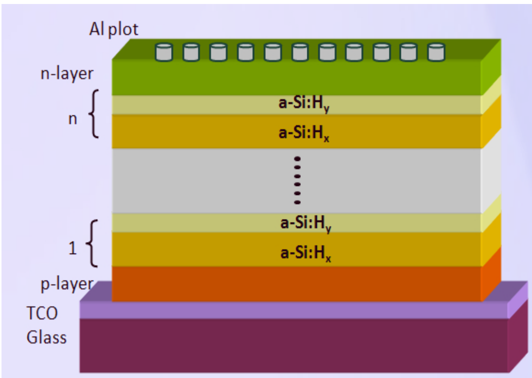
a-Si:H$_x$/a-Si:H$_y$超晶格結構之θ–2θ X光繞射



M_AA_BB
AA: A sublayer 7.5 Å
BB: B sublayer 27.5 Å

Period: 35 Å

超晶格矽薄膜太陽電池

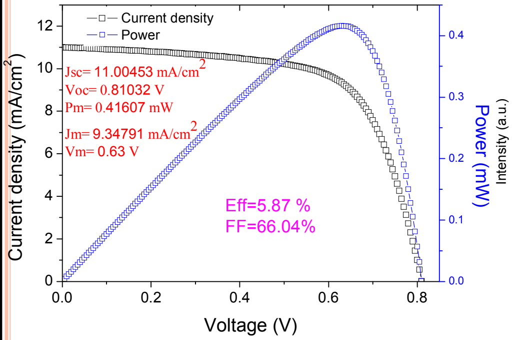


a-Si:Hx/a-Si:Hy 超晶格矽薄膜太陽電池結構圖

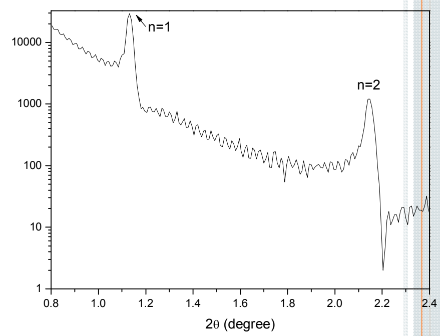
國立中興大學 National ChungHsing University

尖端光電元件實驗室

超晶格矽薄膜太陽電池



a-Si:Hx/a-Si:Hy 超晶格矽薄膜太陽電池光電轉換特性圖



a-Si:Hx/a-Si:Hy 超晶格矽薄膜低略XRD繞射圖

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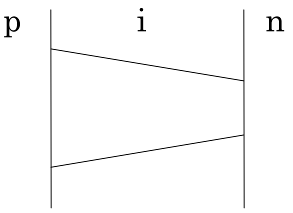
尖端光電元件實驗室

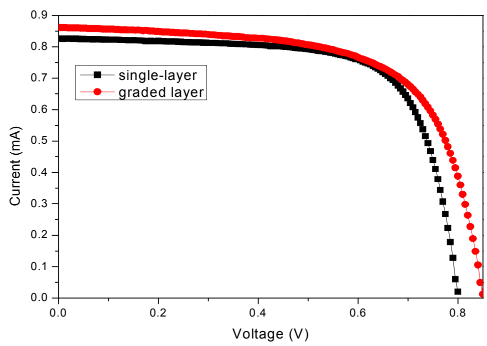
漸變能隙矽薄膜太陽電池



漸變能隙的矽薄膜太陽電池光吸收層能隙示意圖

單層膜與漸變能隙的矽薄膜太陽電池特性比較表

Sample	J_{sc} (mA/cm²)	Eff (%)	V_{oc} (V)	FF (%)
Single layer	11.46	6.47	0.79	71.2
Graded layer	12.39	6.85	0.84	66.23



單層膜與漸變能隙的矽薄膜太陽電池光電轉換效率圖

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尖端光電元件實驗室

a-Si:H/μc-Si:H/μc-Ge:H

Material	E_{gap} [eV]	Ref.
c-Si	1.1	[5]
a-Si:H	1.5-1.8	[5]
a-SiC:H	1.76-2.2	[6]
μc-Si:H	1.1	[5]
a-SiGe:H	1.6-1.4	[3]
μc-SiGe:H	0.7-1.1	[7]
c-Ge	0.67/0.79	[8]

T [K]	**single**	**tandem**		**triple**		
	Top	top	bot	top	mid	bot
293	1.34	1.60	0.94	1.90	1.36	0.94
301	1.34	1.60	0.94	1.90	1.36	0.94
333	1.34	1.60	0.94	1.90	1.36	0.94
401	1.36	1.72	1.12	1.90	1.36	0.94

C. Feser, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

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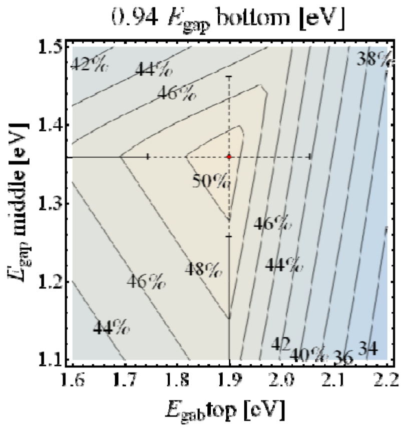
尖端光電元件實驗室

a-Si:H/μc-Si:H/μc-Ge:H



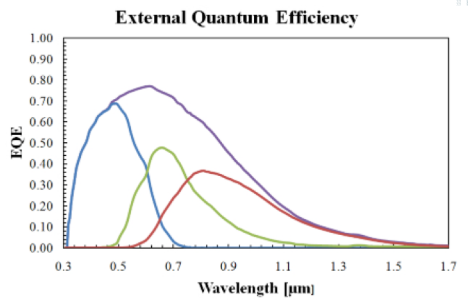


Fig. 4 : EQE of an triple cell with IR of a-Si:H/μc-Si:H/μc-Ge:H solar cell simulated with Sentaurus TCAD. The purple line describes the EQE of the whole cell, the blue, green and red curves the EQE's of the top (180 nm), middle (3μm) and bottom (90 nm) cell.

