



Akreditasi A
Universitas Mulawarman
Nomor. 1466/SK/BAN-PT/Akred/PT/V/2017 Tgl. 23 Mei 2017



Pengembangan Sel Surya Berbasis Film-Tipis Amorfus Silikon Terhidrogenisasi ($a\text{-Si:H}$): Peluang dan Tantangan Pengembangannya

Disampaikan Oleh:

Dr. Dadan Hamdani

Laboratorium Fisika Teori dan Material

Jurusan Fisika FMIPA Universitas Mulawarman

2022

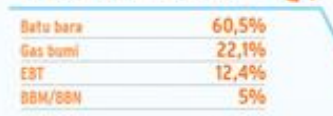
Samarinda, 30 Agustus 2022

Program Mandiri Energi

“MEMPERBARUI” PEMANFAATAN ENERGI BARU TERBARUKAN DI INDONESIA

Pemanfaatan Energi Baru Terbarukan (EBT) di Indonesia sudah lama dibahas dan dikembangkan. Namun, progresnya tak secepat yang diharapkan meski sudah ada pemangkasan regulasi oleh Kementerian Energi dan Sumber Daya Mineral (ESDM). Dengan terus naiknya konsumsi listrik, potensi sumber energi alternatif ini makin mendesak untuk digunakan secara lebih luas.

BAURAN ENERGI PRIMER PEMBANGKIT LISTRIK



KONSUMSI LISTRIK 2014-2018



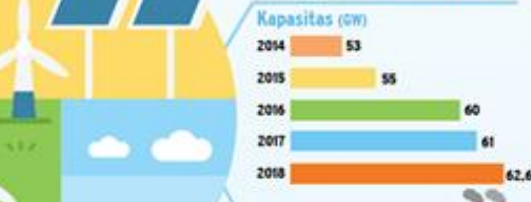
PROGRES KONTRAK PEMBANGKIT EBT 2014-2018



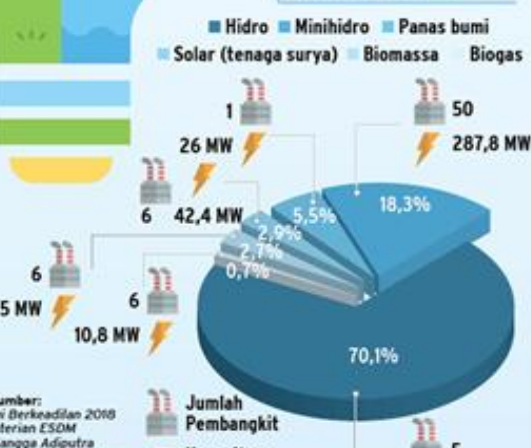
Sumber: Booklet Energi Berkeadilan 2018 Kementerian ESDM Bisnis/Erlangga Adiputra

Facebook: @bisnis.com, Twitter: @Bisniscom, Instagram: @bisniscom

KAPASITAS PEMBANGKIT TERPASANG



PERINCIAN KONTRAK PEMBANGKIT EBT 2017-2018



Jumlah Pembangkit: 5, Kapasitas Pembangkit: 1.104 MW

ENERGI ALTERNATIF UNTUK KEMANDIRIAN INDONESIA

Pengembangan sumber energi alternatif mendesak untuk mengantisipasi ancaman krisis energi di masa depan. Namun potensi energi ini belum banyak dimanfaatkan. Dari total potensi energi alternatif sebesar 443.208 megawatt (MW), pemanfaatannya baru 8.216 MW.

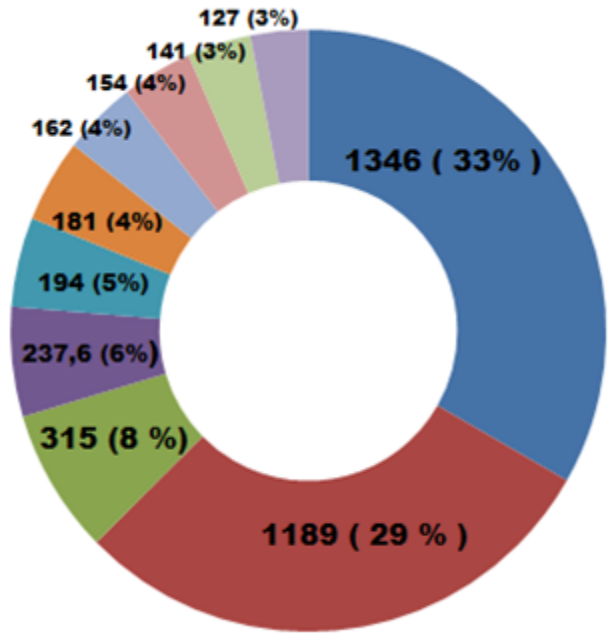


Ket: MBOEPD = Juta barel setara minyak per hari, MTOE = Juta ton setara minyak, TCF = Triliun kaki kubik

Cadangan Menipis	Rata-Rata Produksi Per Tahun		Perkiraan Habis*	Ancaman Defisit Migas
	Terbukti	Rata-Rata Produksi Per Tahun		
Minyak Bumi	3,6 miliar barel	288 juta barel	12 tahun	Kebutuhan (MBOEPD): 5.315 (2050) ↑143% 2.190 (2015)
Gas Bumi	98 TCF	3 TCF	33 tahun	Pasokan: 535 (2050) ↓75% 2.190 (2015)
Batubara	32,4 miliar ton	393 juta ton	82 tahun	

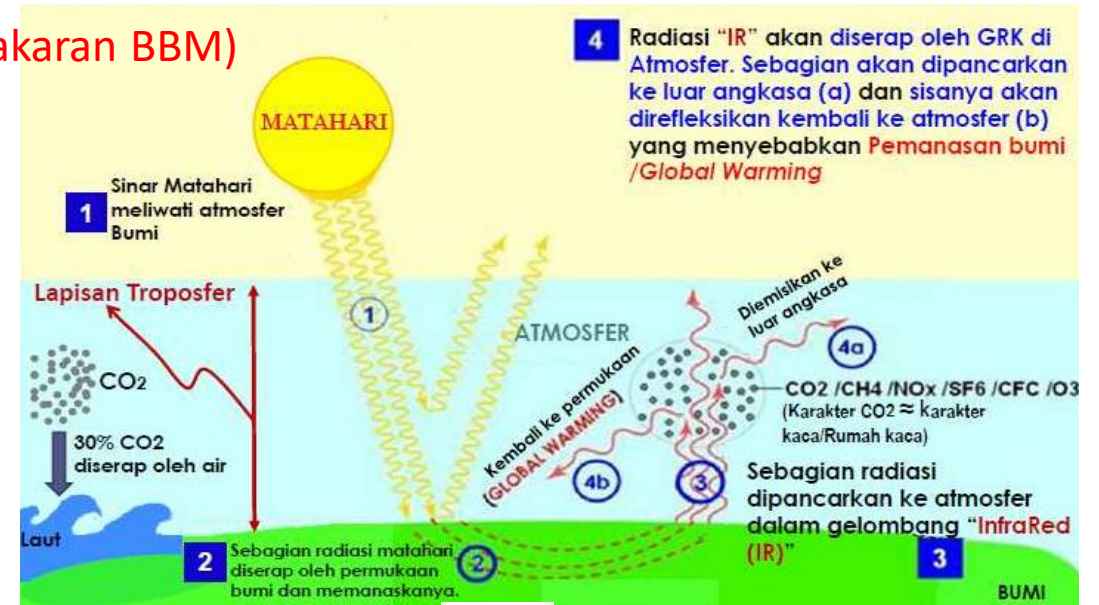
*Asumsi bila tidak ada temuan baru

Bauran Energi Alternatif

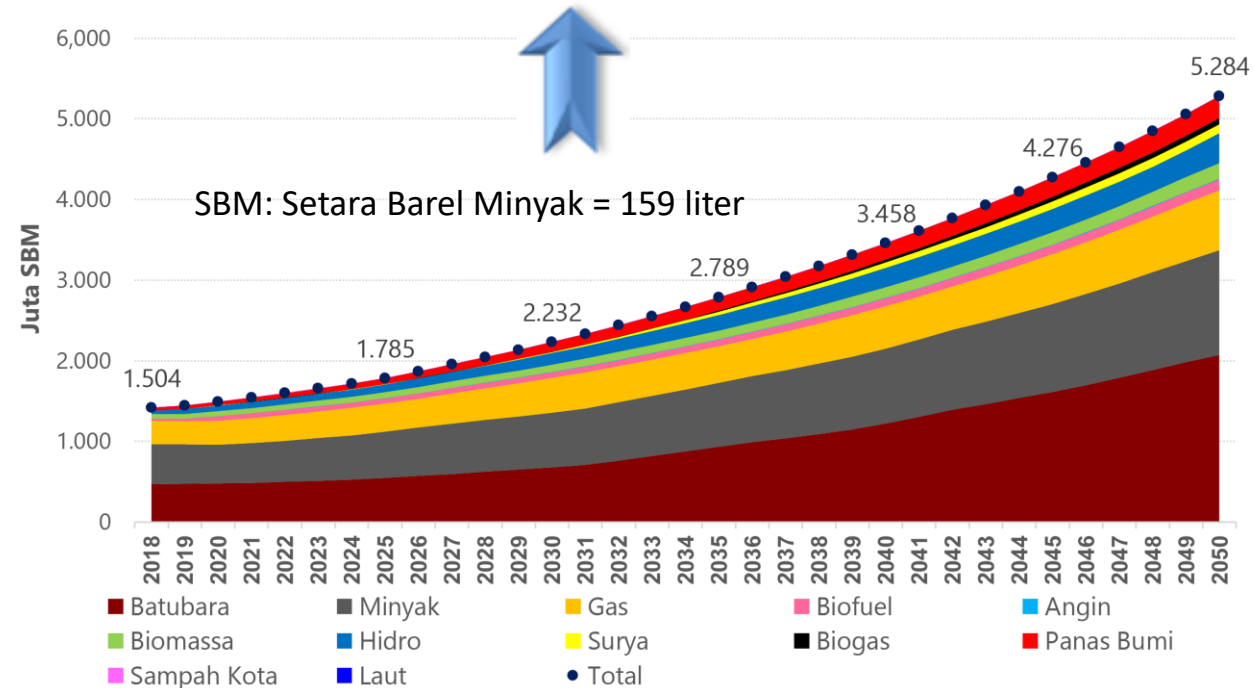


1. China
2. India
3. AS
4. Indonesia
5. Brazil
6. Pakistan
7. Banglades
8. Nigeria
9. Rusia
10. Jepang

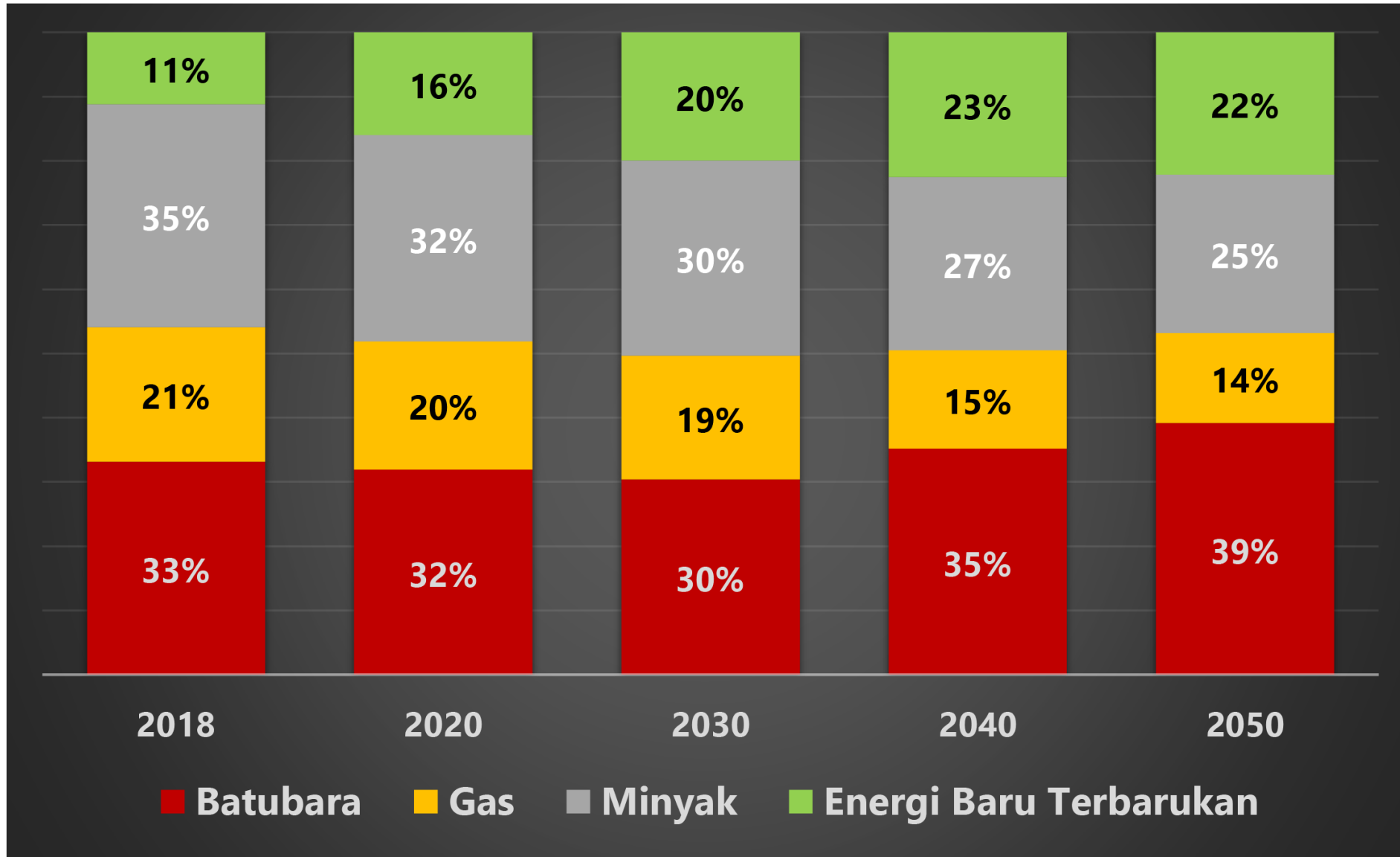
66% (pembakaran BBM)



Permintaan energi semakin meningkat

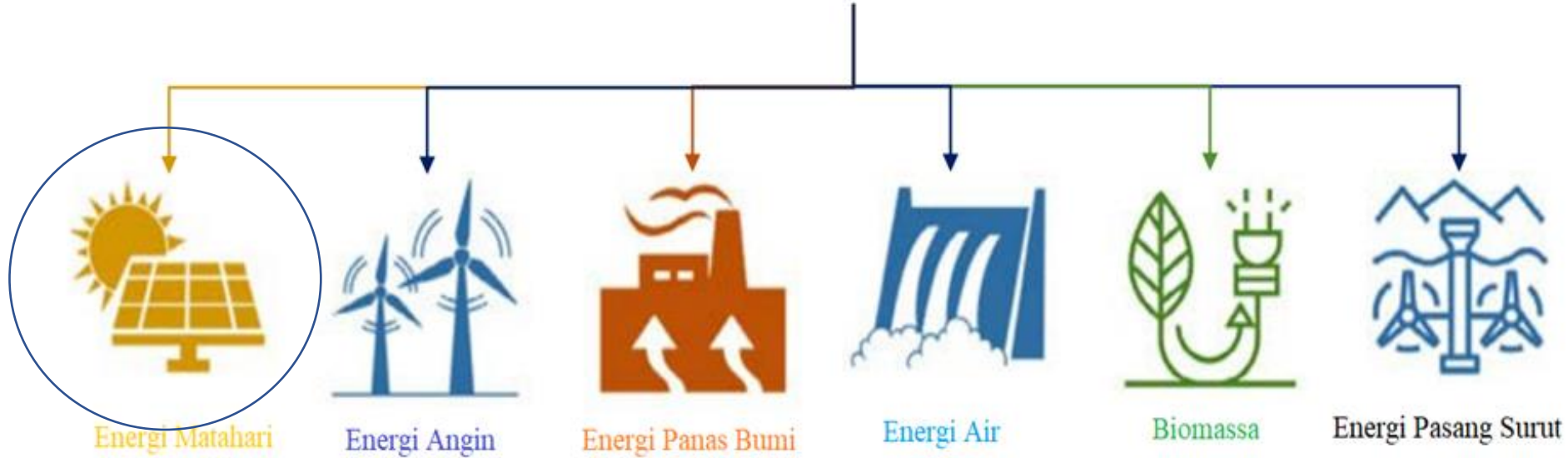


Bauran Energi Baru dan Terbarukan (EBT)

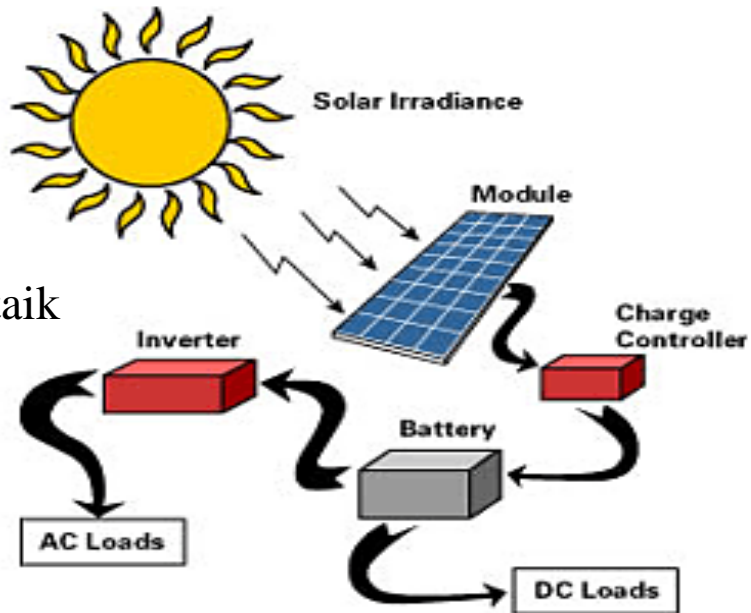


Sumber-Sumber EBT

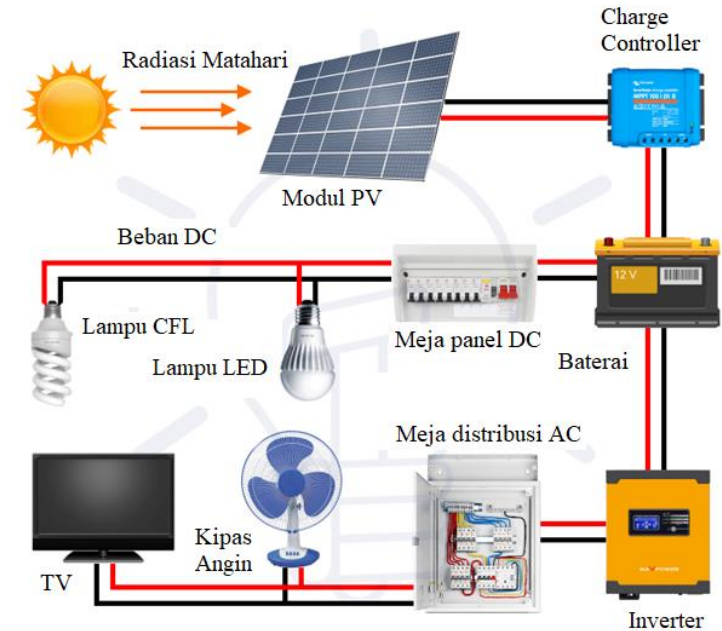
Energi Baru dan Terbarukan (EBT)




