Lecture 7

Thin Film PV

The Reading assignment for this lecture is:

Armin G. Aberle, “Thin-Film solar cells”, Thin Solid Films, 517 (2009), pp4706-4710

Lawrence Kasmerski, J. Electron Spectroscopy And Related Phenomena, V. 150 (2006), pp. 105-135

Several images are from these references

Thin Film Amorphous Si (a-Si:H) Solar Cells

Hydrogenated Amorphous Silicon is a dominate low-cost PV technology more known for its low cost than performance.

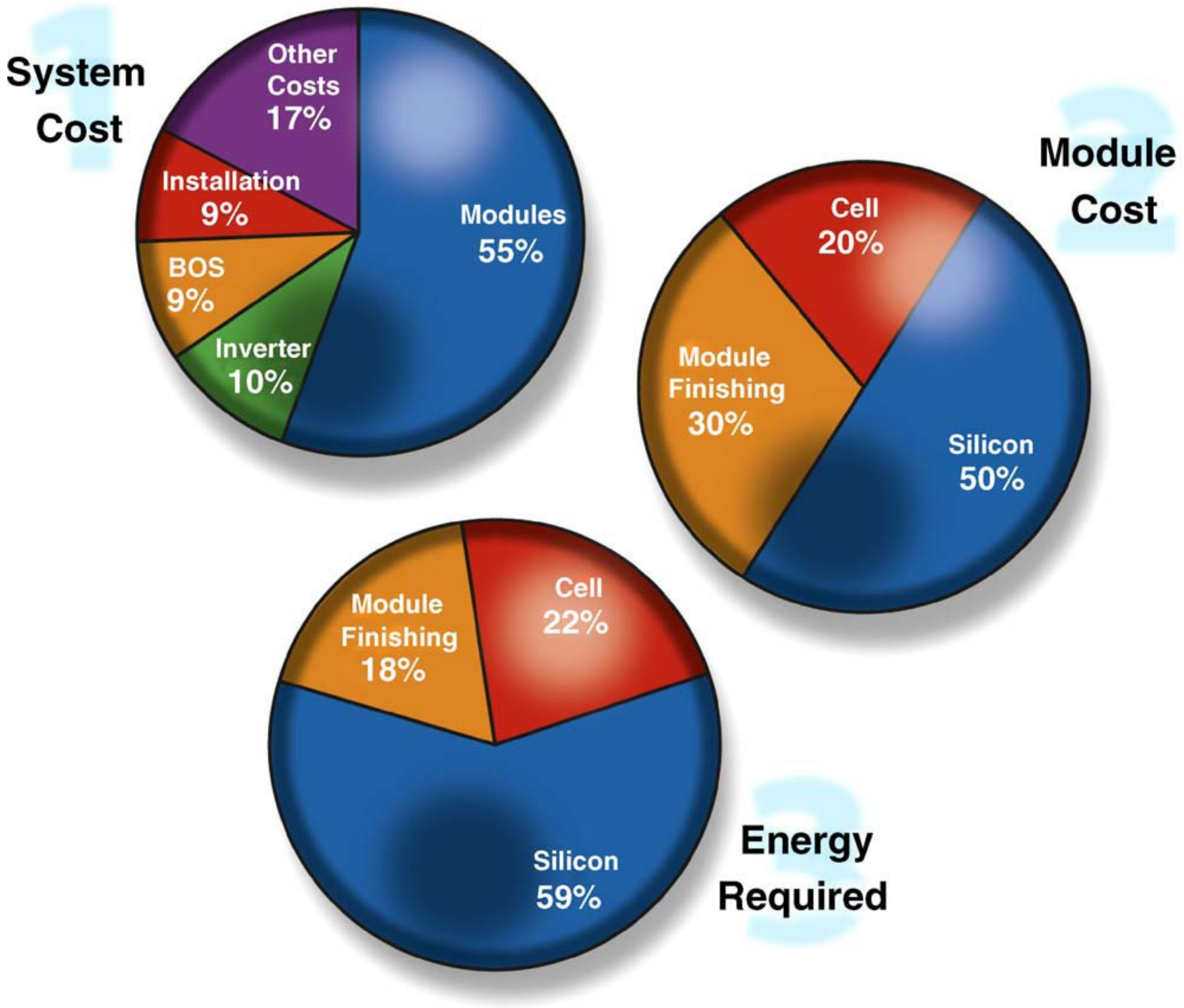
Advantages:

- Deposition is typically on inexpensive glass at low temperature (<200 degrees C)
- Relatively high absorption results in the need for very little material (<300nm)
- Small area efficiencies as high as 9.5% have been reported
- Module interconnects can be integrated making module costs very low.

Disadvantages:

- Low (stable) efficiencies (<6%) limit use to primarily cheap consumer electronics
- Staebler-Wronski effect (light induced degradation of the material) is a primary efficiency limitation
- Requires a transparent conductive oxide layer (hurts transmission and series resistance)