- The E_{gap} combination with (1.90/1.34/0.94)eV leads to a the maximum efficiency of 51 % .

C. Feser, *et al*, 25th EU PVSEC, 6-10 Sep. 2010, Valencia, Spain

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尖端光電元件實驗室

研發與生產現況

世界各國主要研究單位在單接面、疊層及三接面矽薄膜太陽電池研發最高效率的整理表

Single junction		
研究單位	結構	效率(%)
AIST	a-Si:H	9.4[51]
	a-SiGe:H	7.26[52]
	μc-Si:H	9.1[53]
Kaneka	a-Si	10.6[54]
MHI	a-Si:H	9.5[55]
	μc-Si:H	8.8[55]
Sanyo	a-SiGe:H	8.9[56]
Sharp	a-Si:H	8.25[57]
	μc-Si:H	9.4[58]
United solar	a-Si:H	10.6[44]
	μc-Si:H	9.2[50]
IMT-Neuchâtel	a-Si:H	10.2[59]
	μc-Si:H	10.9[60]
Ecole Polytechnique	μc-Si:H	8.3[61]
	a-Si:H	7.69[62]
天津南開大學	a-Si:H	6.57[63]
	μc-Si:H	8.65[64]

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尖端光電元件實驗室

世界各國主要研究單位在單接面、疊層及三接面矽薄膜太陽電池研發最高效率的整理表

Tandem		
研究單位	結構	效率(%)
AIST	a-Si:H/μc-Si:H	10.4[65]
	a-Si:H/μc-$Si_{1-x}Ge_x$:H	11.2[52]
Kaneka	a-Si:H/ interlayer/μc-Si:H	15[11]
	a-Si:H/μc-Si:H	14.7[66]
MHI	a-Si:H/μc-Si:H	13.4[67]
	a-Si:H/a-SiGe:H	8.69[68]
Sharp	a-Si:H/μc-Si:H	12.14[56]
United solar	a-Si:H/a-Si:H	11.4[44]
	a-Si:H/a-SiGe:H	14.4[44]
	a-Si:H/μc-Si:H	11.9[69]
IMT-Neuchâtel	a-Si:H/μc-Si:H	12.3[70]
Ecole Polytechnique	a-Si:H/μc-Si:H	11.2[71]
	a-Si:H/μc-Si:H	12.4[72]

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世界各國主要研究單位在單接面、疊層及三接面矽薄膜太陽電池研發最高效率的整理表

Triple junction		
研究單位	結構	效率(%)
United Solar	a-Si:H/a-SiGe:H/a-SiGe:H	14.6[44]
	a-Si:H/nc-Si:H/nc-Si:H	13.4[49]
	a-Si:H/a-SiGe:H/nc-Si:H	15.4[50]
Sharp Corporation	a-SiC:H/a-SiGe:H/a-SiGe:H	12.4[73]

我國及世界重要廠商之產品規格整理表

國內矽薄膜太陽能電池產品資訊						
廠商	聯相					
Model name	NH-100AX-1_3A	NH-100AX-1_4A	NH-100AT_3A	NH-100AT_4A	NT-135AX	NT-140AX
Cell type	a-Si:H				a-Si:H/μc-Si:H	
Pmax (W)	95	100	95	100	135	140
Dimension (m)	1.1x1.4				1.1x1.4	
效率 (%)	6.17	6.49	6.17	6.49	8.8	9.1
廠商	綠能	宇通光能	奇美能源	旭能		
Model name	GET	M140000	CSSS-100	SA-100	SA-130	
Cell type	a-Si:H	a-Si:H/μc-Si:H	a-Si:H	a-Si:H	a-Si:H/μc-Si:H	
Pmax (W)	343	140	100	100	130	
Dimension (m)	2.6 x 2.2	1.1x1.3	1.1x1.4	1.1x1.4		
效率 (%)	6	10	6.49	6.49	8.5	

我國及世界重要廠商之產品規格整理表

國外矽薄膜太陽能電池產品資訊								
廠商	MHI		Kaneka				Sharp	
Model	MT130	MA100	G-EA060	T-EC120	T-ED120	P-LE055	NA-V142H5	NA-V135H5
Cell type	a-Si:H/μc-Si:H	a-Si:H	a-Si:H				a-Si:H/μc-Si:H	
Pmax (W)	130	100	60	120	120	55	142	135
Dimension (m)	1.1 × 1.4	1.1 × 1.4	0.99 × 0.96	0.99 × 1.92	0.96 × 1.98	0.99 × 0.99	1.0x1.4	
效率 (%)	8.44	6.49	6.31	6.31	6.31	5.61	10	9.5

結論

- 薄膜特性由製程條件及電漿化學控制。
- 疊層或多接面元件結構可以有效地提升效率及降低衰退。
- 薄膜太陽電池性能的突破需要新材料及元件結構的開發。

謝謝
敬請指教!!