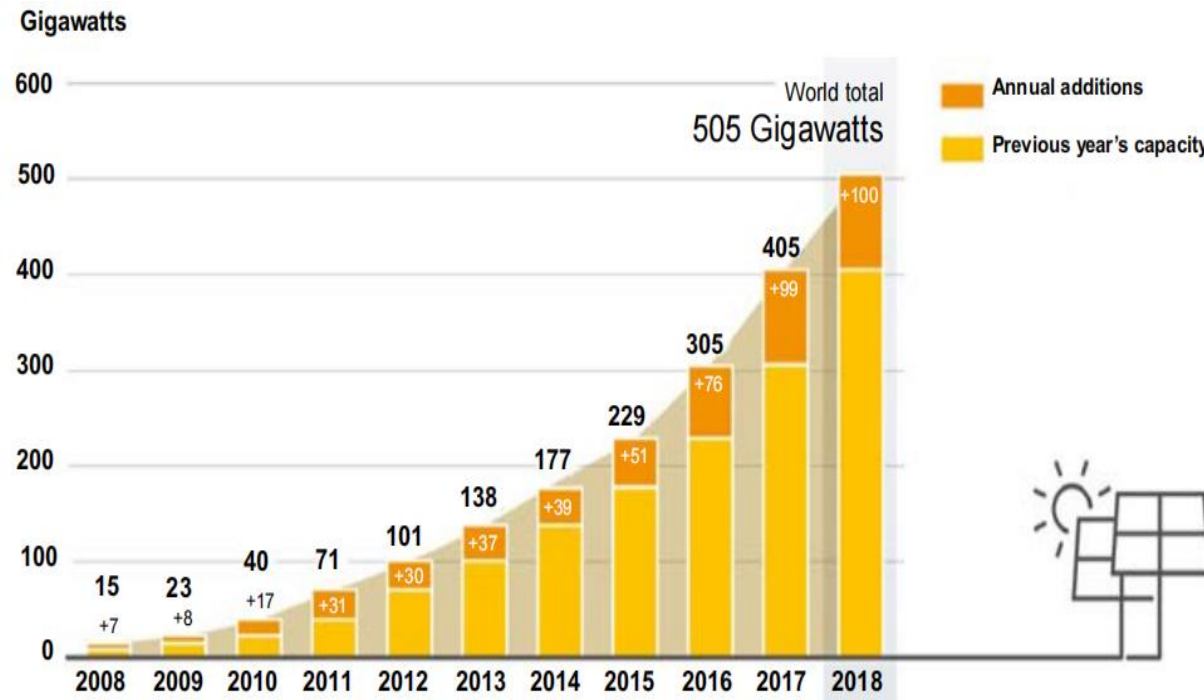
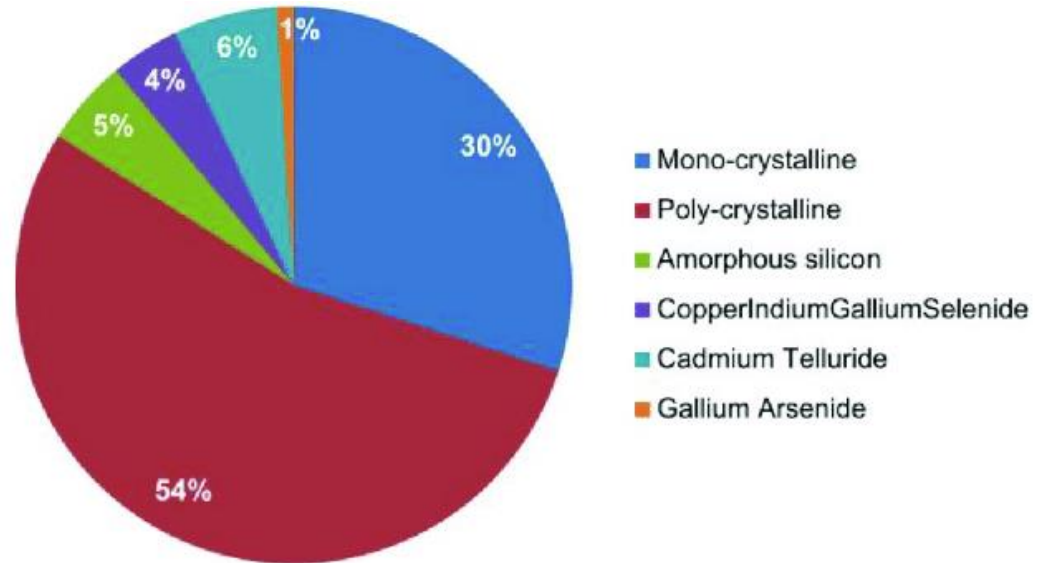
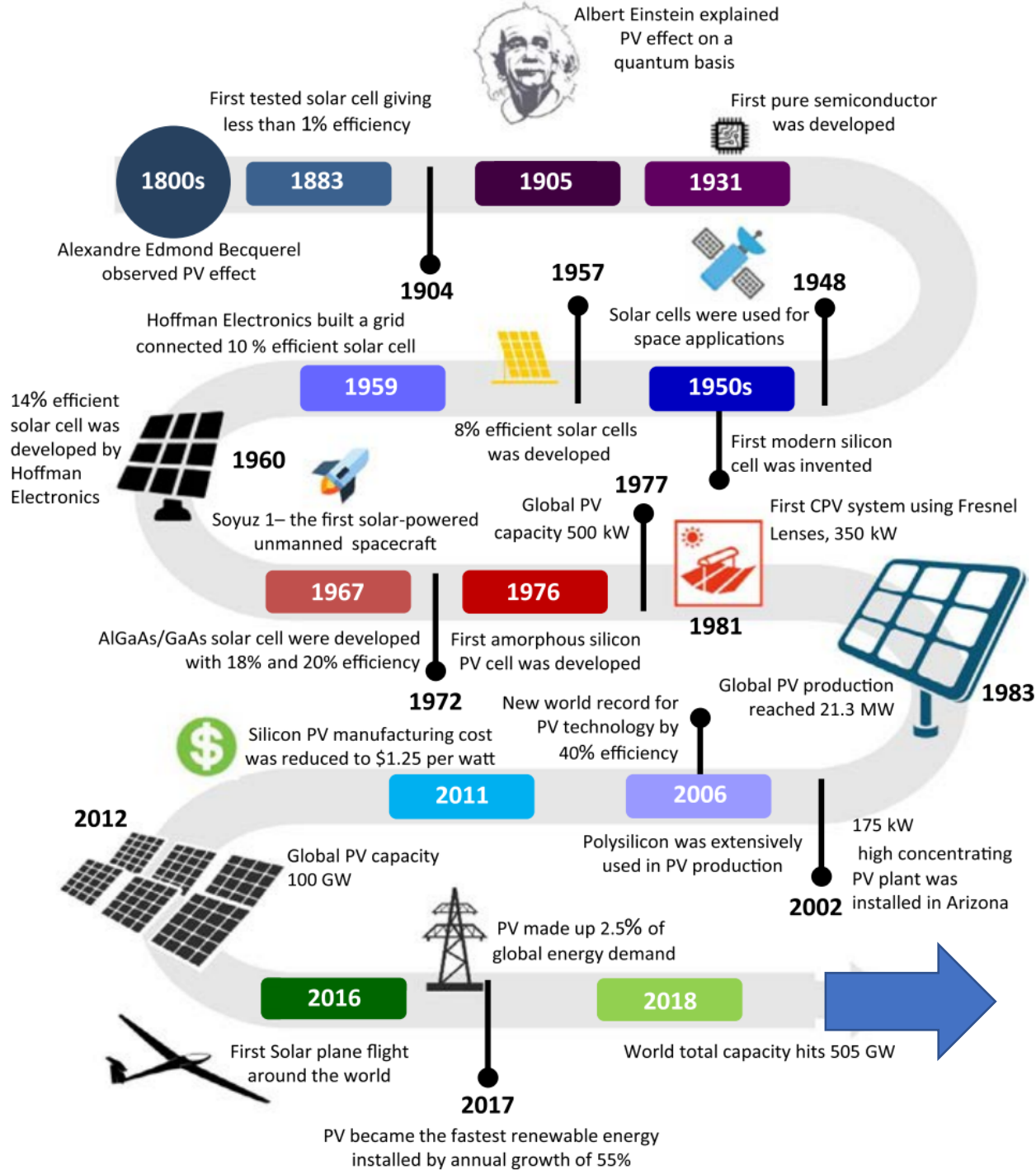
Sistem Fotovoltaik



Aplikasi Fotovoltaik

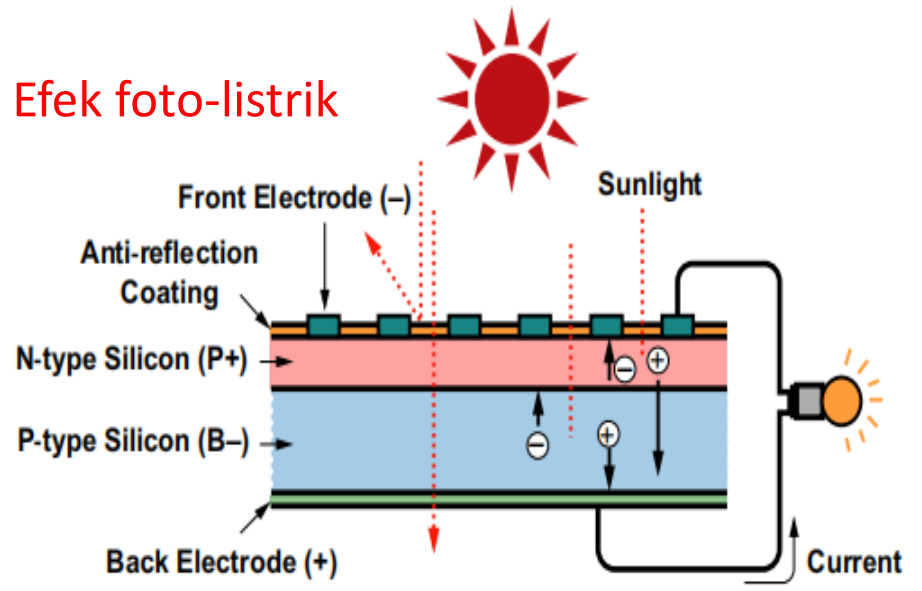


Albert Einstein explained PV effect on a quantum basis

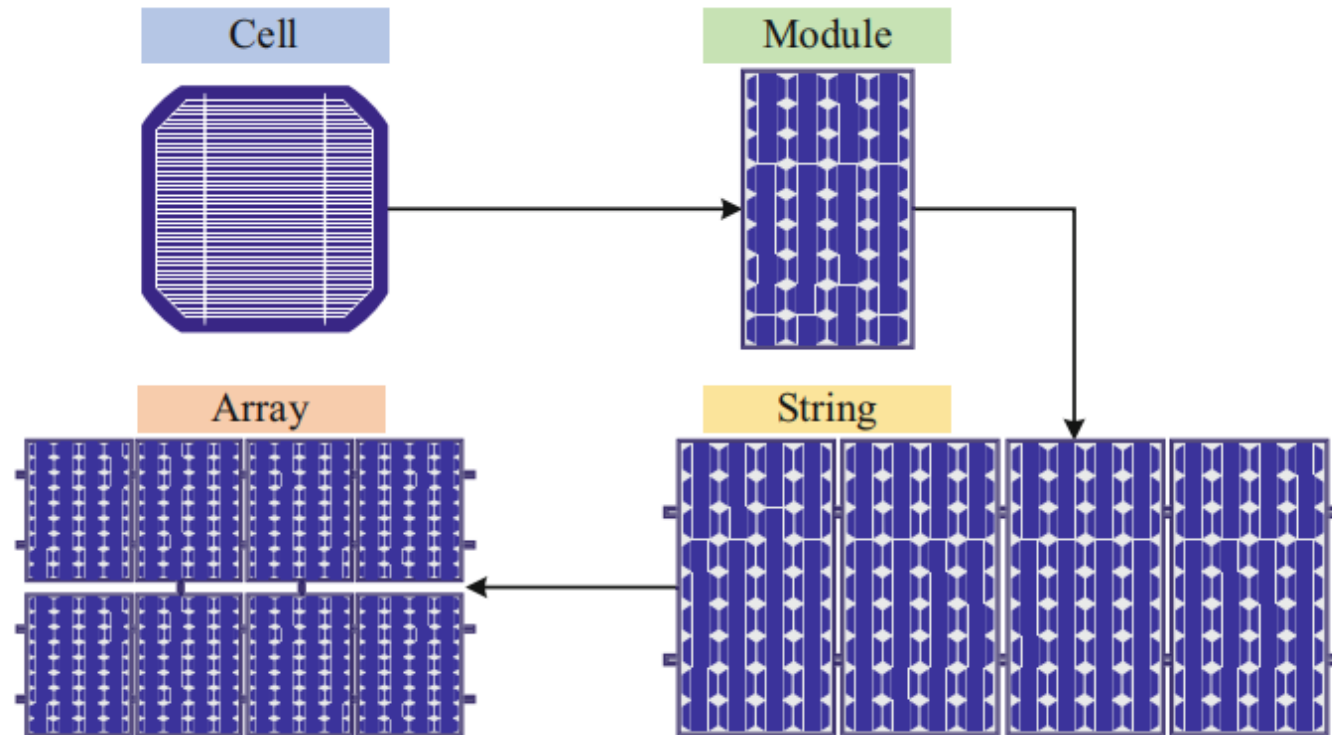
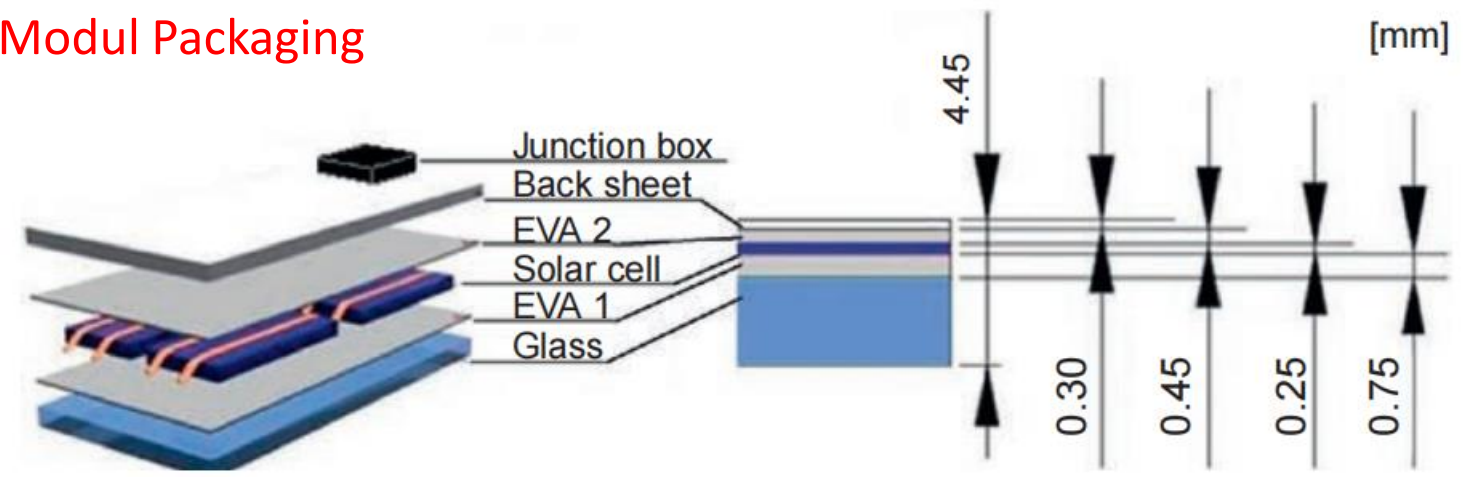