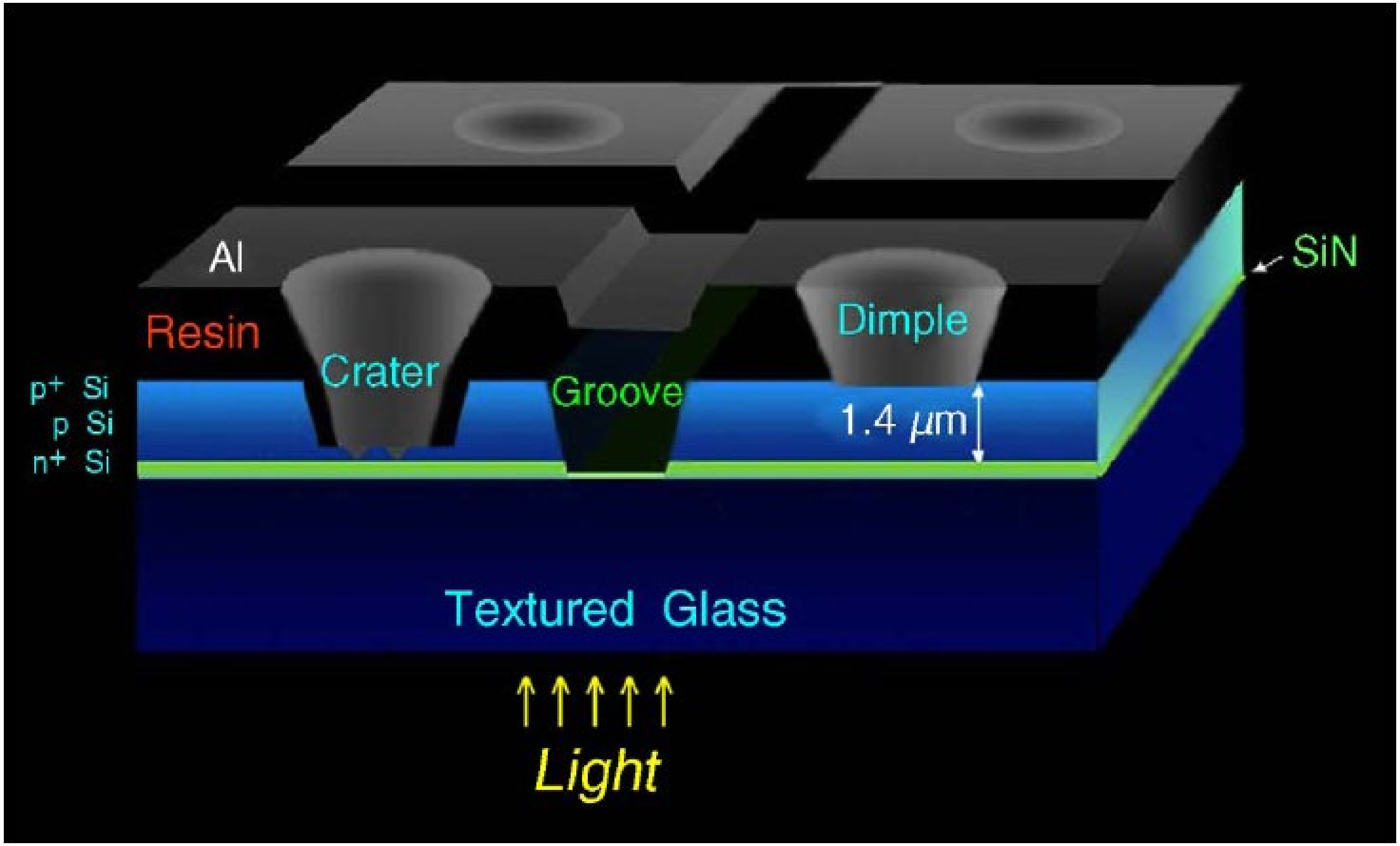
Why "Thin" Silicon



From Kasmerski – 2005: Significant amounts of energy and costs go into making the silicon in a solar cell. If one can lower these costs, solar power can be made significantly cheaper. This does come at a performance penalty.

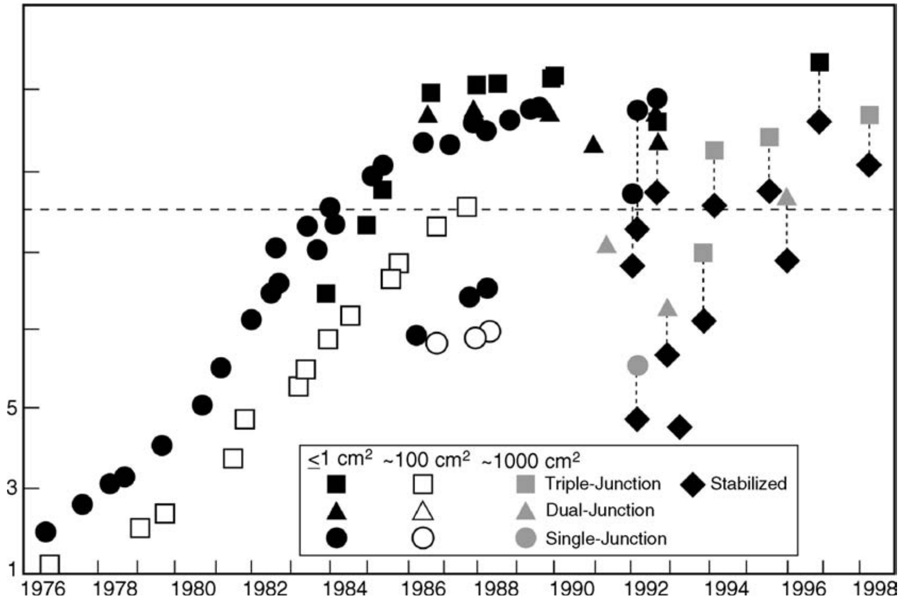
Why “Thin” Silicon:

Advantages in scale of Integrated Module Based Interconnect



From Kasmerski – 2005: Since the module can be made monolithically, enormous advantages in scalability exist compared to “piece together” assembled modules.