Teknologi Fotovoltaik

Efek foto-listrik

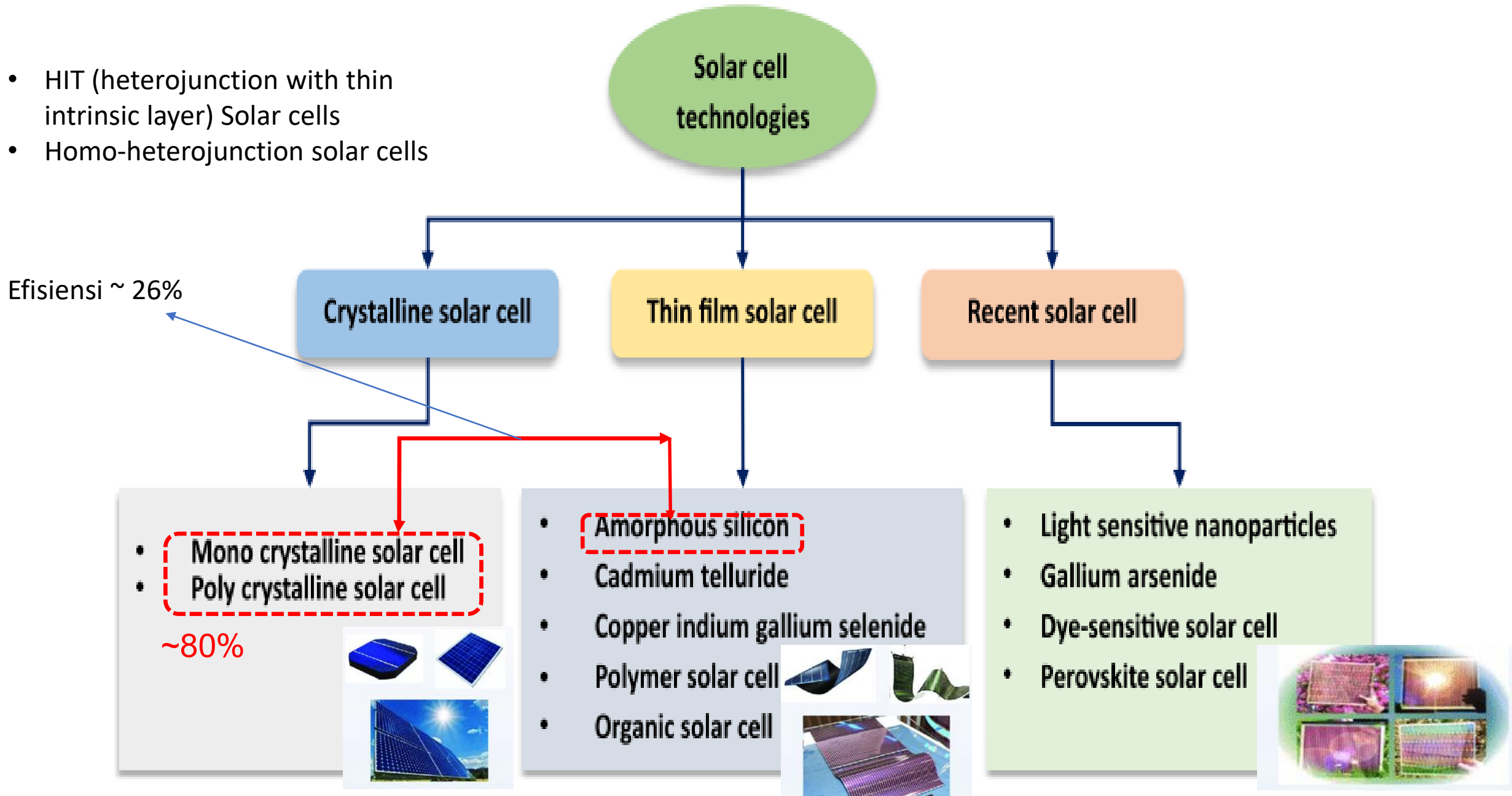


Modul Packaging

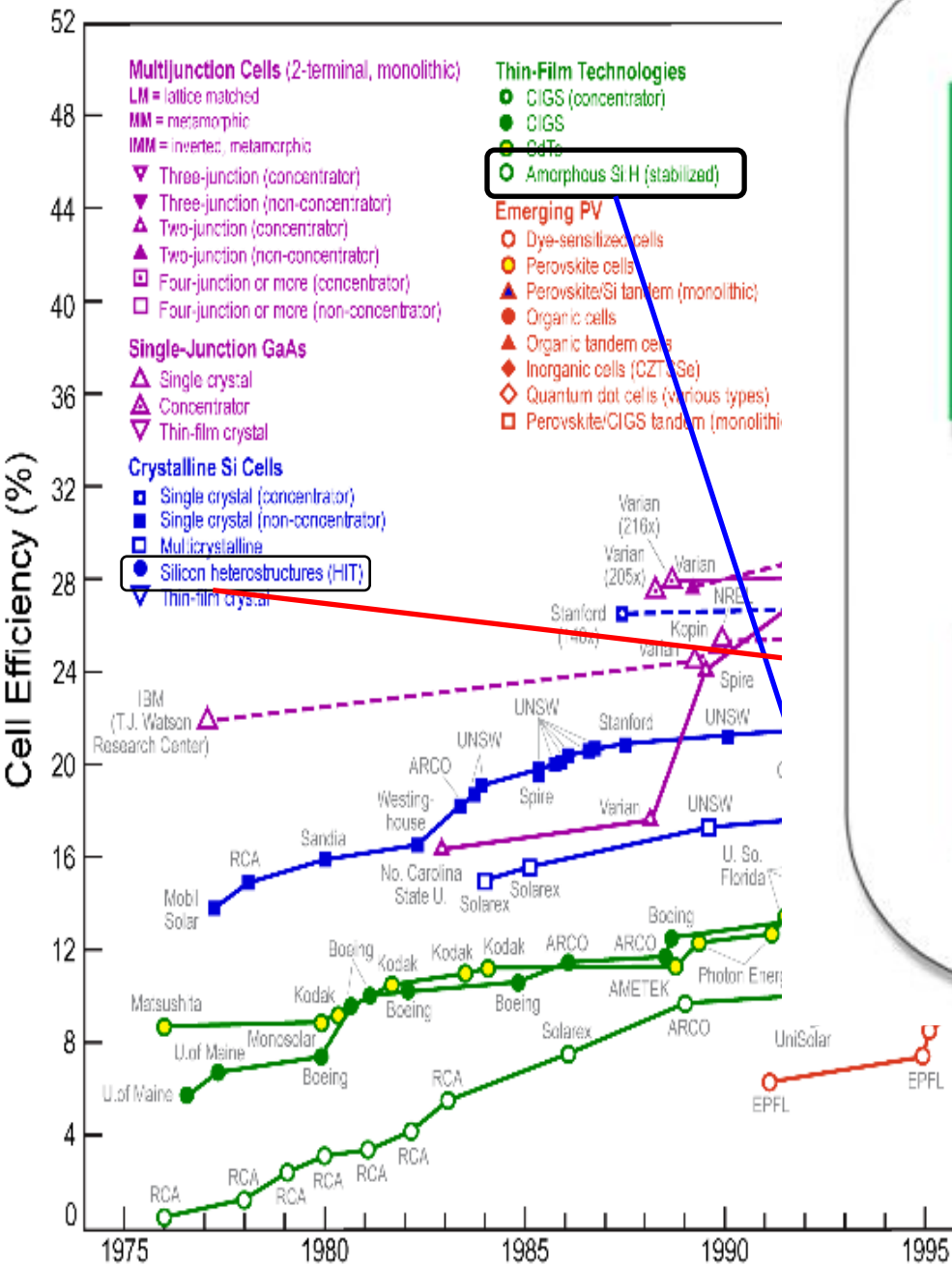


Dimana posisi sel surya a-Si:H?.

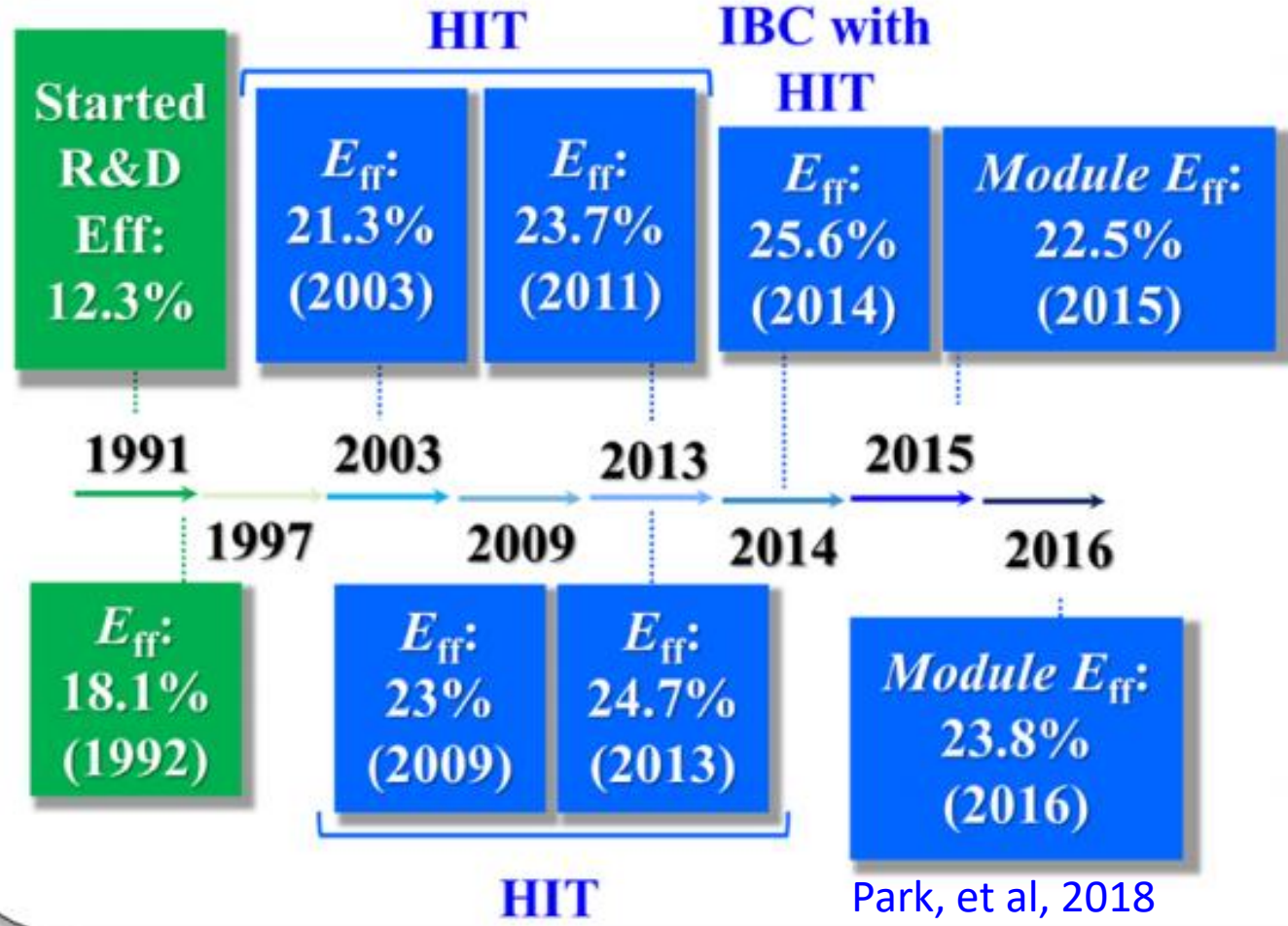
- HIT (heterojunction with thin intrinsic layer) Solar cells
- Homo-heterojunction solar cells



Best Research-Cell Efficiencies

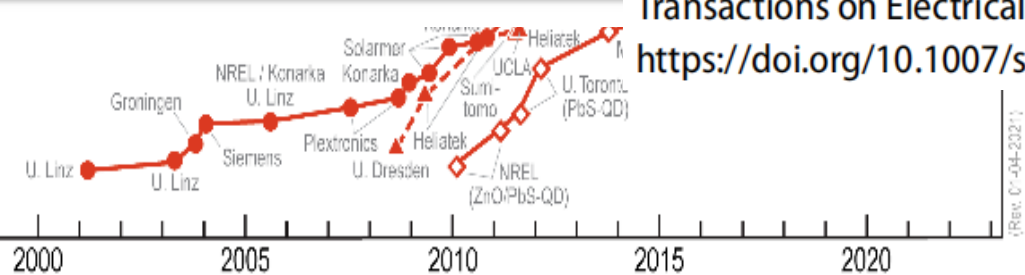


Research timeline of Panasonic HIT solar cells



Park, et al, 2018

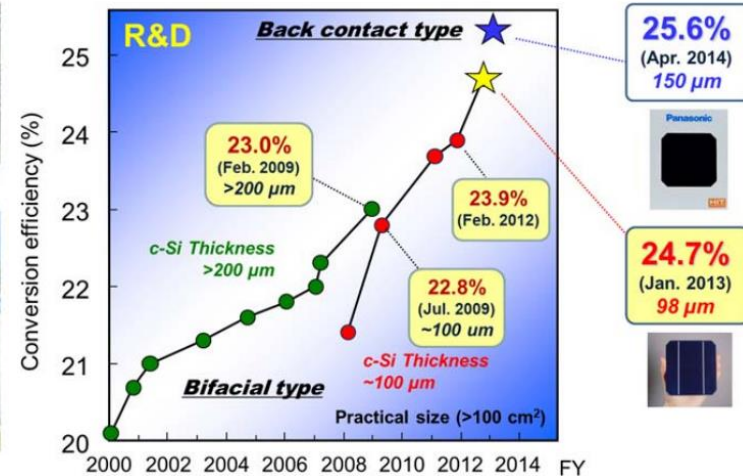
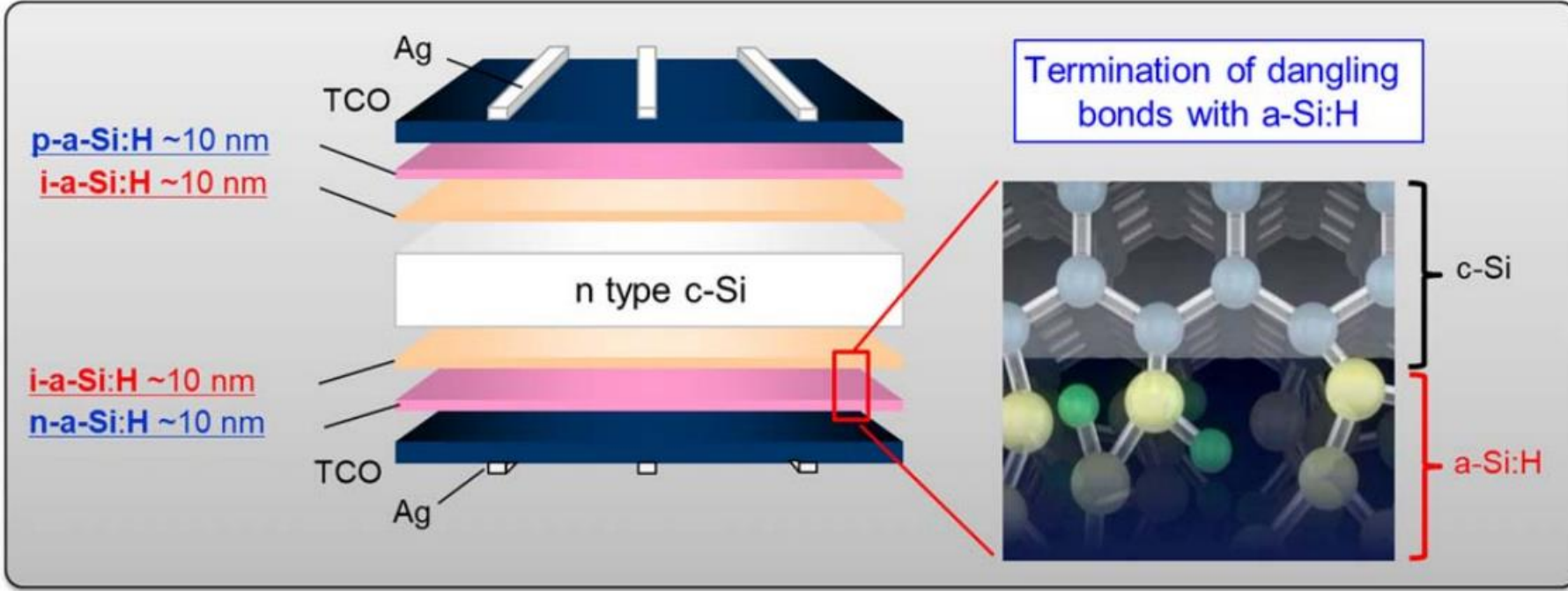
Transactions on Electrical and Electronic Materials
<https://doi.org/10.1007/s42341-018-0026-8>



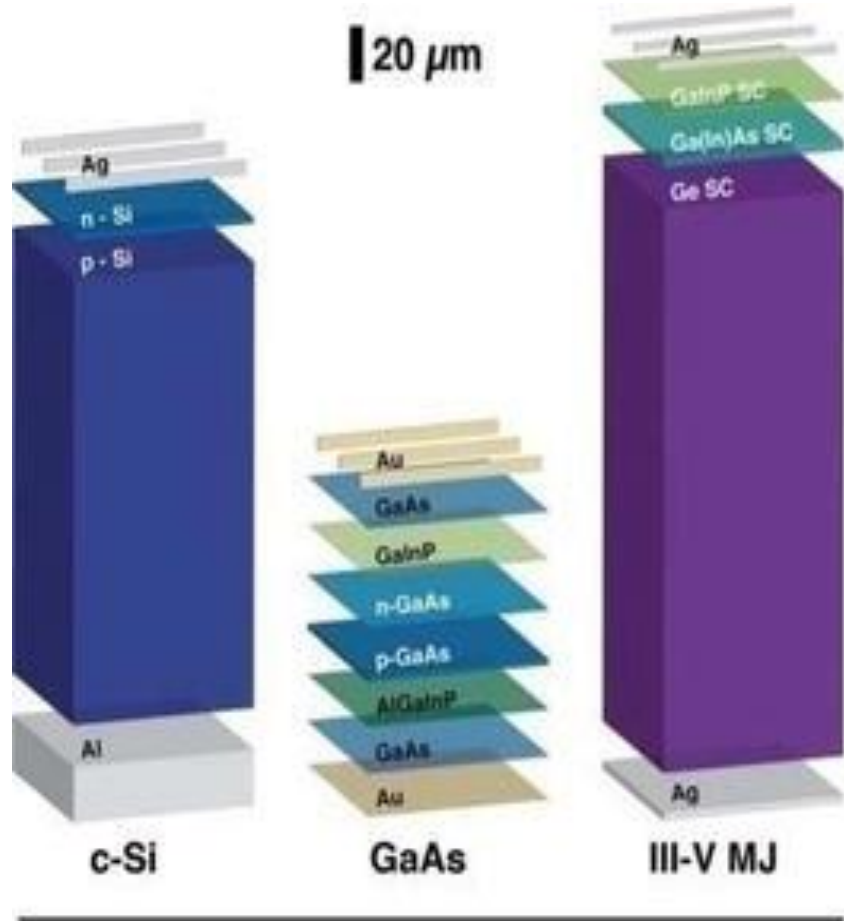
NREL, 2021

HIT (Heterojunction with Intrinsic Thin Layer)

Panasonic
HIT Solar Cell

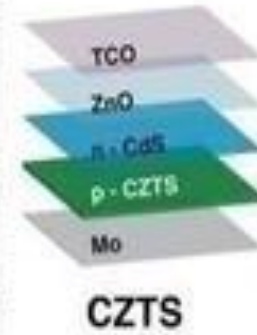
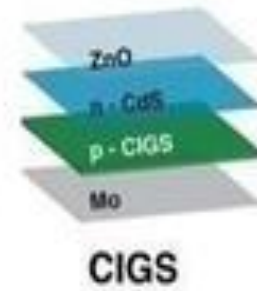
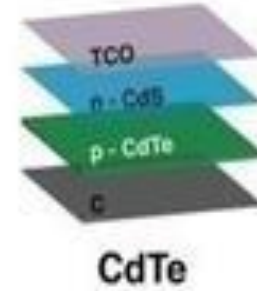
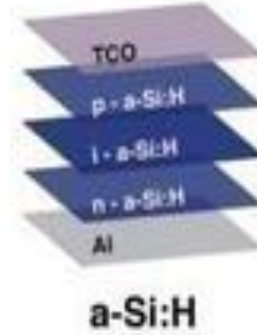


Apa Keunggulan dan Kekurangan sel surya film tipis?.