History of Thin Silicon

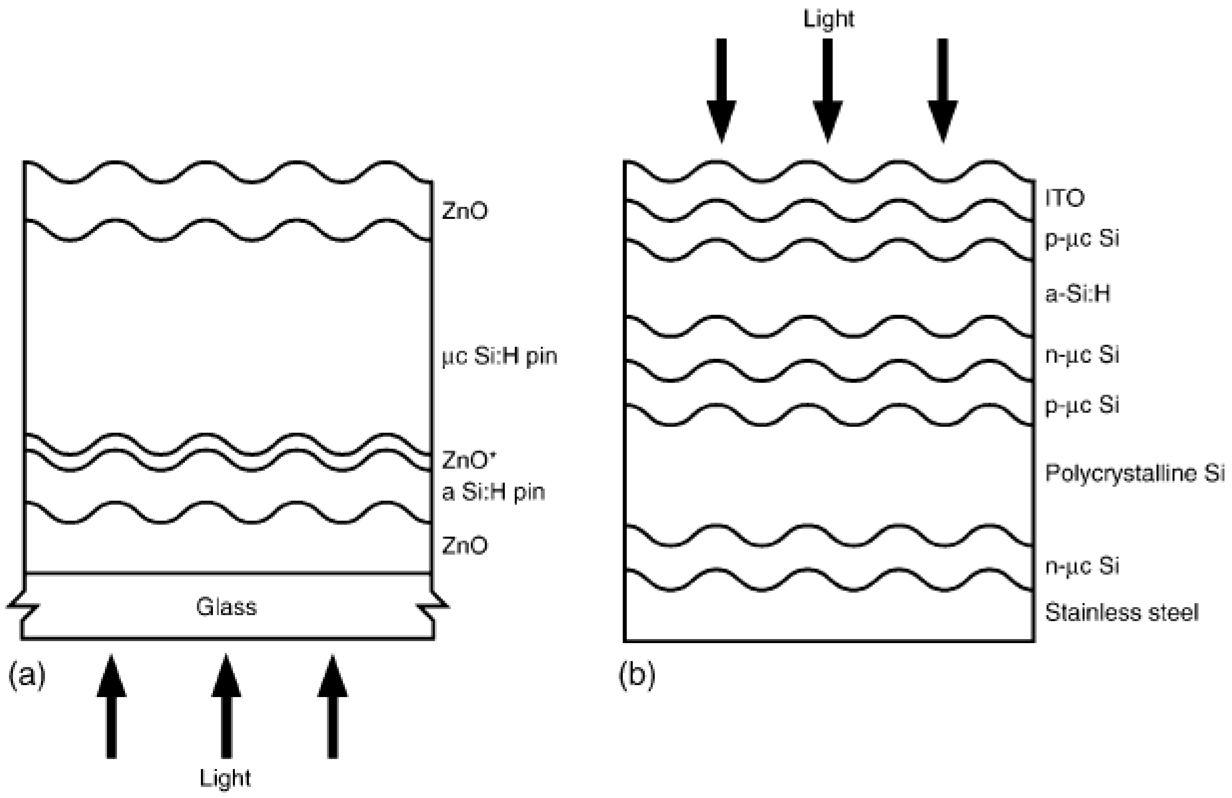


From Kasmerski – 2005: Combinations of a-Si:H and μC Si have shown significant improvement in recent years including modules that are above the magic 10% threshold.

Summary of confirmed, selected a-SiH based solar-cell efficiencies and related parameters, under standard measurement and reporting conditions [194]

V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Area (cm^2)	Efficiency (%)	Organization	Comments
Single-junction cells						
887	19.4	74.1	1.00	**12.7**	Sanyo	a-Si:H (not stabilized) (4/92)
897	18.8	70.1	1.08	**11.5**	Solarex	a-Si:H (not stabilized) (4/87)
886	17.46	70.4	0.99	**10.9**	Glasstech	a-Si:H (not stabilized) (9/89)
Dual-junction cells						
1621	11.72	65.8	0.28	**12.5**	USSC/Cannon	a-Si:H/a-SiGe:H/ss (not stabilized) (1/92)
1685	9.03	68.1	0.76	**10.3**	Solarex	a-Si:H/a-SiGe:H (not stabilized) (10/87)
Triple-junction cells						
2375	7.72	74.4	0.27	**13.5**	USSC	a-Si:H/a-Si:H/a-SiGe:H (not stabilized) (10/96)
2541	6.96	70	0.27	**12.4**	EDC	a-Si:H/a-Si:H/a-SiGe:H (not stabilized) (12/88)
2289	7.9	68.5	1.00	**12.4**	Sharp	a-Si:H/a-Si:H/a-SiGe:H (not stabilized) (10/96)
						SiGe:H (not stabilized) 12/92)

History of Thin Silicon

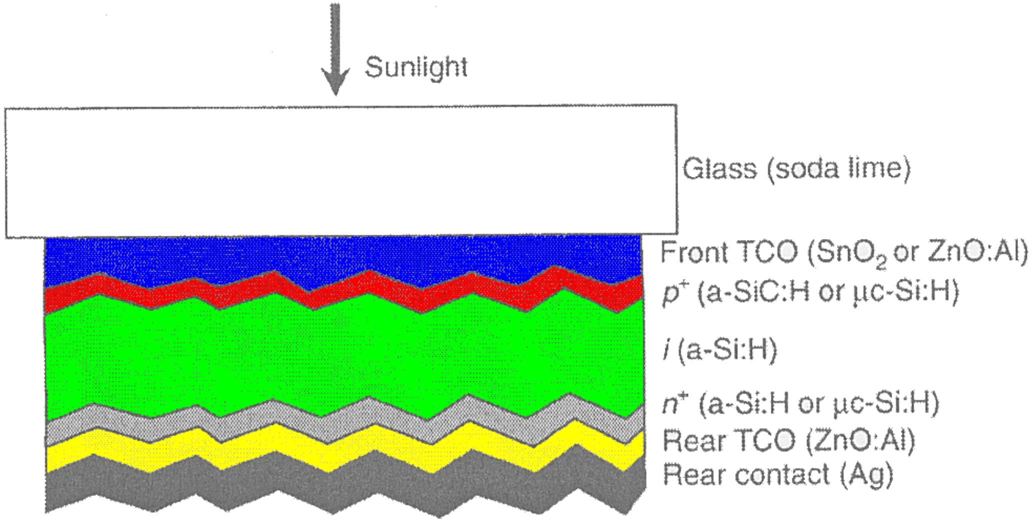


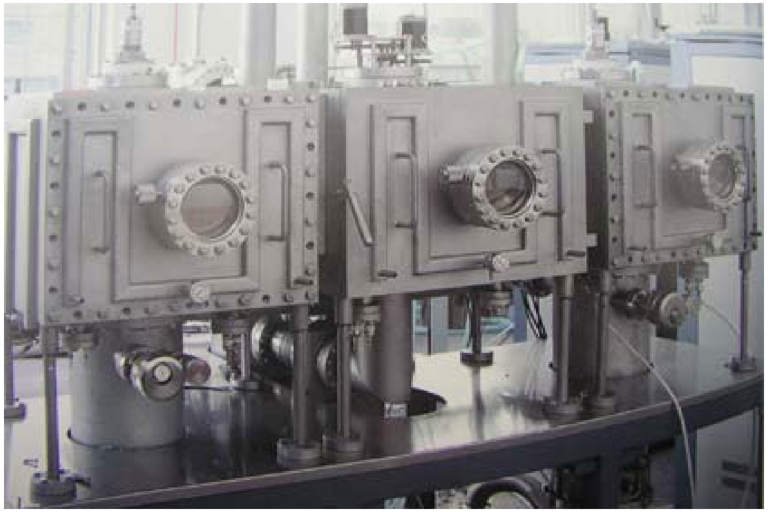
From Kasmerski – 2005:
Examples of Single junctions and double junction tandems. Most thin films require a transparent semiconductor layer most often implemented as Indium Tin Oxide (ITO) or Zinc Oxide (ZnO). As a semiconductor, these layers are not as conductive as metals and have some minor absorption losses and thus, hurt performance.