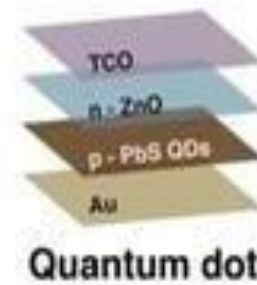
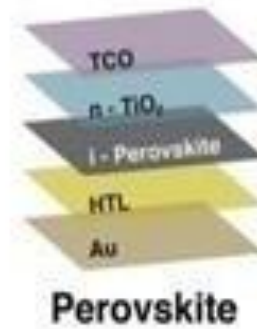


Wafer

*Commercial
Thin film*



*Emerging
Thin film*



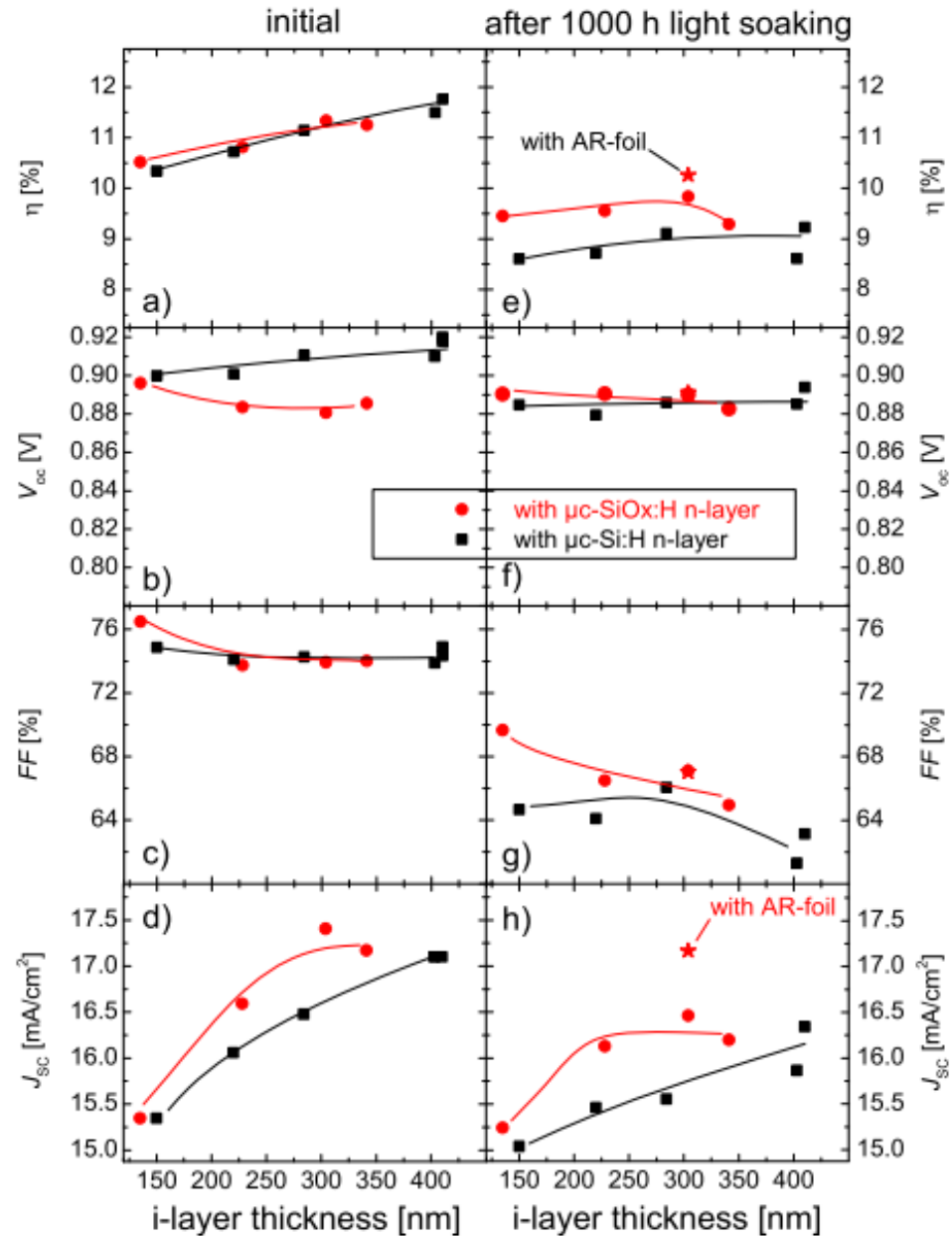
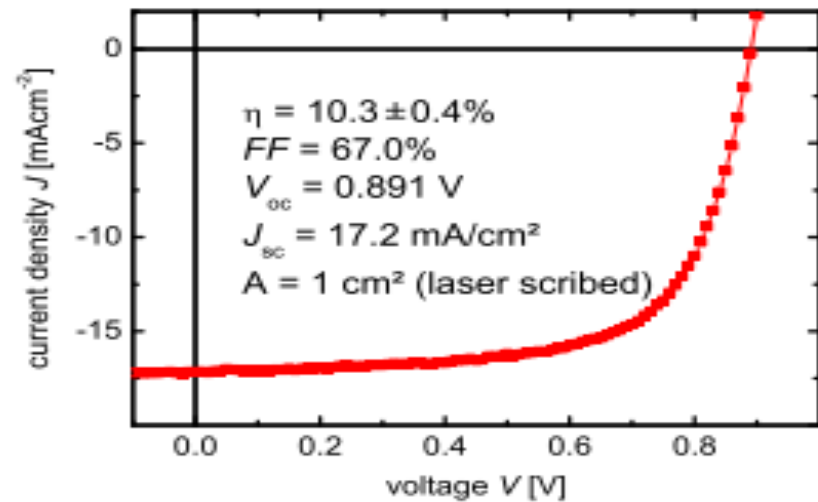
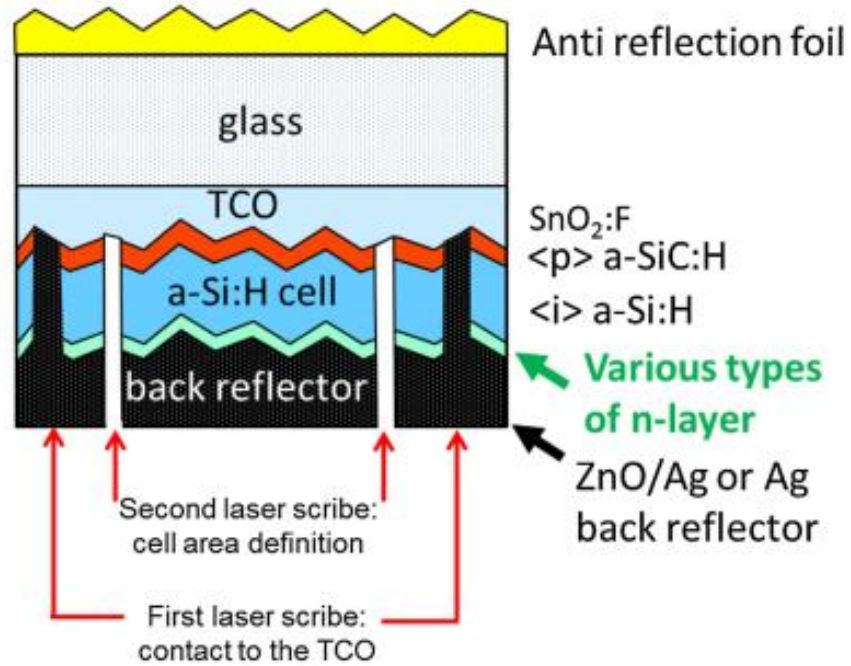
Thin film

Bagaimana dengan posisi sel surya film tipis a-Si:H?

Cell material	Module efficiency	Surface area needed for 1 kW _p	Advantages	Disadvantages
Monocrystalline silicon	15-18 %	7-9 m ²	<ul style="list-style-type: none"> - most efficient PV modules - easily available on the market - highly standardised 	<ul style="list-style-type: none"> - most expensive - waste of silicon in the production process
Polycrystalline silicon	13-16 %	8-9 m ²	<ul style="list-style-type: none"> - less energy and time needed for production than for monocrystalline cells (= lower costs) - easily available on the market - highly standardised 	<ul style="list-style-type: none"> - slightly less efficient than monocrystalline silicon modules
Micromorph tandem (a μ -Si)	6-9 %	9-12 m ²		<ul style="list-style-type: none"> - more space for the same output needed
Thin film: Copper indium diselenide (CIS)	10-12 %	9-11 m ²	<ul style="list-style-type: none"> - higher temperatures and shading have lower impact on performance - lower production costs 	<ul style="list-style-type: none"> - more space for the same output needed
Thin film: Cadmium telluride (CdTe)	9-11 %	11-13 m ²	<ul style="list-style-type: none"> - higher temperatures and shading have lower impact on performance - highest cost-cutting potential 	<ul style="list-style-type: none"> - more space for the same output needed
Thin film: Amorphus silicon (a-Si)	6-8 %	13-20 m ²	<ul style="list-style-type: none"> - higher temperatures and shading have lower impact on performance - less silicon needed for production 	<ul style="list-style-type: none"> - more space for the same output needed

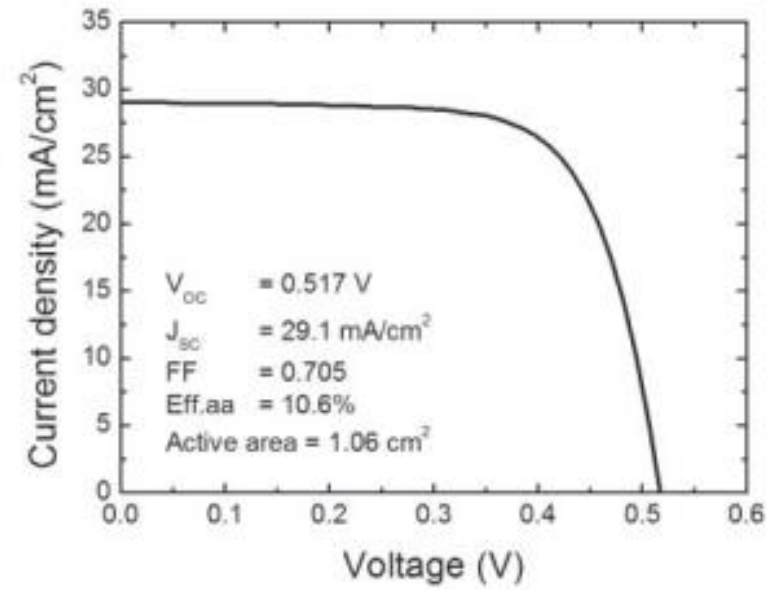
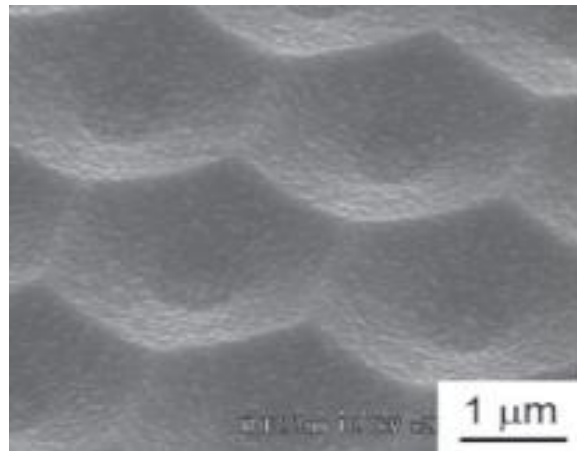
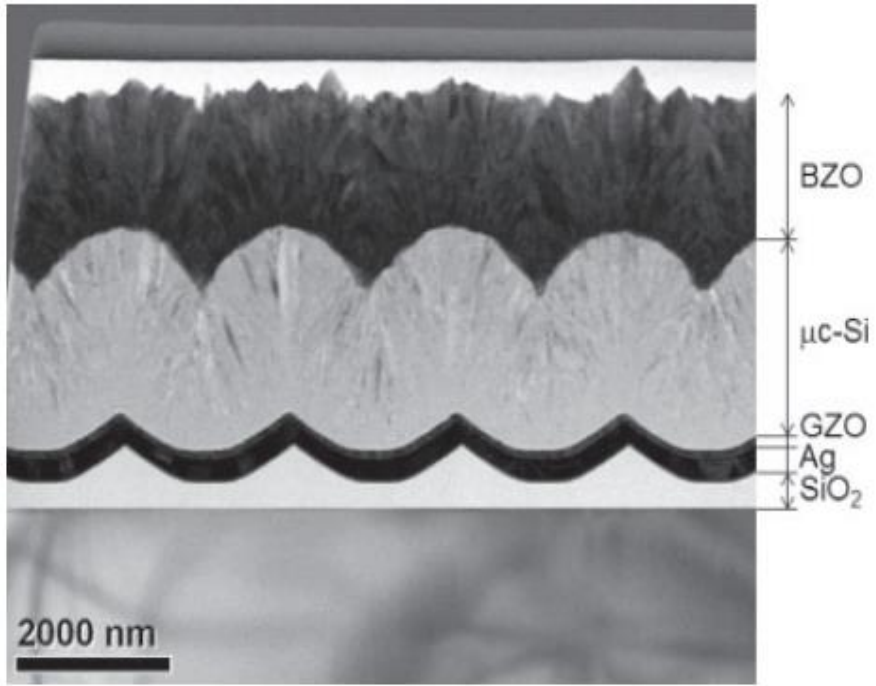
			<i>Eff.</i> (%)	<i>V_{oc}</i> (V)	<i>J_{sc}</i> (mA/cm ²)	<i>FF</i> (%)	Year	Institute	
α-Si:H	Single-junction		9.47	0.859	17.52	63.0	2004	IMT	
			10.09	0.877	17.28	66.6	2009	Oerlikon	
			10.11	0.906	16.06	69.5	2013	AIST	
			10.22	0.896	16.36	69.8	2014	AIST	
		Lambertz, dkk. Prog. Photovolt. Res. Appl, 2015	10.3	0.891	17.20	67.0	2015	Jülich	
μc-Si:H	Single-junction		10.1	0.539	24.35	76.8	1999	Kaneka	
			10.3	0.568	25.50	71.3	2006	Jülich	
			10.5	0.521	28.17	71.6	2013	AIST	
			10.69	0.549	26.55	73.3	2013	IMT	
			10.8	0.523	28.24	73.2	2013	AIST	
		Sai, dkk (2015) Appl. Phys. Lett. 96, 213504	10.97	0.542	27.44	73.8	2014	AIST	
			11.4	0.535	29.07	73.1	2014	AIST	
	11.77	0.548	29.39	73.1	2015	AIST			
α-S:H	μc-Si:H	Tandem-junction	11.7	5.462	2.99	71.3	2004	Kaneka	
			11.91	1.346	12.92	68.5	2010	Oerlikon	
			12.16	?	?	?	2011	Oerlikon	
			12.2	?	?	?	2011	Sanyo	
			11.9	1.322	13.02	69.0	2012	AIST	
			12.0	1.330	12.92	70.0	2013	AIST	
			12.1	1.411	12.60	67.8	2013	HZB	
			12.3	1.365	12.93	69.4	2013	Kaneka	
			Matsui, dkk (2015) Jpn. J. Appl. Phys. 54, 08KB10	12.63	1.382	12.82	71.3	2014	IMT
				12.69	1.342	13.45	70.2	2015	AIST
α-Si:H	μc-Si:H	triple-junction	12.0	1.840	8.54	76.2	2004	Kaneka	
			12.41	1.936	8.96	71.5	2011	United Solar	
			13.44	1.963	9.52	71.9	2013	LG	
			13.46	1.967	9.84	69.6	2015	TEL solar	
			Sai, dkk (2016) Appl. Phys. Lett. 109, 183506	13.6	1.901	9.92	72.1	2015	AIST
				14.0	1.922	10.39	73.4	2016	AIST

Single-junction solar sel a-Si:H

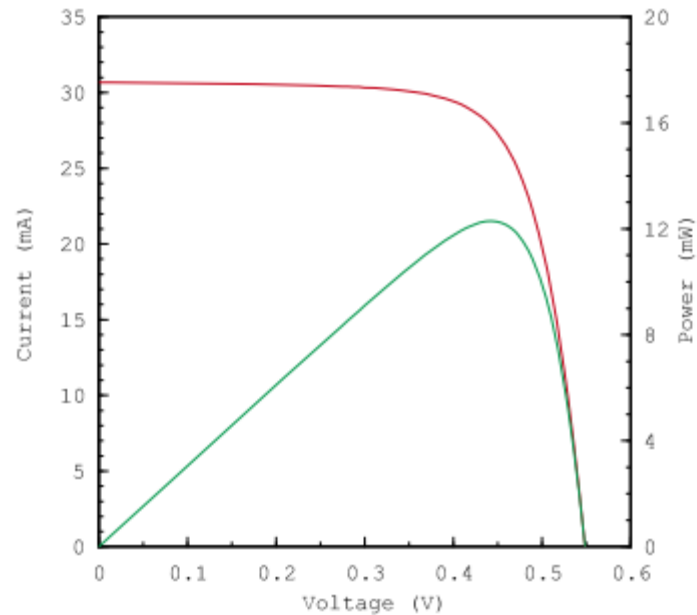


Lambert, dkk, 2015
 Prog. Photovolt: Res. Appl. 2015; 23:939-948

Struktur single-junction $\mu\text{-Si:H}$



I-V CURVE
 C60904-3Ed.2 1.044 cm² (designated area) WHSS



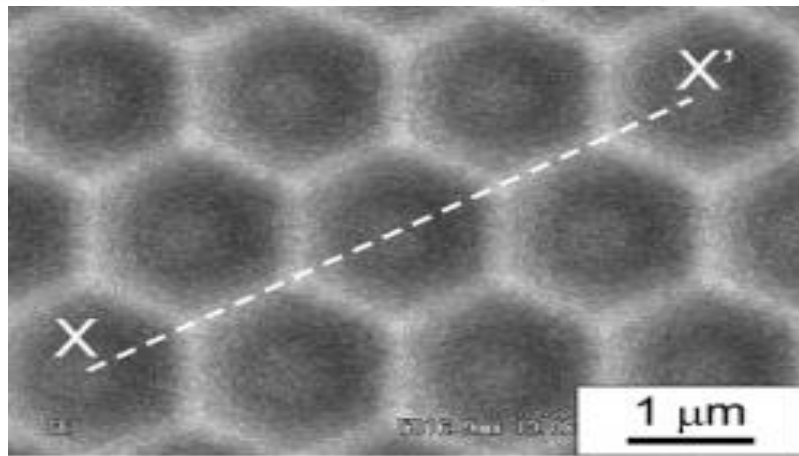
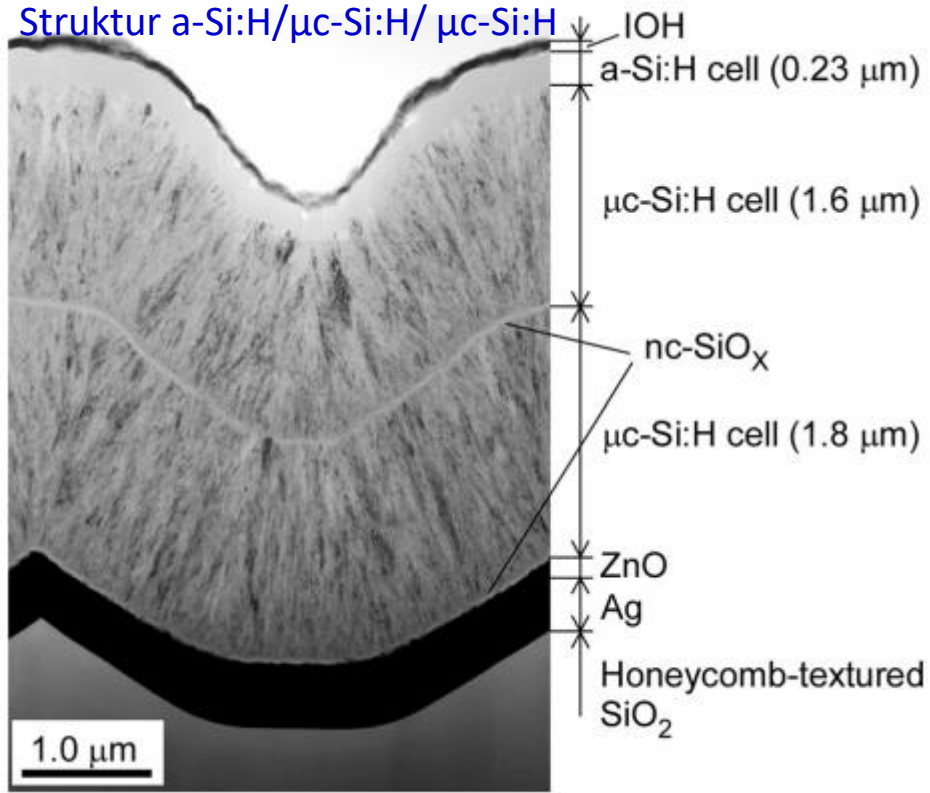
Date : 22 Oct 2014
 Data No :
 SC1915A1-1
 Sample No :
 SC1915A1
 Repeat Times : 5