Thin Film Amorphous Si (a-Si:H) Solar Cells

Hydrogenated Amorphous Silicon is almost always produced by plasma deposition methods (PECVD – plasma enhanced chemical vapor deposition)

PECVD can also be used to deposit anti-reflection coatings that simultaneously hydrogenate other materials (c-Si).





Plasmas

Consider the thermal energy required to break apart the nitrogen molecule. The bond energy is 9.7 eV =3kT/2 ==> T~75,000 degrees C! This is not possible by thermal means, but is possible by hyper thermal processes like plasmas. A plasma is a gaseous collection of ions, electrons, energetically excited molecules, and neutral gas species, normally created by the application of electromagnetic fields.

Plasmas can be used to drive reactions that would otherwise be thermally prohibited.
Plasmas can be used to deposit, chemically etch or sputter materials

Many reactions can occur in a plasma. If e* is an excited electron in a plasma:

Dissociation:	$e^* + AB \leftrightarrow A + B + e$
Atomic Ionization:	$e^* + A \leftrightarrow A^+ + 2e$
Molecular Ionization:	$e^* + AB \leftrightarrow AB^+ + 2e$
Atomic Excitation:	$e^* + A \leftrightarrow A^* + e$
Molecular Excitation:	$e^* + AB \leftrightarrow AB^* + e$

Most modern plasmas are generated by either a DC current flowing through the gas or a radio frequency (RF) field exposed to the gas(RF plasmas do not require DC current flow, and thus, can be used to process insulating and conducting materials)

Types of Plasma Systems

Parallel Plate Systems

Advantages: Cheaper

Disadvantages: Lower plasma density, difficult to keep clean in production due to particulates flaking off the upper plate.

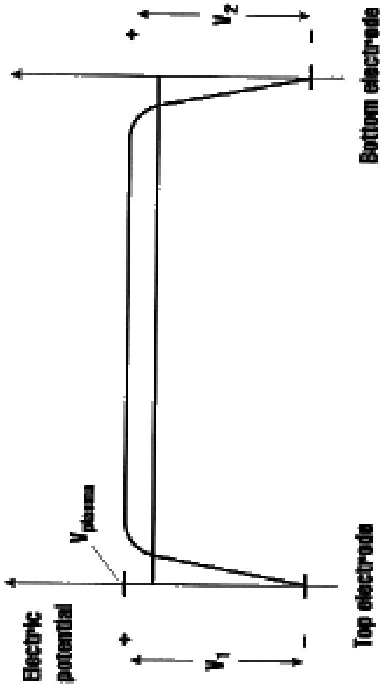
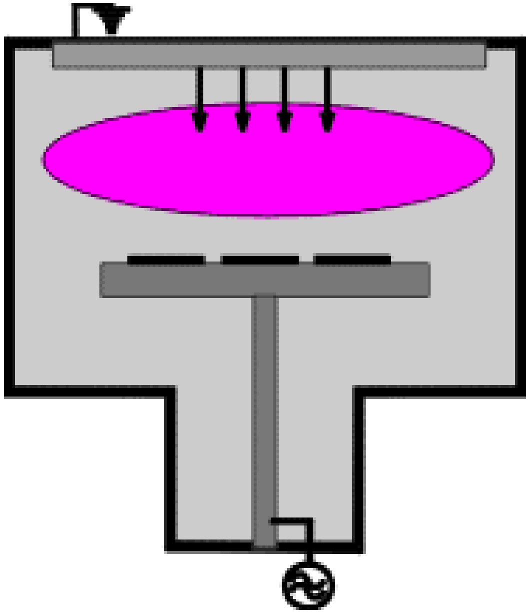


Figure 10-18 Typical plot of dc voltage as a function of position in an RF plasma.

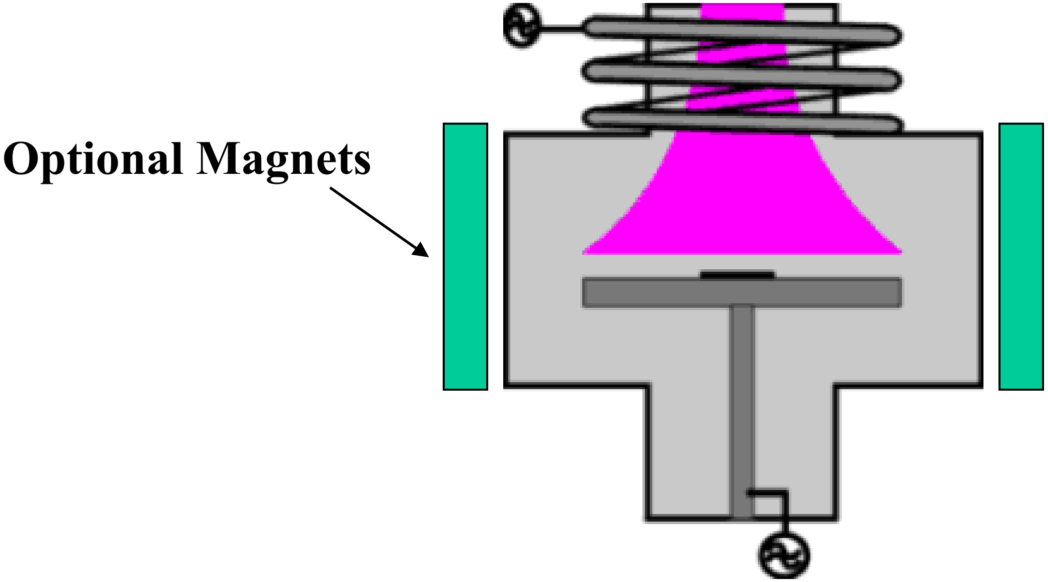


Every half cycle, the electric field accelerates electrons into the plates causing them to become negatively charged. The atoms/molecules can not respond fast enough to the E-field to gain a net momentum. However, the induced negative charge on the plates causes an electric field to be created that drifts ions out of the “glow discharge region” toward the plates. By having plates with different capacitances (area changes or external capacitors) the voltage on the top plate can be made to be different from the bottom plate resulting in a net movement of ions. Note all uncharged species simply diffuse away from the glow discharge region where they are created.