$I_{sc} = 30.68 \text{ mA}$
 $V_{oc} = 0.548 \text{ V}$
 $P_{max} = 12.29 \text{ mW}$
 $I_{pmax} = 27.93 \text{ mA}$
 $V_{pmax} = 0.440 \text{ V}$
 $F.F. = 73.1 \%$
 $Eff(da) = 11.77 \%$
 $DTemp. = 25.0 \text{ }^\circ\text{C}$
 $MTemp. = 24.9 \text{ }^\circ\text{C}$
 $DIrr. = 100.0 \text{ mW/cm}^2$
 $MIrr. = 99.6 \text{ mW/cm}^2$

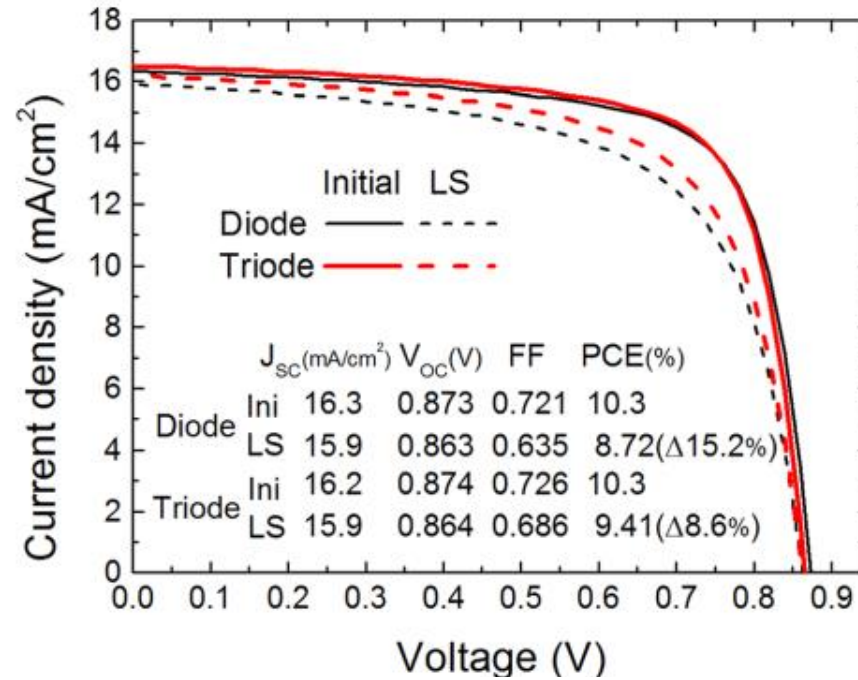
Ref. Device No
 93307
 Cal. Val. of Ref.
 126.05 [mA at 100mW/cm²]
 Scan Mode
 Isc to Voc

Sai, dkk (2015)
Jpn. J. Appl. Phys. 54, 08KB05

Struktur a-Si:H/ μ c-Si:H/ μ c-Si:H

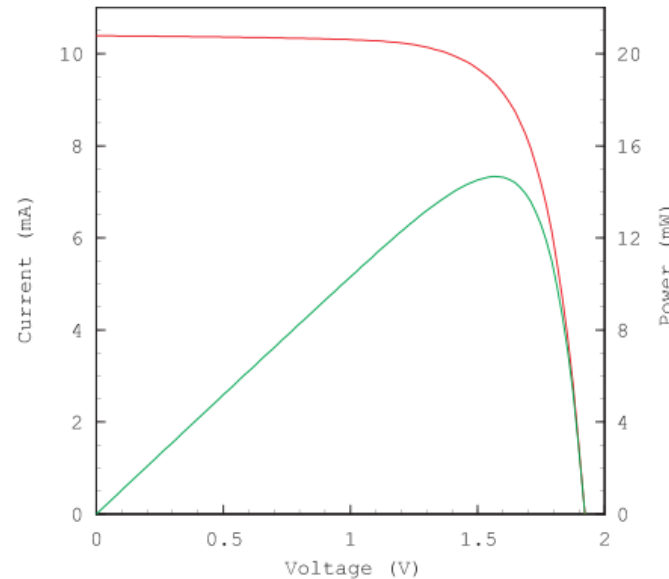


Sai, dkk (2016)
Appl. Phys. Lett. 109, 183506



I-V CURVE
 IEC60904-3Ed.2 1.045 cm²(designated area) WHSS

Date : 26 May 2016
 Data No : SC2510A1-01
 Sample No : SC2510A1
 Repeat Times : 5

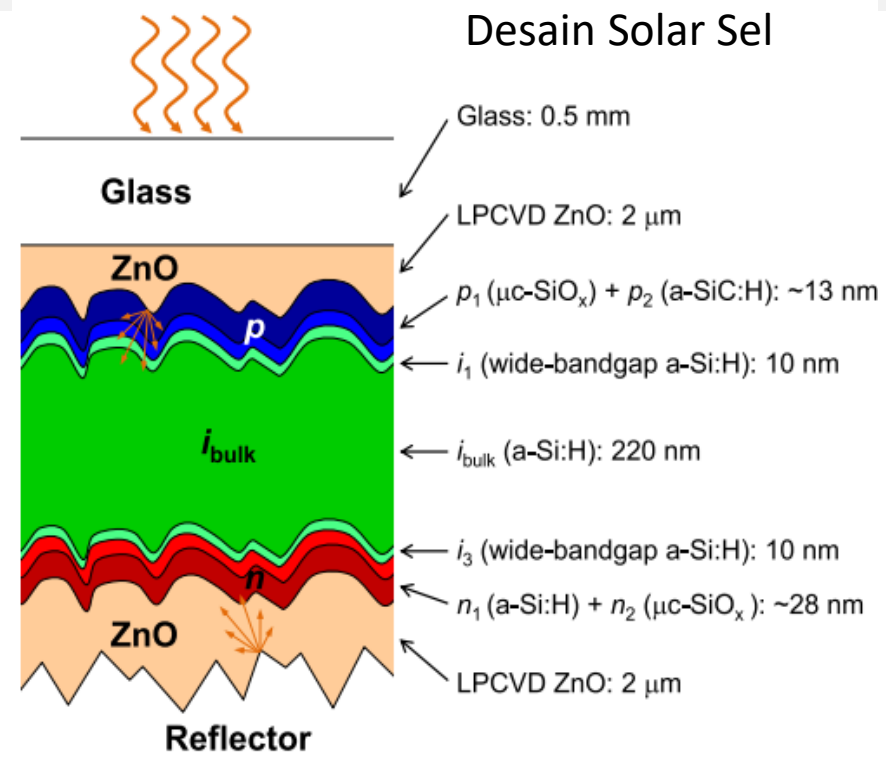
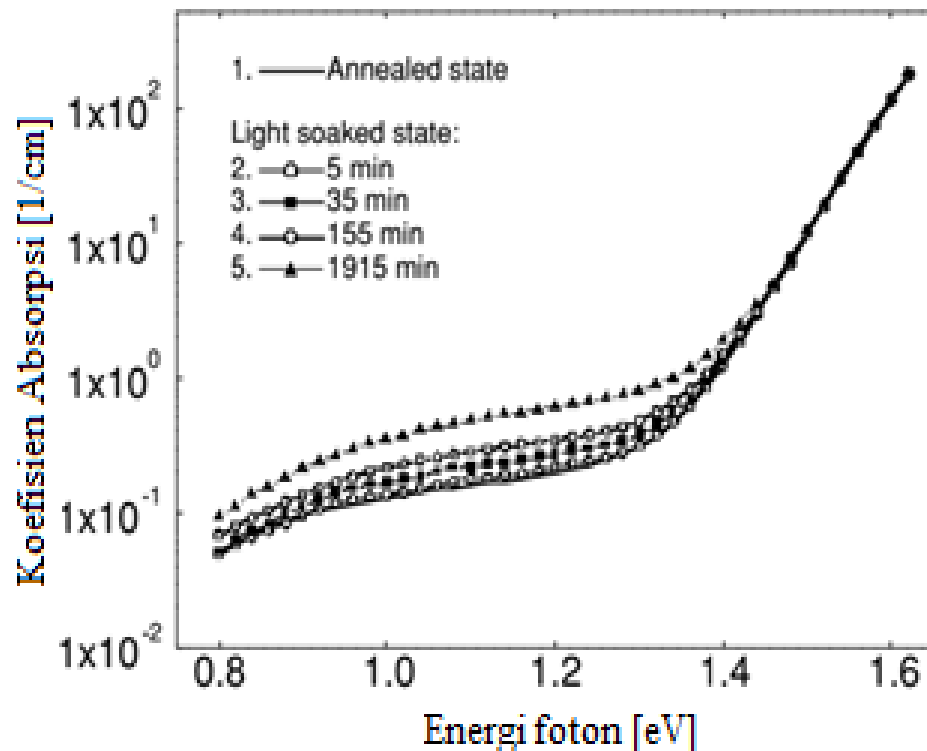


Isc 10.39 mA
 Voc 1.922 V
 Pmax 14.67 mW
 Ipmax 9.38 mA
 Vpmax 1.563 V
 F.F. 73.4 %
 Eff (da) 14.04 %
 DTemp. 25.0 °C
 MTemp. 24.9 °C
 DIrr. 100.0 mW/cm²
 MIrr. 99.4 mW/cm² (top)
 100.8 mW/cm² (middle)
 100.2 mW/cm² (bottom)

Scan Mode
 Isc to Voc

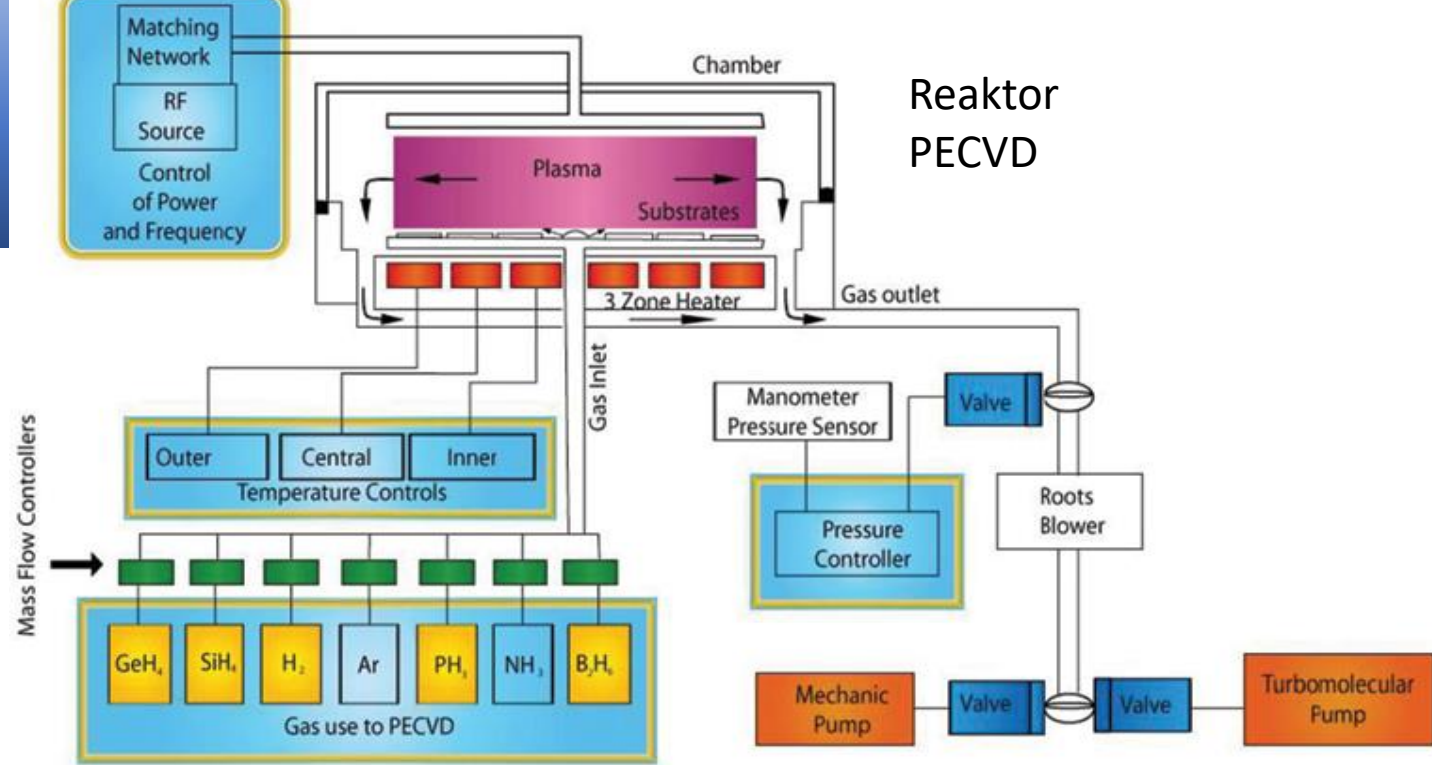
Efek Staebler-Wronski (SWE)

- Perubahan perilaku Sel surya a-Si:H, yaitu penurunan sifat foto-konduktivitas pada saat disinari dan penurunan konduktivitas setelah diterangi. Fenomena ini dikenal dengan efek Staebler-Wronski (SWE) terjadi karena proses induksi cahaya (*light-induced*), yaitu degradasi sifat aliran selama penyinaran pada Sel surya a-Si:H.
- Secara fisis fenomena ini terjadi karena terbentuknya cacat oleh rekombinasi non-radiatif antara foto-eksitasi elektron dan hole pada ikatan lemah SiSi yang menghubungkan ikatan SiHHSi

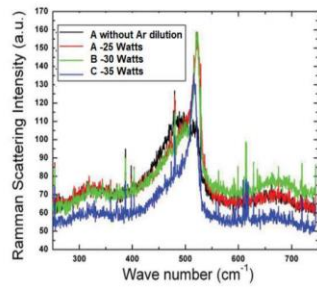
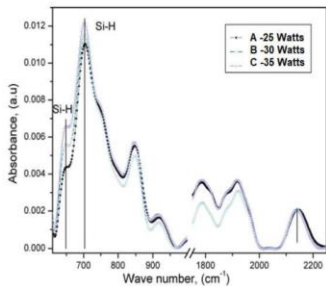
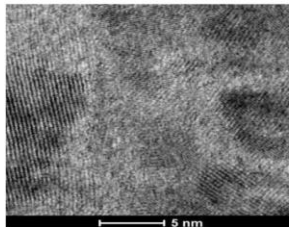
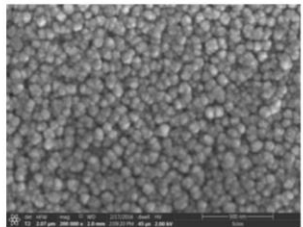


FOKUS a-Si:H

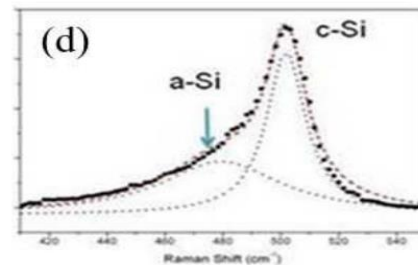
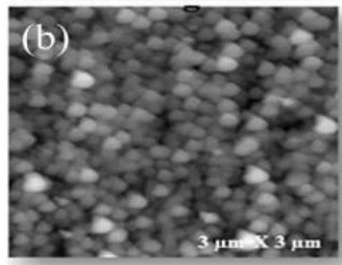
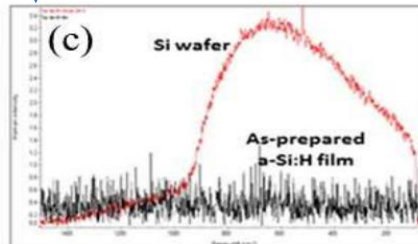
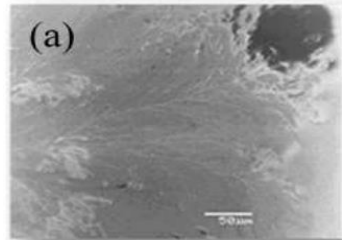
- Pengenceran hidrogen dinaikkan
- Laju deposisi diturunkan



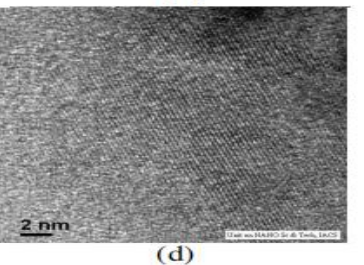
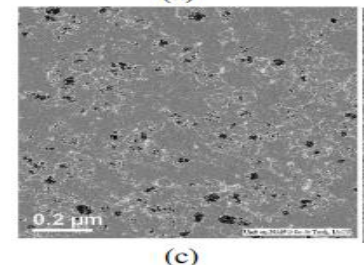
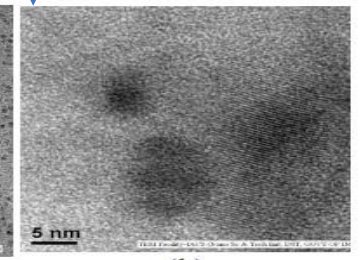
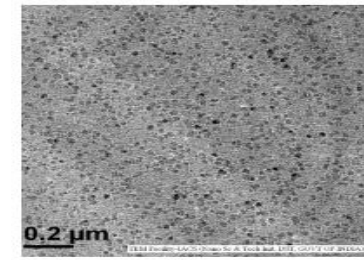
a-Si:H