Types of Plasma Systems

Inductively Coupled Systems

Advantages: Higher plasma density (~10-50 x), easier to clean (low particulate), better uniformity over large areas.
Disadvantages: Nearly 3 time the cost of a comparable parallel plate system.



Electromagnetic fields are induced into the gas by one or more coils located on the periphery of the vacuum chamber. Magnets may be used to enhance confinement of the plasma and control recombination (ions and electrons annihilating each other) at the chamber walls.

Other Details of Plasma Systems

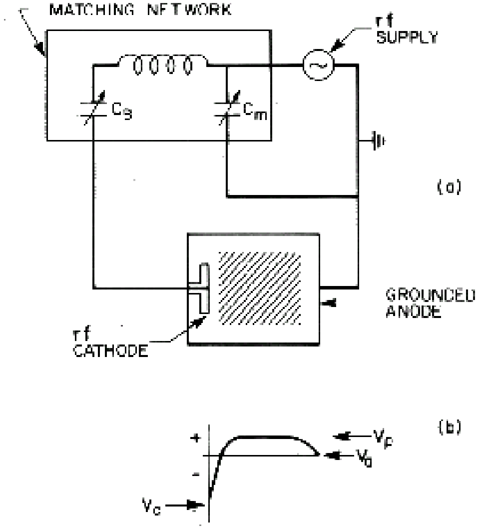


FIGURE 2
(a) A schematic representation of an rf plasma discharge where the power is supplied to the rf cathode through a matching network. (b) A plot of the average potential between the anode (V_a), the cathode (V_c), and the plasma (V_p). The horizontal position axis is meant to coincide with (a).

- The glow region contains many electrons, and thus is highly conducting.==> Resistor Model element
- The Sheaths have had their electrons stripped via the induced electric field. Thus, only limited ionic conduction occurs, along with a "depletion region capacitance" (this region is depleted of electrons).
- The above lumped model results.
- Note the frequency dependence of the plasma impedance.

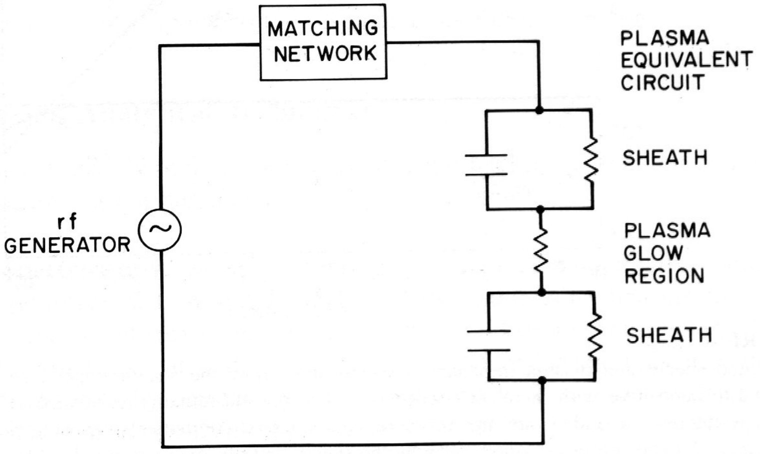


FIGURE 3
An equivalent circuit for an rf plasma discharge.

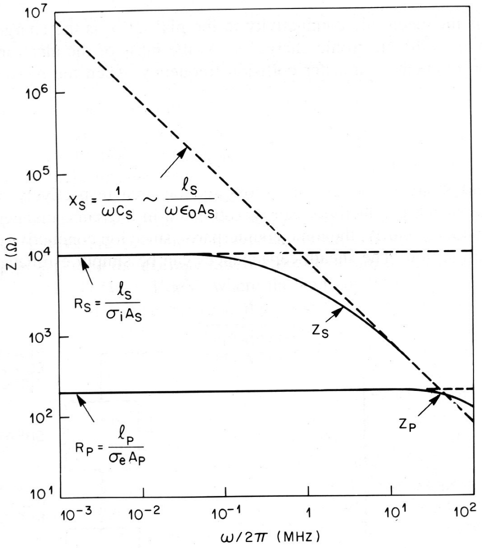


FIGURE 4
Calculated sheath and plasma impedances which show how the sheath impedance changes from resistive to capacitive with increasing frequency. The plasma remains resistive over the frequency range of interest. R and X are the resistive and reactive components respectively of the total impedance, Z. The subscripts s and p denote the sheath and plasma respectively. (*After Dautremont-Smith, Gottscho, and Schutz, Ref. 6.*)

Other Details of Plasma Systems

Note also that at low frequencies, the ions are accelerated to higher energies (longer times) before the field reverses, resulting in higher energy ions bombarding the surface.

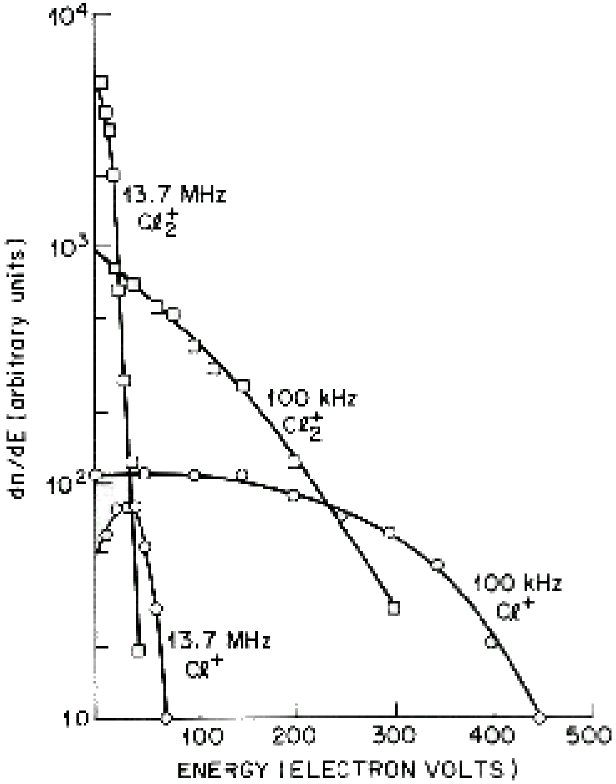
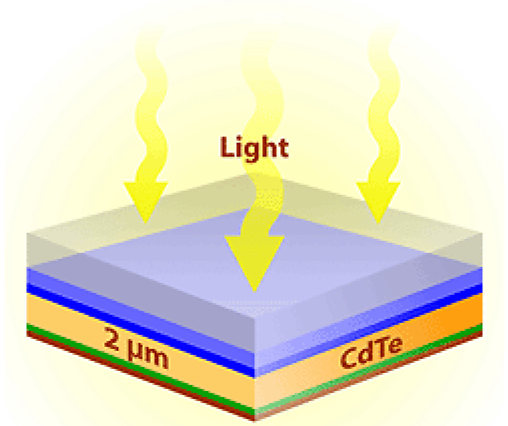


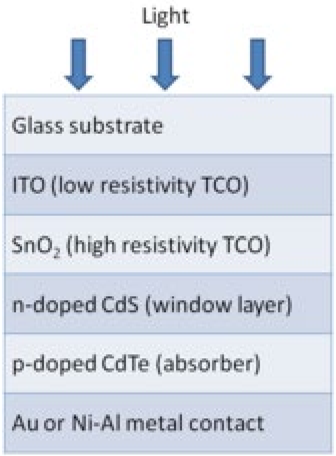
FIGURE 5

Ion bombardment energy distribution in a 40 Pa Cl_2 plasma with 0.6 W/cm^2 and a 1.0 cm electrode spacing. (*After Bruce, Ref. 8.*)

Thin Film II-VI Solar Cells



A thin layer of CdTe can absorb more than 90% of visible light



Glass substrate

ITO (low resistivity TCO)

SnO_2 (high resistivity TCO)

n-doped CdS (window layer)

p-doped CdTe (absorber)

Au or Ni-Al metal contact

- Concerns over Cadmium contamination.
  - Real but perhaps over blown.
  - Module recycling programs exist.

Sources and Relative Contributions of Cadmium Exposure to Humans (in Europe)

Phosphate fertilizers	41.3 %
Fossil fuel combustion	22.0 %
Iron and steel production	16.7 %
Natural sources	8.0 %
Non-ferrous metals	6.3 %
Cement production	2.5 %
Cadmium products	**2.5 %**
Incineration	1.0 %

Thin Film II-VI Solar Cells

Many cheap methods of production:

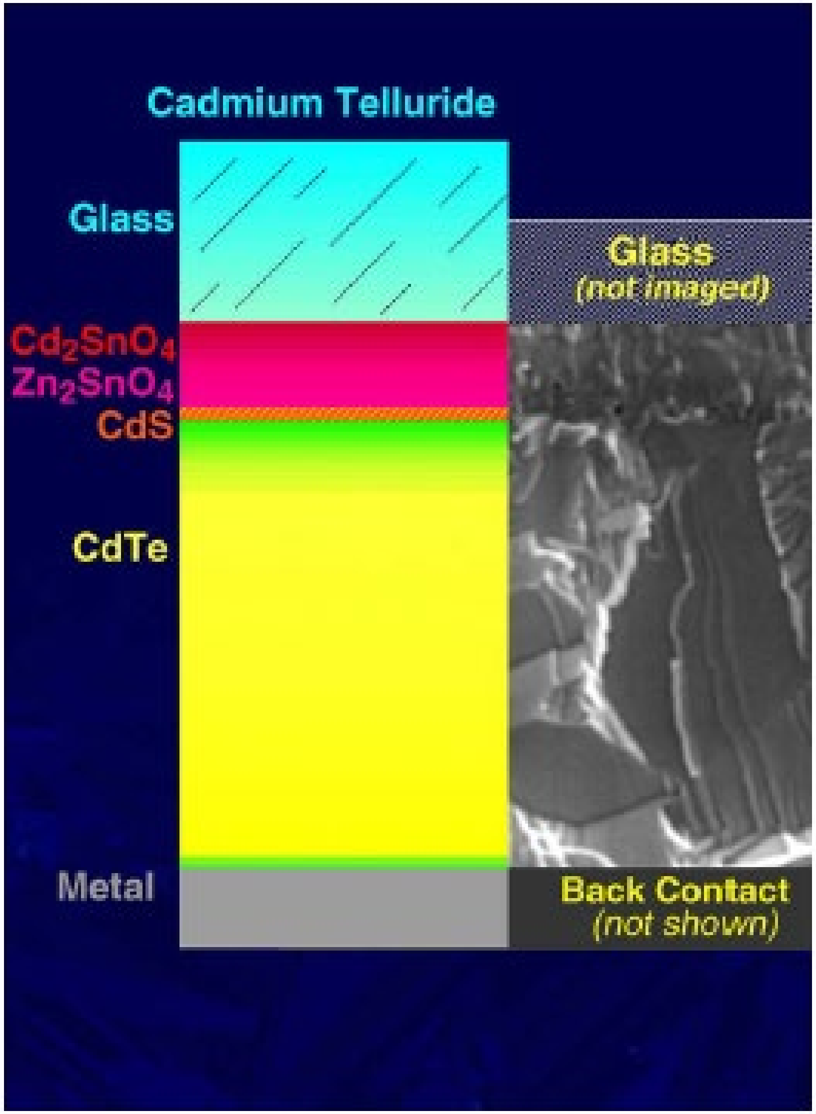
- Physical deposition:
- Sputtering, evaporation
- Spray pyrolysis
- Screen printing
- Electro deposition

$CdCl_2$: Methanol anneal treatment lowers surface energy between grains, promoting the fusing of grains together promoting grain growth.