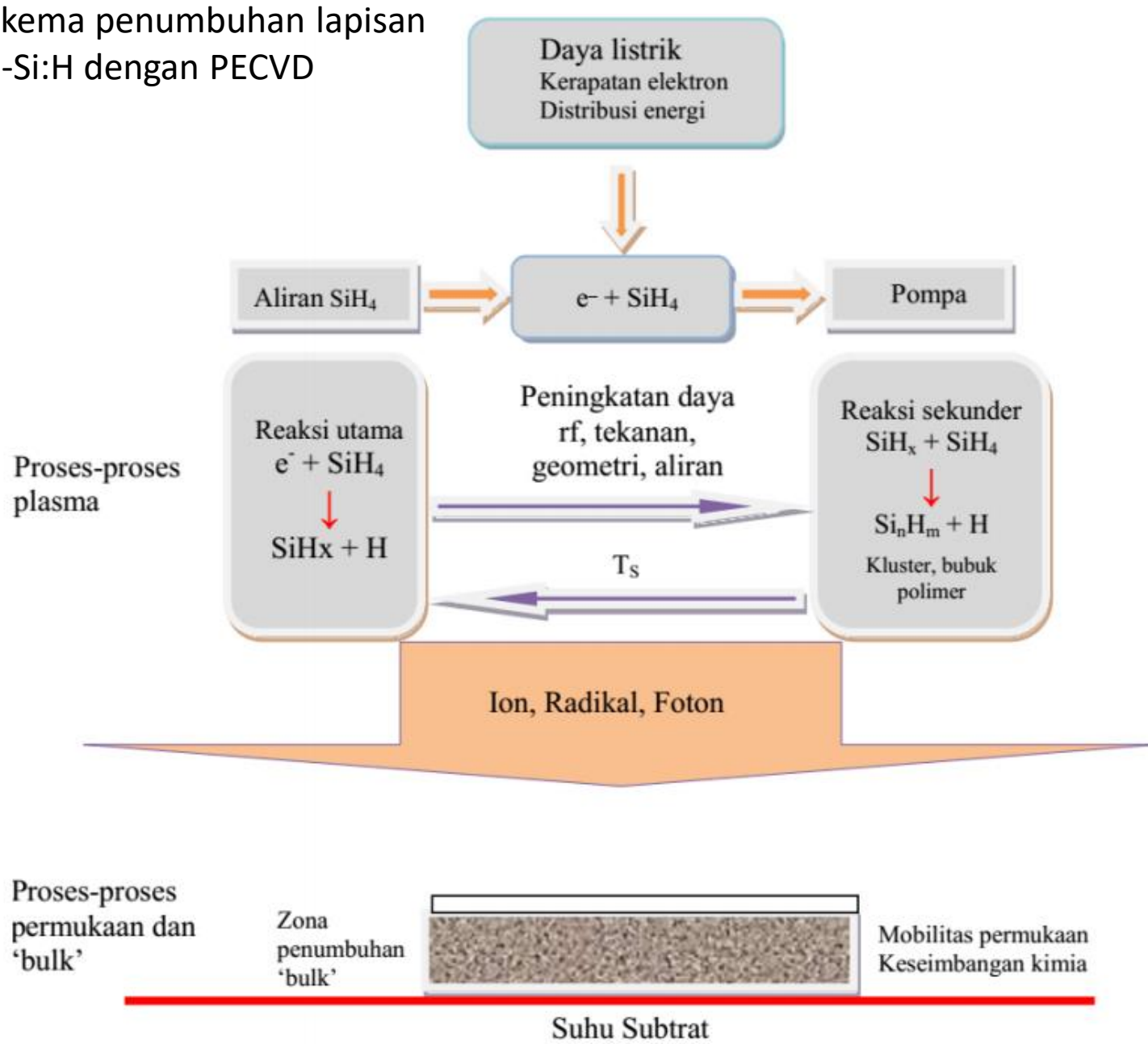
μ c-Si:H



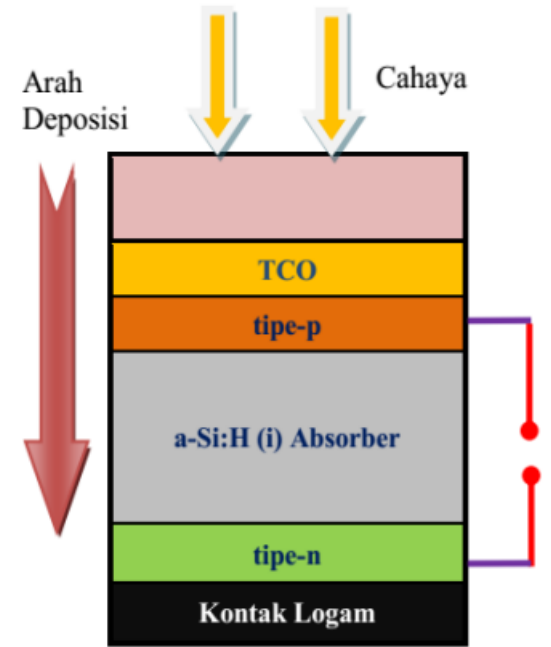
nc-Si:H



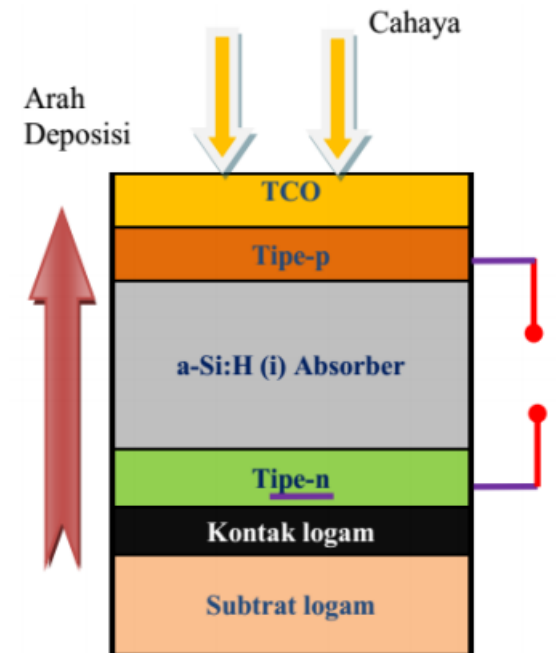
Skema penumbuhan lapisan a-Si:H dengan PECVD



Superstrate



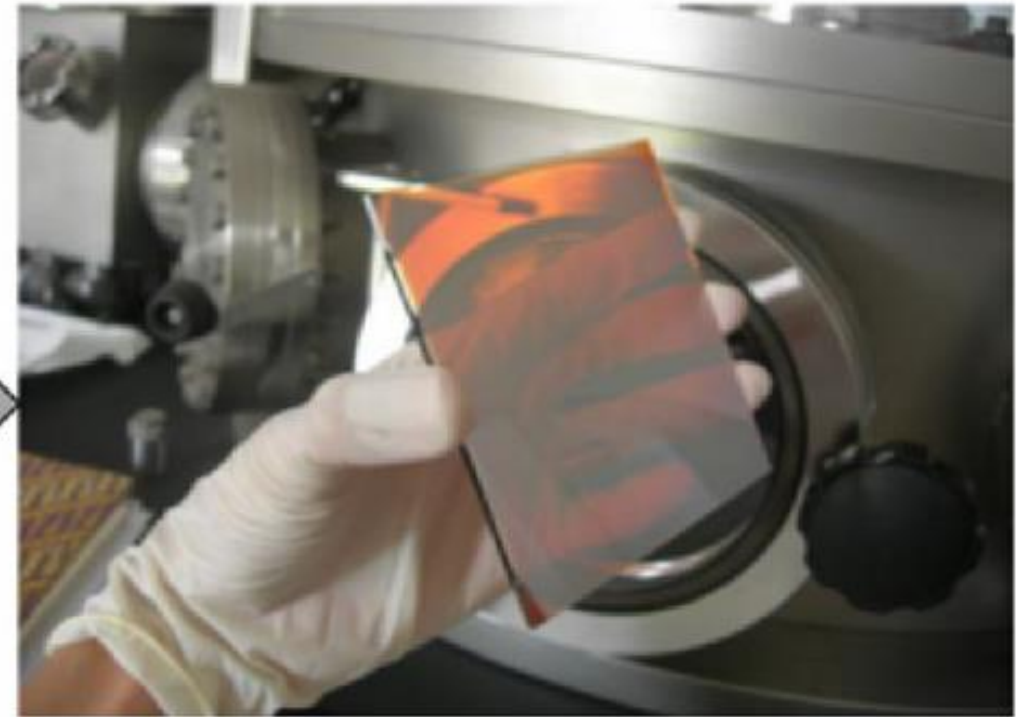
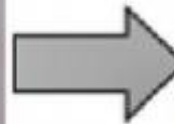
Substrate



RF-PECVD (Radio Frequency-Plasma Enhanced Chemical Paviour Deposition)



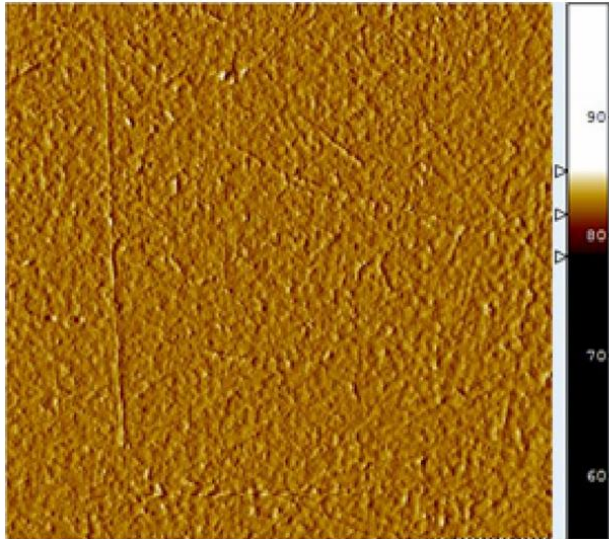
(a)



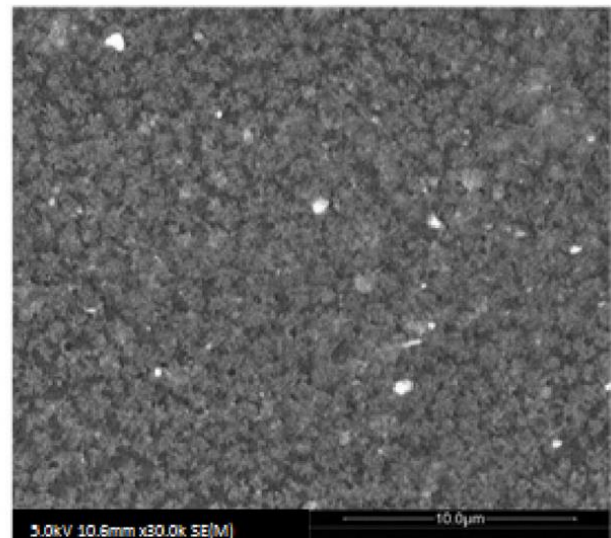
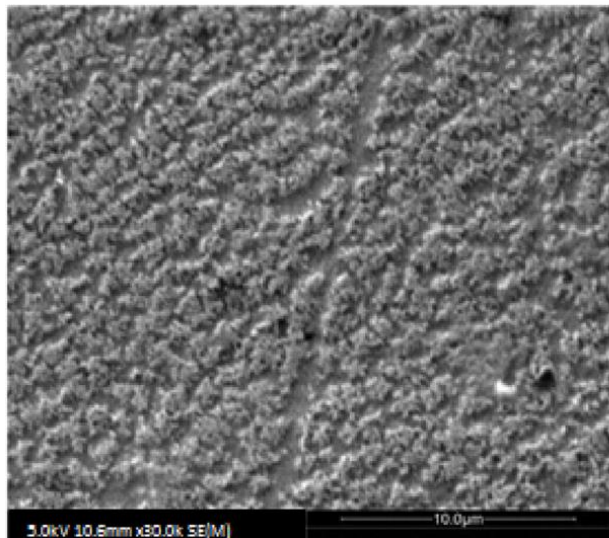
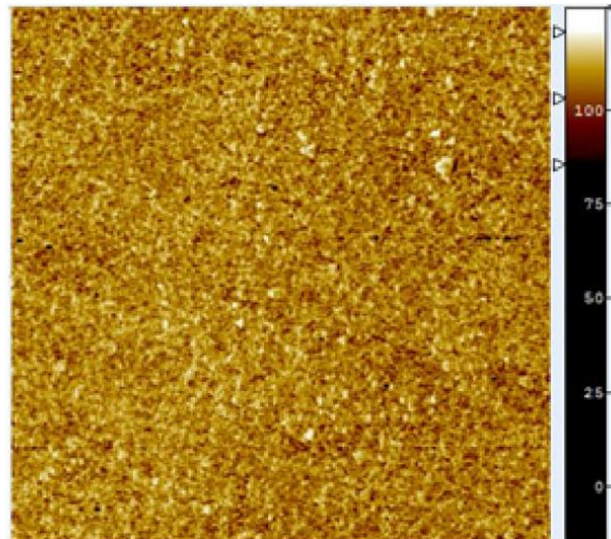
(b)

Citra SEM Sel Surya Struktur p-i-n dan p-i₁-i₂-n

p-i-n

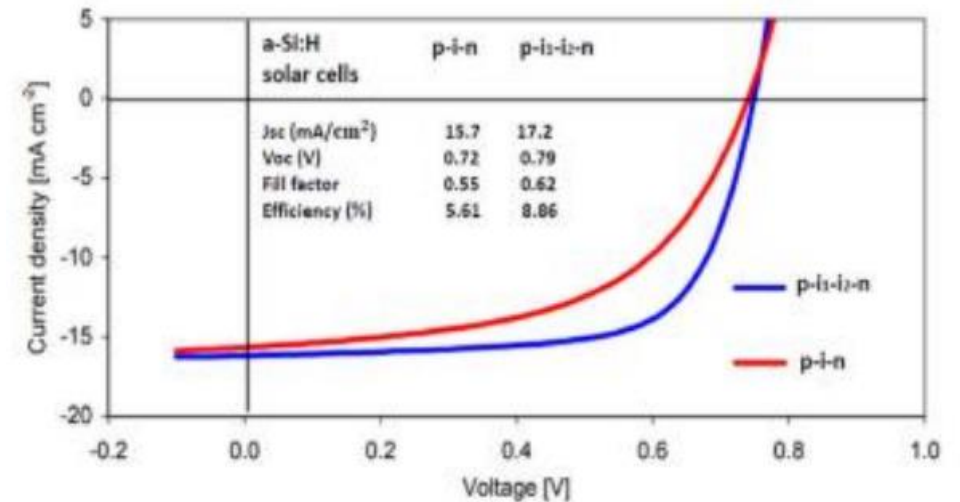


p-i₁-i₂-n

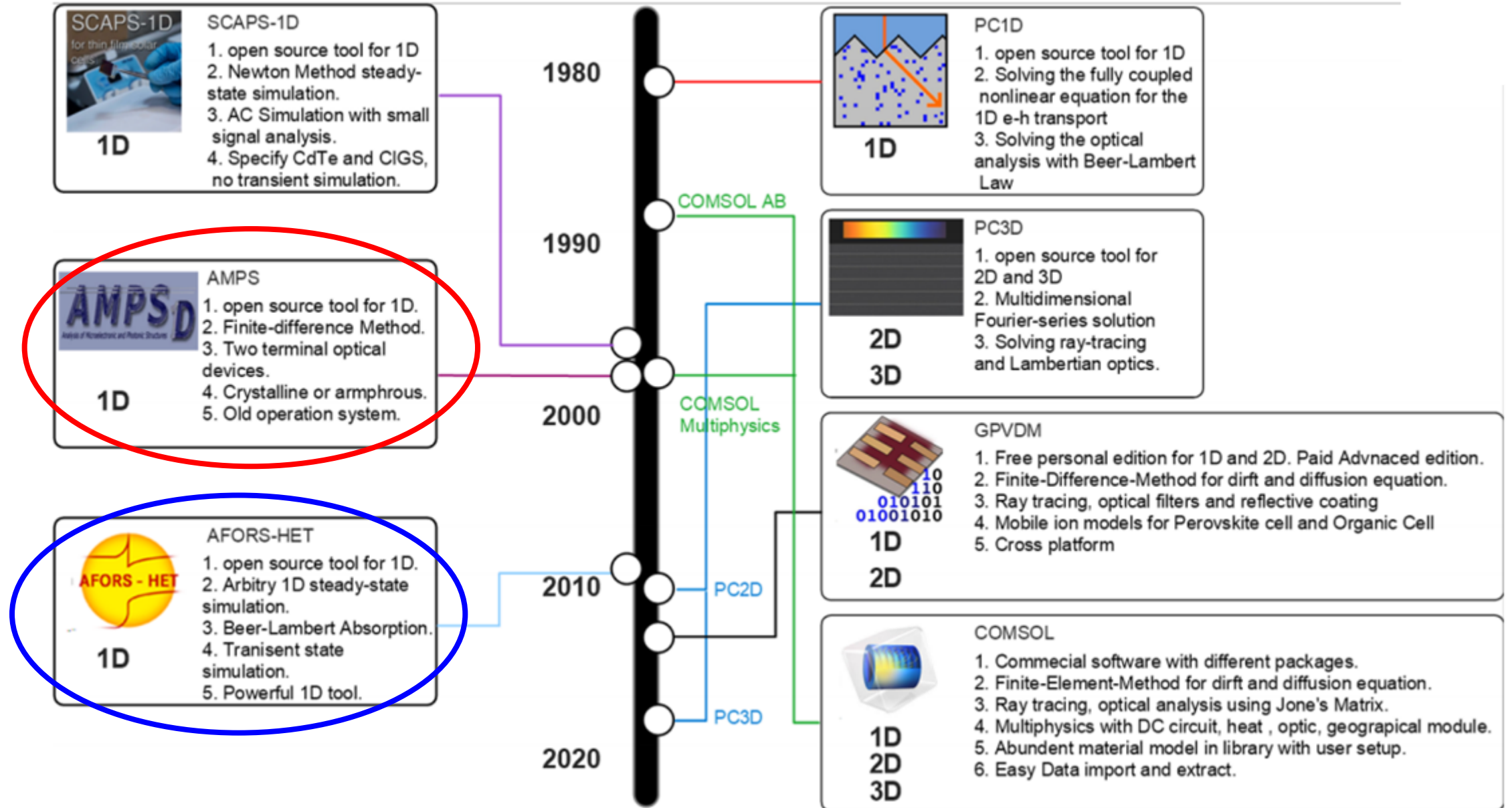


Deposition parameters	p-i-n		
	p (B ₂ H ₆)	i ₁ (H ₂ /SiH ₄)	n (PH ₄)
Gas flow ratio (sccm)	2	16	5
Thicknesses (nm)	15	600	25
Band gap (eV)	2.00	1.70	2.20
Conductivity (Ω ⁻¹ cm ⁻¹)	2.80 × 10 ⁻³	6.20 × 10 ⁻⁵	9.50 × 10 ⁻³