Uses p- I- n structure.

Cell efficiencies ~ 16.5%
Modules ~11%

Thin Film II-VI Solar Cells



- Many variations exist.
- Many companies have come and gone.

- First Solar with significant investment from the "Walmart" owners is currently the largest PV company in the world and is arguably the cheapest PV source in the world (claims of less than $1/watt).

Thin Film $CuInX_2$ Solar Cells (X=S, Se, Te)

(Chalcopyrites)

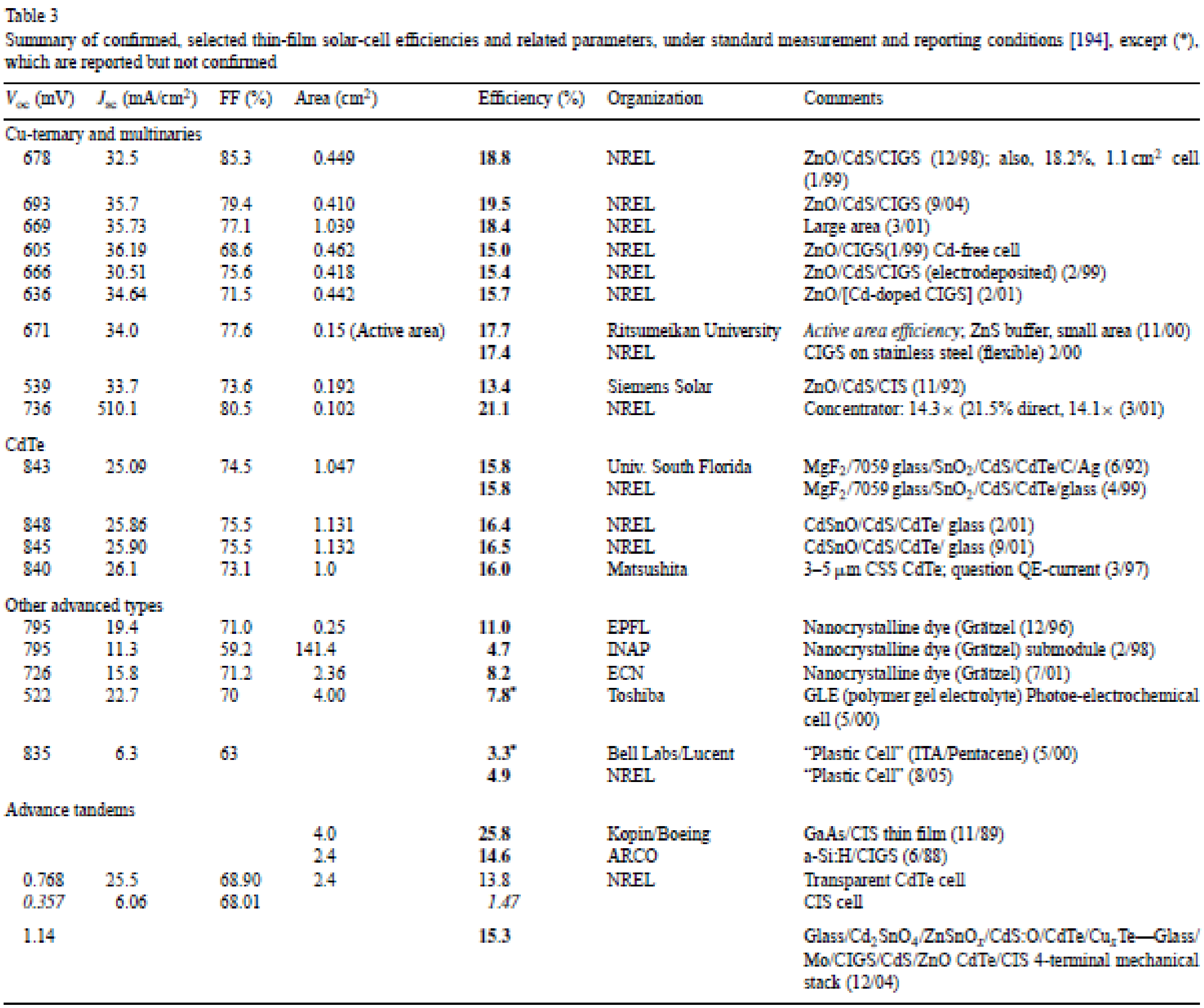


Table 3

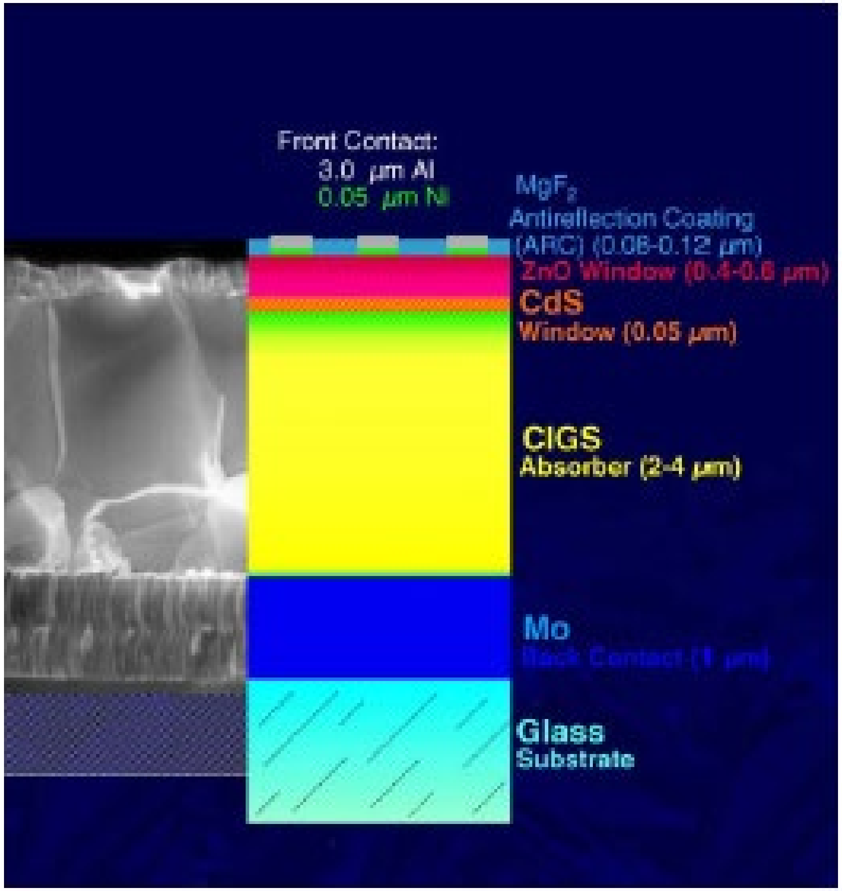
Summary of confirmed, selected thin-film solar-cell efficiencies and related parameters, under standard measurement and reporting conditions [194], except (*), which are reported but not confirmed