Deposition parameters	p-i ₁ -i ₂ -n			
	p (B ₂ H ₆)	i ₁ (H ₂ /SiH ₄)	i ₂ (H ₂ /SiH ₄)	n (PH ₄)
Gas flow ratio (sccm)	2	16	36	5
Thicknesses (nm)	15	300	300	25
Band gap (eV)	2.00	1.70	1.85	2.20
Conductivity (Ω ⁻¹ cm ⁻¹)	2.80 × 10 ⁻³	6.20 × 10 ⁻⁵	3.40 × 10 ⁻⁴	9.50 × 10 ⁻³



Peran Pemodelan dan Simulasi




AFORS-HET (Open Source)

AFORS-HET v2.5

Automat FOR Simulation of HETero structures

Press F1 for help concerning the active window.



external parameters

Illumination

On Side
 Front
 Back

spectral

monochromatic

Measurement list

- I-V
- 1DM
- I-V2DNet
- QE
- PEL
- TR-PEL
- intTR-PEL
- VD-SPV
- WD-SPV
- ID-SPV
- TR-SPV
- Goodman
- IMP
- ADM
- C-V
- C-T
- QSSPC
- PMCC
- EDMR

show only latest graph

Temperature

device temperature [K]:

Boundary

zero potential at:

Boundary control DC:

ext. Voltage [V]:

program control

Exit **Define Structure**

Settings Spectra Results

Parameter Variation

Set Go

Parameter Fit / Optimization

Set Go Results

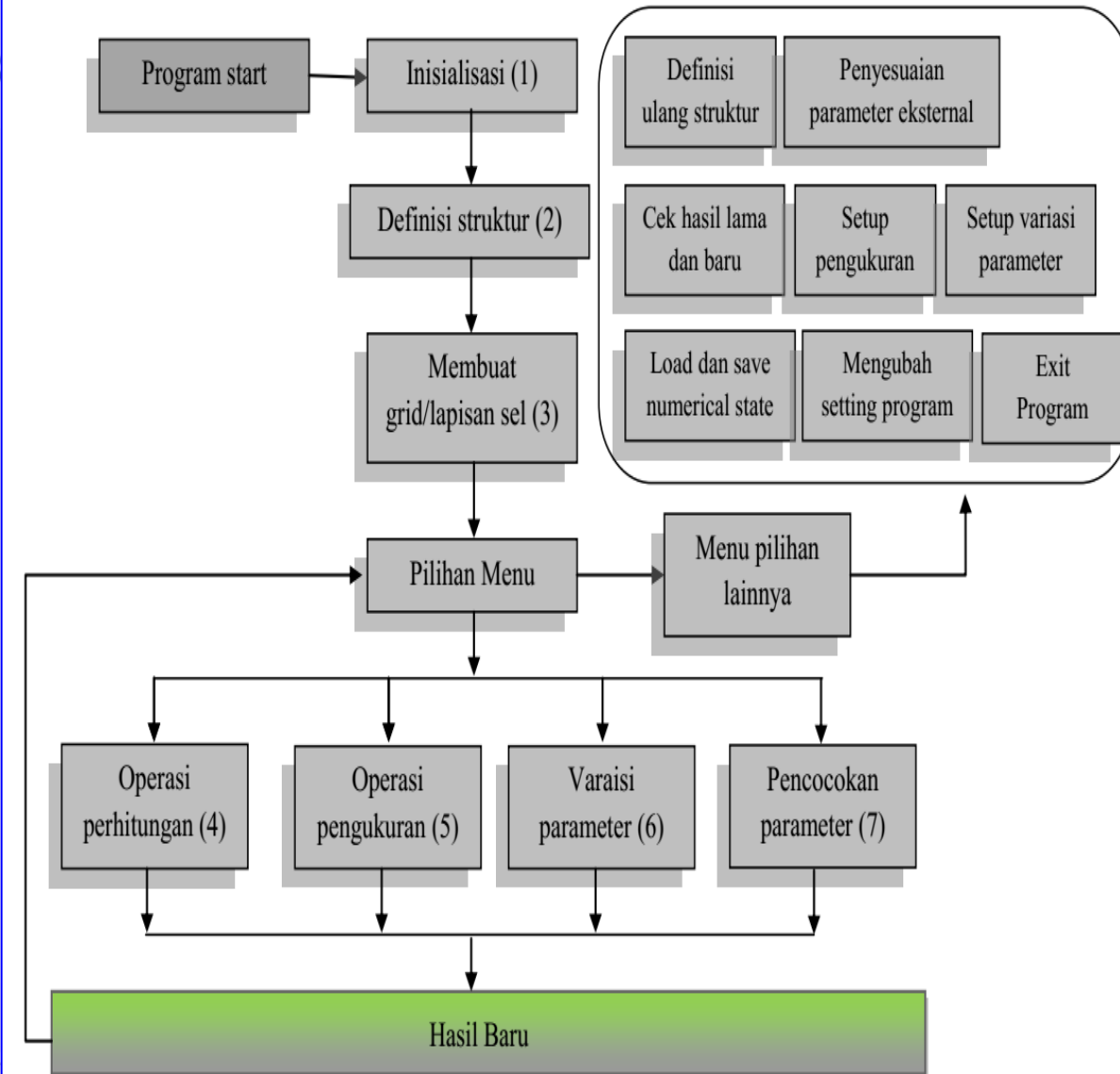
Calculation

mode:

Initial values for calculation:

Save Load

Initialize Calculate



PARAM

name: db Acceptor

Type

- Single
- Continous
- Gauss
- CorrGauss
- ValenceTail
- CondcTail
- RadioButton1

Distribution

- const
- linear
- exp

Charge

- Acceptor
- Donor
- Neutral
- DanglingBond

Hurkx rec. model

- off
- Hurkx homo
- Hurkx hetero
- Hurkx hetero num.

m*: 0.25

electronic capture

cn: 1E-15 cm²

cp: 1E-14 cm²

optic capture

cno: 0 cm²

cpo: 0 cm²

Ntr (total): 7.9999999E+17 cm⁻³

Ntr(specific): 1.3876253E+18 cm^{-3/eV}

= Ntr(total)/((2pi)^{0.5}*sigma)

E: 0.7 eV

Sigma: 0.23 eV

secondary parameters

Tau n [s]: 1.250000015625E-10

Tau p [s]: 1.250000015625E-10

L n [cm]: 5.684631389341

L p [cm]: 1.797638284880

implied Voc @ G=41mA [V]:

impVoc

Settings for computational accuracy

Defect distributions: integration over full band gap

0.01 Hurkx model: accuracy of numerical integration

1 Hurkx model: min E field

OK Cancel

name 15nm_aSi(p)

bulk model standard specify thickness [cm]: 1.5E-6

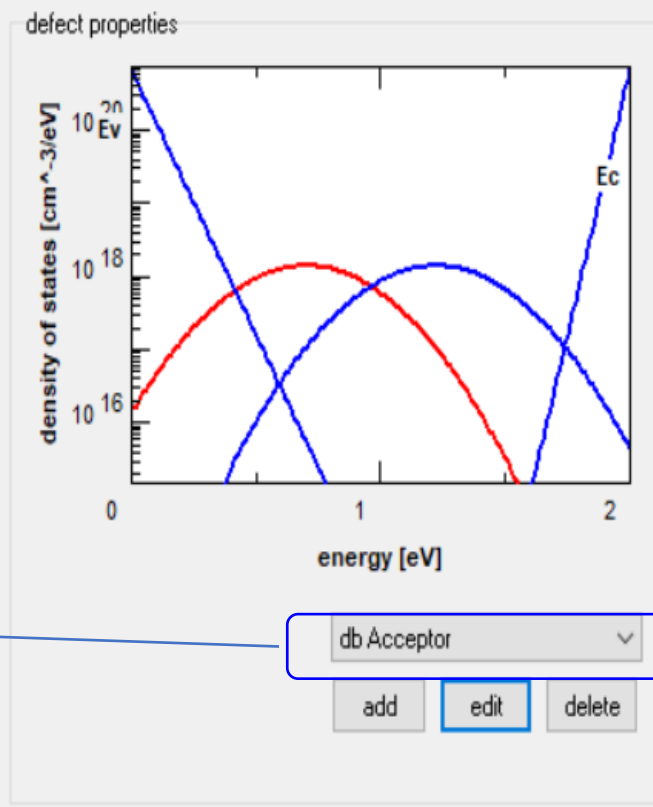
Load Save Delete

electrical properties

functional dependance: Constant

dk [-]	11.9
chi [eV]	3.8
Eg [eV]	2
Eg opt. [eV]	1.72
Nc [cm ⁻³]	2.5E20
Nv [cm ⁻³]	2.5E20
μn [cm ² /Vs]	10
μp [cm ² /Vs]	1
Na [cm ⁻³]	3E18
Nd [cm ⁻³]	0
ve [cm/s]	1E07
vh [cm/s]	1E07
rho [g*cm ⁻³]	2.328
rae [cm ⁶ /s]	0
rah [cm ⁶ /s]	0
rbb [cm ³ /s]	0

FTM on F0 [V/cm] 2E05



layer properties

Taun [s] Lp [cm]

Taup [s] Ln [cm]

OK

optical properties

nk-File aSi.nk

constant nk:

alpha = 4 * pi * k / lambda

incoherent

Ref, AbsT00

ottky S1e7)

ottky S1e7)

list to

eters

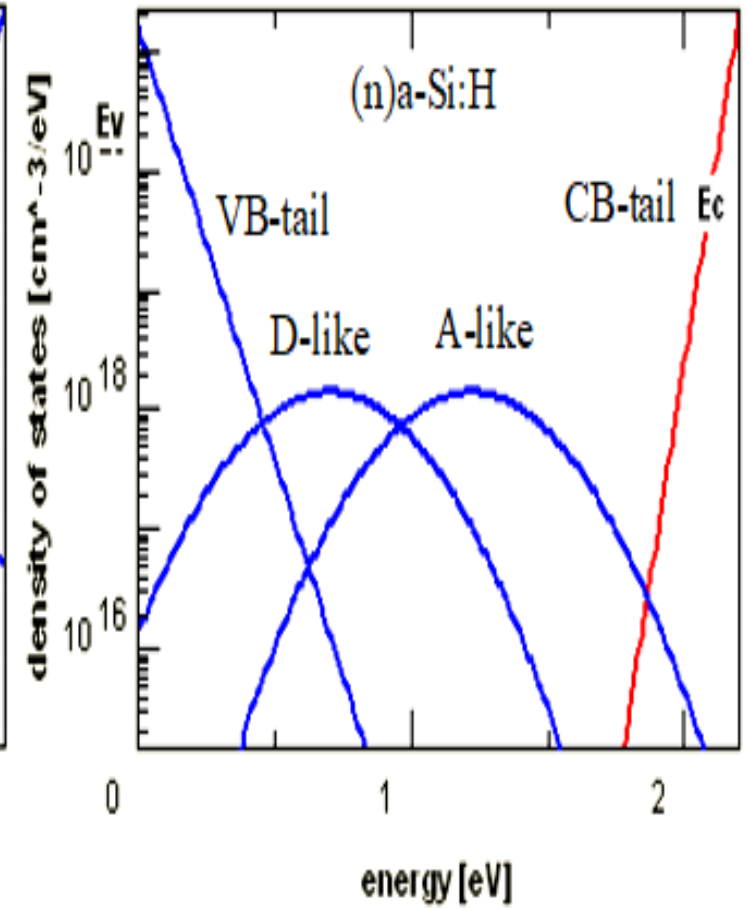
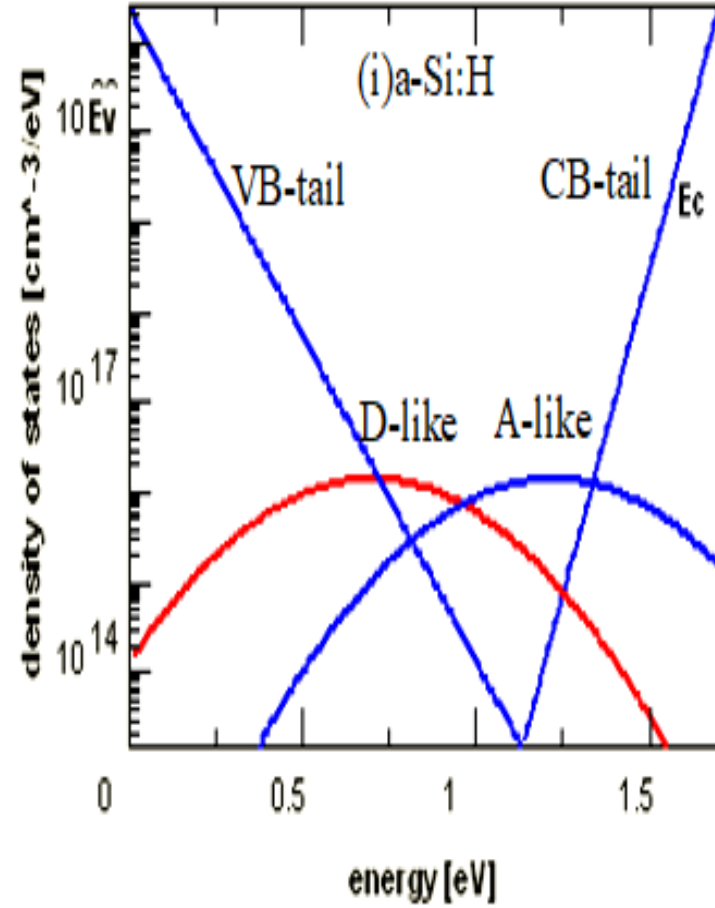
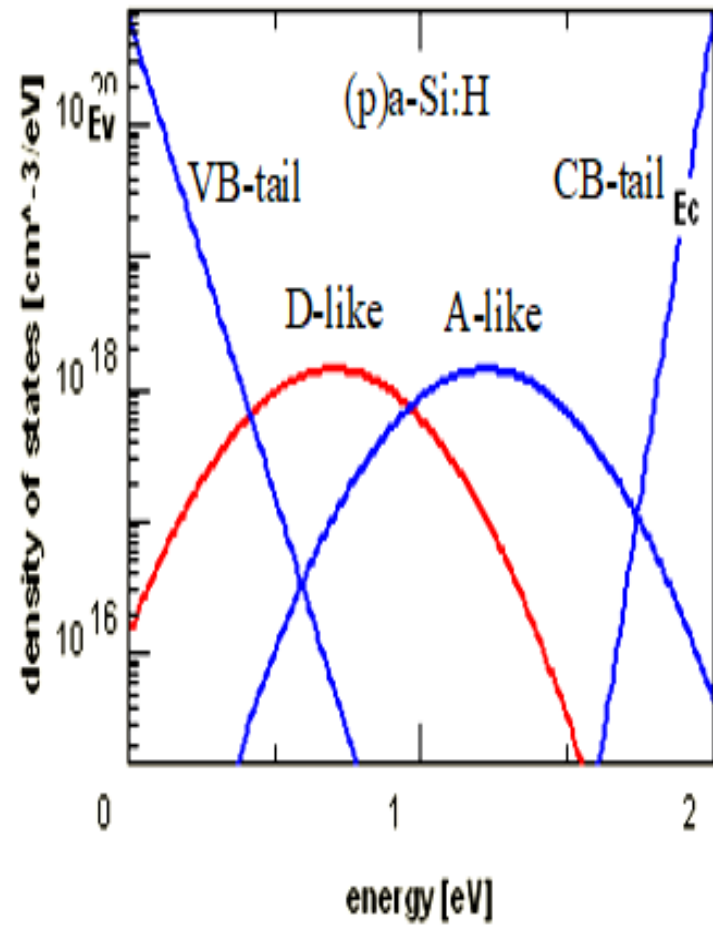
cor

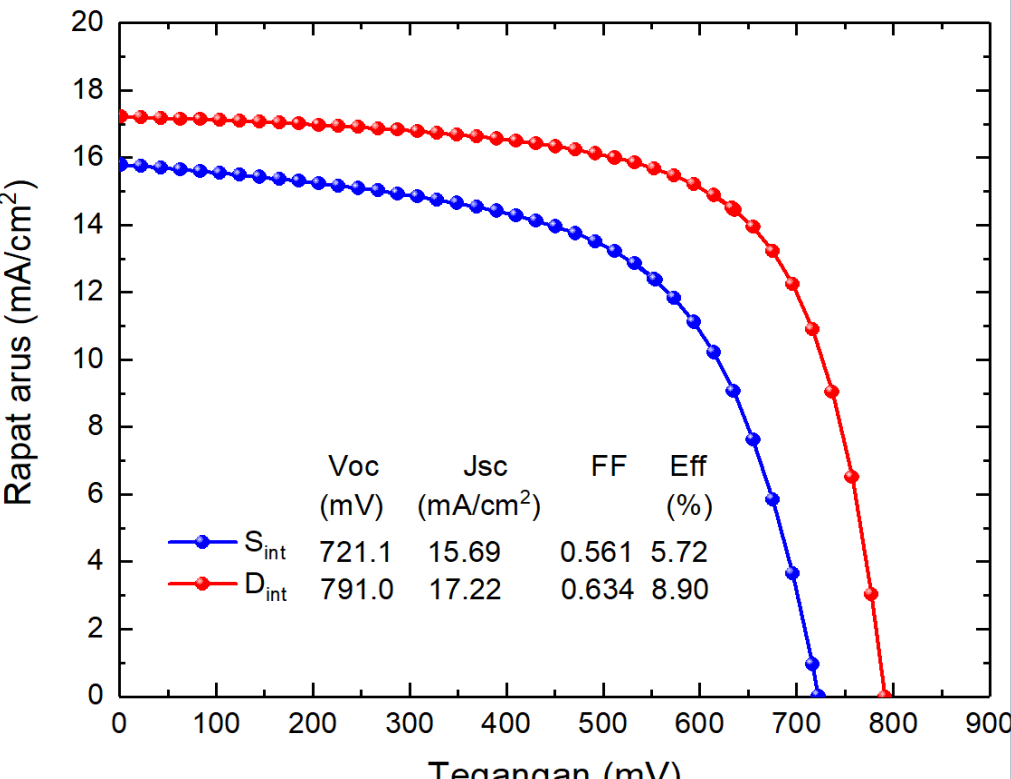
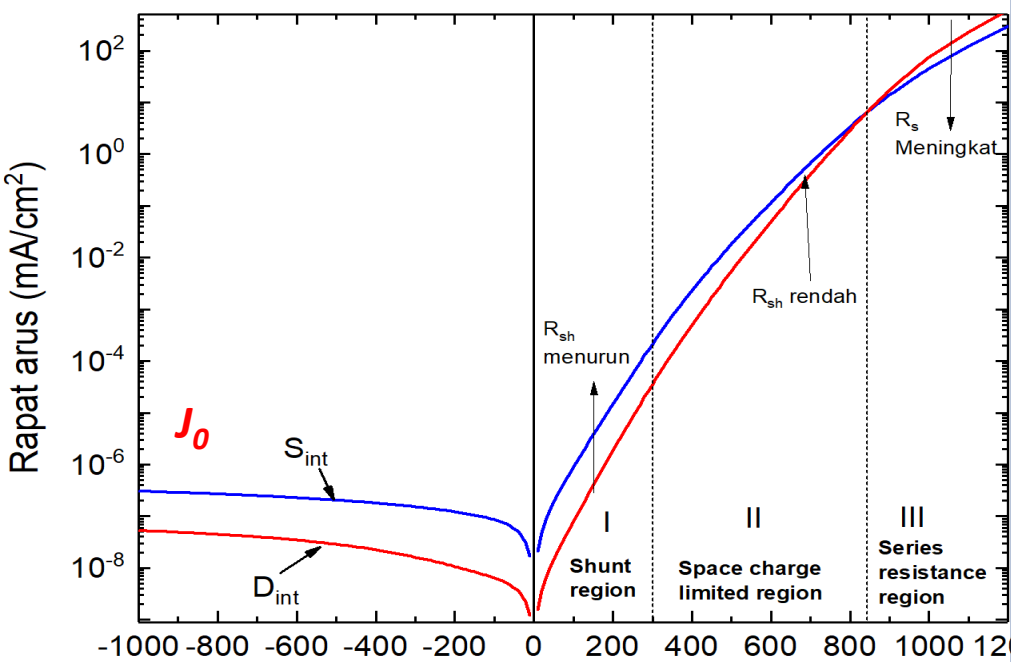
cont

back

Load

Defect State sel surya p-i-n dan p-i1-i2-n





$$J_{Dark} = J_0 \left[\exp \left(\frac{q(V - J \cdot R_s)}{n \cdot kT} \right) - 1 \right] + \frac{V + J \cdot R_s}{R_{sh}}$$

$$R_{sh} \cong \frac{V_{maks}}{J_{SC} - J_{maks}}$$

$$R_s \cong \frac{V_{OC} - V_{maks}}{J_{maks}}$$

$$J_{Tot}(G, V, T) = J_{SC}(G) + J_{Dark}(V, T)$$

$$J_{Tot}(G, V, T) = J_{SC}(G) + J_0(T)(e^{qV/k_B T} - 1)$$

Kurva karakteristik J-V dalam kondisi gelap memuat informasi:

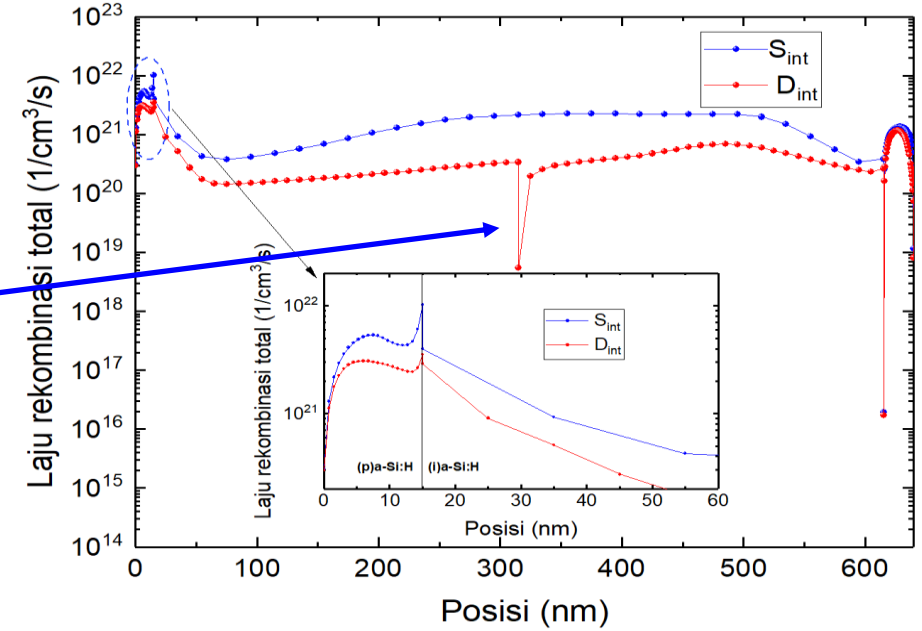
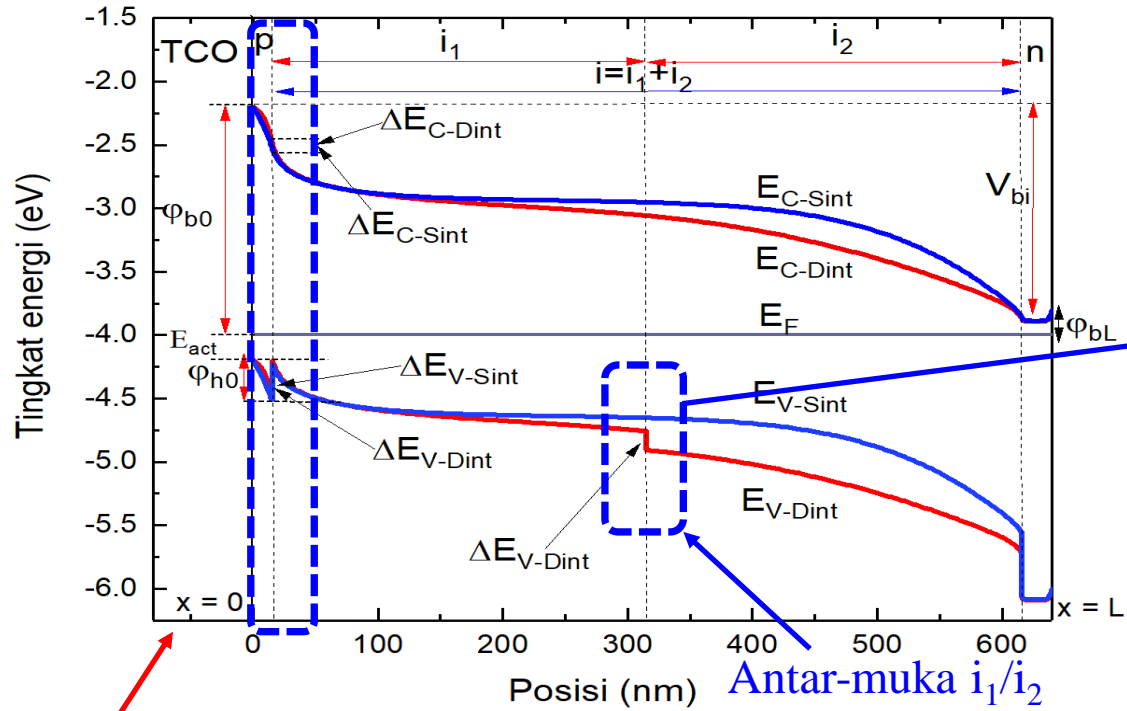
- (1) mekanisme rekombinasi : antar-muka p/i daerah cacat
- (2) kualitas sambungan; $R_{sh} \cong \frac{V_{maks}}{J_{SC} - J_{maks}}$
- (3) hambatan kontak.

Daerah I (shunt region) : arus gelap secara keseluruhan dipengaruhi oleh proses rekombinasi pasangan elektron-hole melalui *mid-gap states* pada lapisan absorber

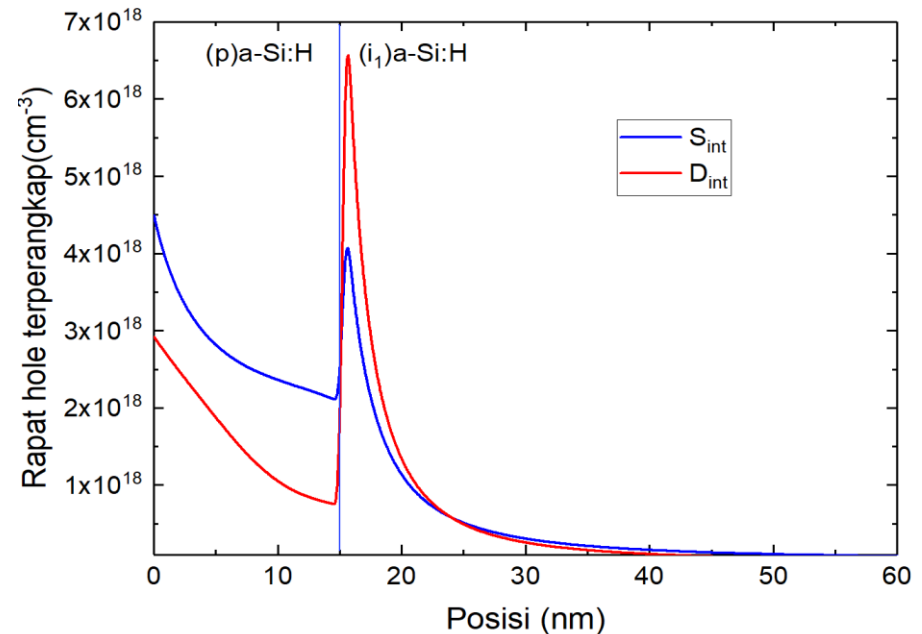
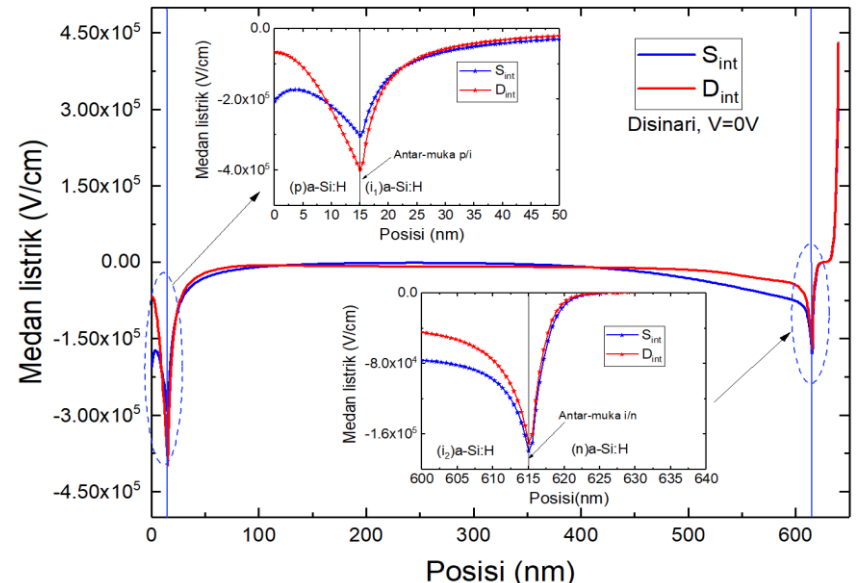
Daerah II (SCLC) : secara keseluruhan dikontrol oleh difusi elektron yang merupakan daerah *space charge limiting current* tergantung pada konsentrasi hole dan elektron yang terperangkap

Daerah III (series resistance region) : arus gelap bertambah besar dan secara keseluruhan diatur oleh injeksi hole pada antar-muka ITO/(p)a-Si:H

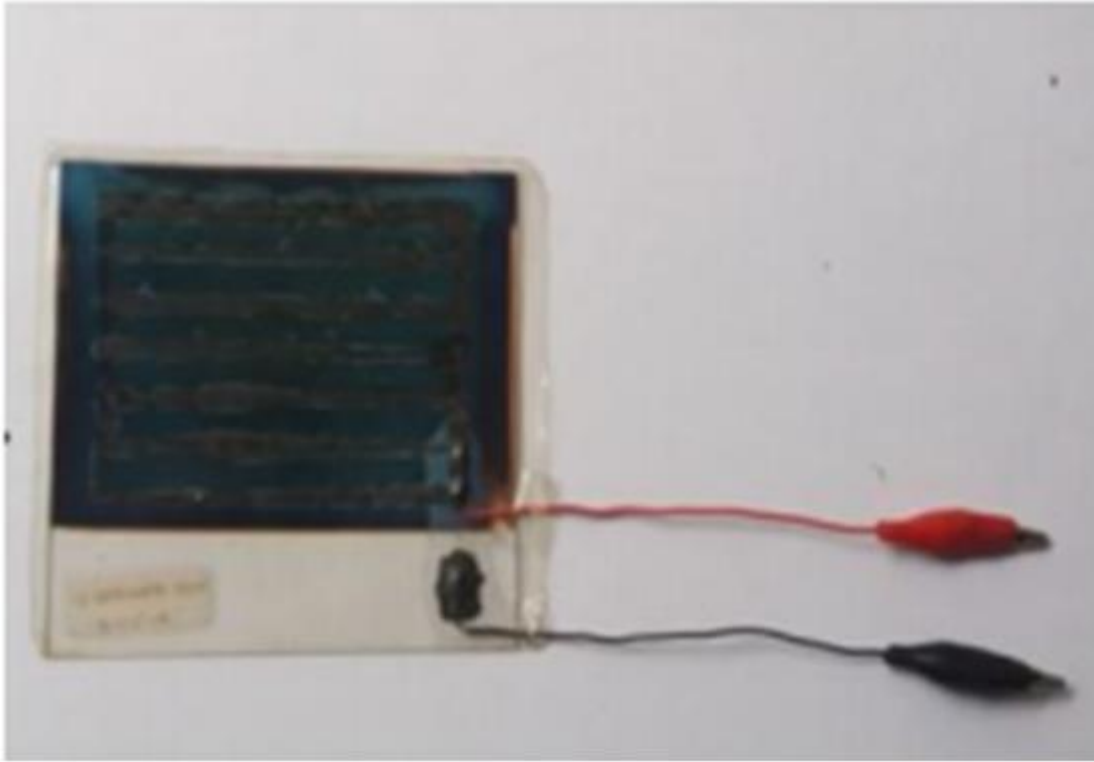
Validasi numerik struktur p-i-n dan p-i1-i2-n



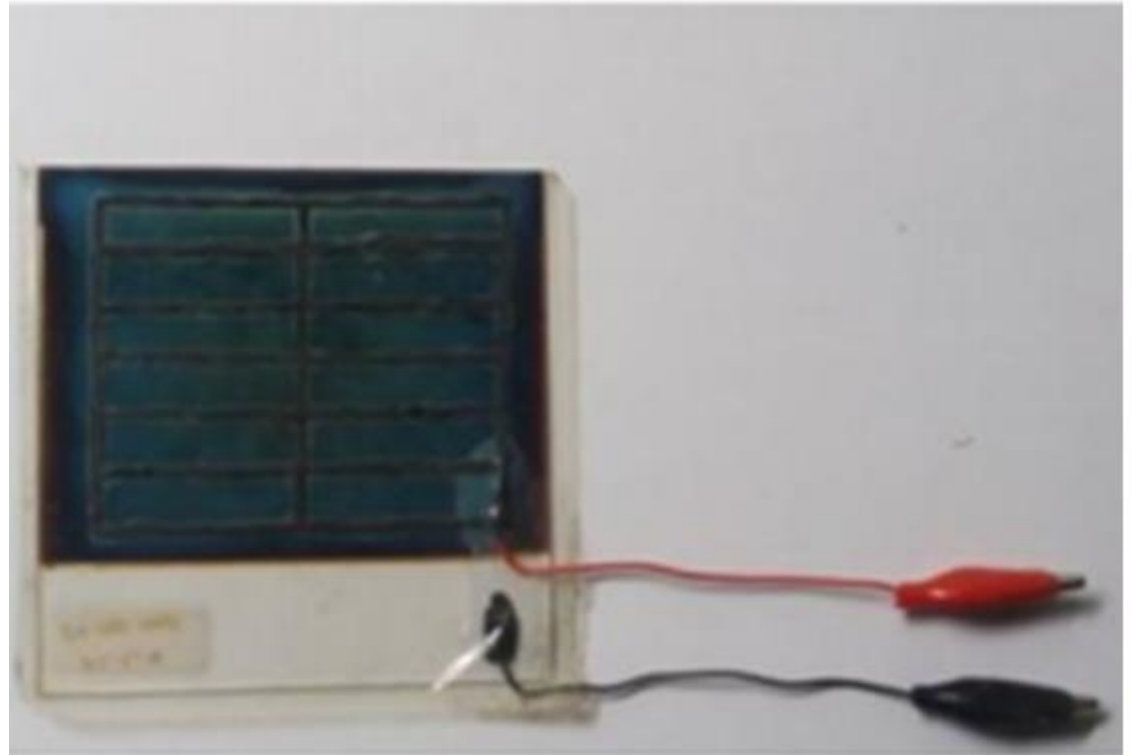
Antar-muka p/i



Sel Surya Berbasis a-Si:H



p-i-n (S_{int})



p-i₁-i₂-n (D_{int})

Structures	Results	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF	E _{ff} (%)
S_{int}	Eksperimen (Prayogi, et al, 2021)	720.0	15.70	0.550	5.61
	AFORS-HET	721.1	15.69	0.561	5.72
D_{int}	Eksperimen (Prayogi, et al, 2021)	790.0	17.20	0.620	8.86
	AFORS-HET	791.0	17.22	0.634	8.90

Luaran Paper Sel Surya Berbasis a-Si:H

No.	Tahun	Judul artikel ilmiah	Volume/Nomor	Nama Jurnal
1.	2020	Band Gap Optimization of Thin Film a-Si:H Bifacial Solar Cells (BFSCs) Using AFORS-HET	Vol. 966, Hal 409-414	<u>Materials Science Forum (MSF)</u>
2.	2021	The effect of adding an active layer to the structure of a-Si:H solar cells on the efficiency using RF-PECVD	Vol. 32, Hal 7609-7618	<u>Journal of Materials Science: Materials in Electronics</u>
3.	2021	Performances analysis of heterojunction solar cells through integration of hydrogenated nanocrystalline silicon bilayer by using numerical study	Vol. 725 Hal 91-110	<u>Molecular Crystals and Liquid Crystals</u>
4.	2022	Effect of active layer thickness on the performance of amorphous hydrogenated silicon solar cells	Vol. 49 Hal 201-208	<u>Engineering and Applied Science Research</u>
5.	2022	The Effects of Dopant Concentration on the Performances of the a-SiO _x :H(p)/a-Si:H(i ₁)/a-Si:H(i ₂)/μc-Si:H(n) Heterojunction Solar Cell	Vol. 11 Hal 173-181	<u>International Journal of Renewable Energy Development</u>
6.	2022	Pengaruh Rapat Cacat Dangling-Bond Lapisan (p)a-Si:H Pada Kinerja Sel Surya Struktur p-i-n	Vol. 06 Hal 1-13	<u>Jurnal Ilmu dan Inovasi Fisika</u>
7.	2022	The influences of the front work function and intrinsic bilayer (i ₁ , i ₂) on p-i-n based amorphous silicon solar cell's performances: A numerical study	Accepted, 31 Juli 2022	<u>Cogent Engineering, Taylor & Francis</u>
8.	2022	Analysis increase in the efficiency of a-Si:H solar cell due to the addition of an intrinsic layer to the p-i ₁ -i ₂ -n structure by ellipsometry spectroscopy.	Accepted, 25 Juli 2022	<u>Optical and Quantum Electronics</u> Springer

Sekian dan Terimakasih