V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Area (cm^2)	Efficiency (%)	Organization	Comments
Cu-ternary and multinaries						
678	32.5	85.3	0.449	**18.8**	NREL	ZnO/CdS/CIGS (12/98); also, 18.2%, 1.1 cm^2 cell (1/99)
693	35.7	79.4	0.410	**19.5**	NREL	ZnO/CdS/CIGS (9/04)
669	35.73	77.1	1.039	**18.4**	NREL	Large area (3/01)
605	36.19	68.6	0.462	**15.0**	NREL	ZnO/CIGS(1/99) Cd-free cell
666	30.51	75.6	0.418	**15.4**	NREL	ZnO/CdS/CIGS (electrodeposited) (2/99)
636	34.64	71.5	0.442	**15.7**	NREL	ZnO/[Cd-doped CIGS] (2/01)
671	34.0	77.6	0.15 (Active area)	**17.7**	Ritsumeikan University	*Active area efficiency*; ZnS buffer, small area (11/00)
				17.4	NREL	CIGS on stainless steel (flexible) 2/00
539	33.7	73.6	0.192	**13.4**	Siemens Solar	ZnO/CdS/CIS (11/92)
736	510.1	80.5	0.102	**21.1**	NREL	Concentrator: 14.3× (21.5% direct, 14.1× (3/01)
CdTe						
843	25.09	74.5	1.047	**15.8**	Univ. South Florida	MgF_2/7059 glass/SnO_2/CdS/CdTe/C/Ag (6/92)
				15.8	NREL	MgF_2/7059 glass/SnO_2/CdS/CdTe/glass (4/99)
848	25.86	75.5	1.131	**16.4**	NREL	CdSnO/CdS/CdTe/ glass (2/01)
845	25.90	75.5	1.132	**16.5**	NREL	CdSnO/CdS/CdTe/ glass (9/01)
840	26.1	73.1	1.0	**16.0**	Matsushita	3–5 μm CSS CdTe; question QE-current (3/97)
Other advanced types						
795	19.4	71.0	0.25	**11.0**	EPFL	Nanocrystalline dye (Grätzel (12/96)
795	11.3	59.2	141.4	**4.7**	INAP	Nanocrystalline dye (Grätzel) submodule (2/98)
726	15.8	71.2	2.36	**8.2**	ECN	Nanocrystalline dye (Grätzel) (7/01)
522	22.7	70	4.00	**7.8***	Toshiba	GLE (polymer gel electrolyte) Photoe-electrochemical cell (5/00)
835	6.3	63		**3.3***	Bell Labs/Lucent	"Plastic Cell" (ITA/Pentacene) (5/00)
				4.9	NREL	"Plastic Cell" (8/05)
Advance tandems						
			4.0	**25.8**	Kopin/Boeing	GaAs/CIS thin film (11/89)
			2.4	**14.6**	ARCO	a-Si:H/CIGS (6/88)
0.768	25.5	68.90	2.4	13.8	NREL	Transparent CdTe cell
0.357	6.06	68.01		*1.47*		CIS cell
1.14				**15.3**		Glass/Cd_2SnO_4/$ZnSnO_x$/CdS:O/CdTe/Cu_xTe—Glass/Mo/CIGS/CdS/ZnO CdTe/CIS 4-terminal mechanical stack (12/04)

- Many variations exist.
- Many companies have come and gone.

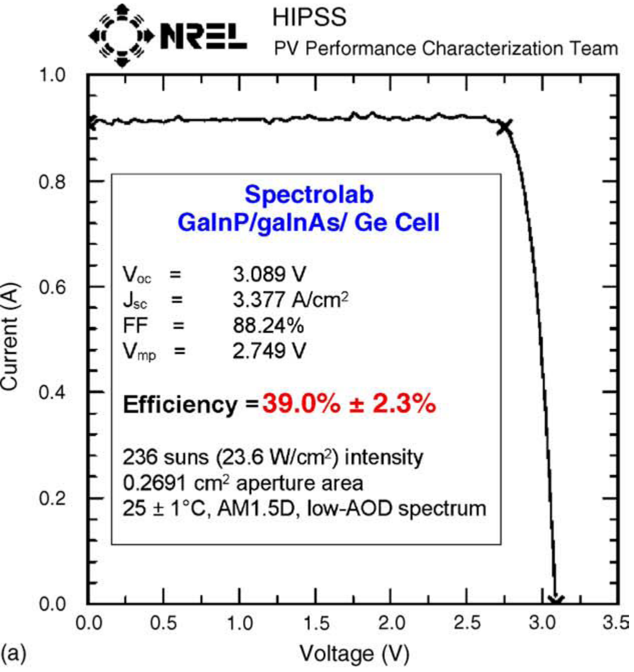
- Seems to be perpetually stuck in the "next great thing" phase of development

Thin Film CuInX$_2$ Solar Cells



- •Produced by elemental deposition (scaled up versions of MBE) . These have highest efficiencies.
- •Sputtering of metals then annealing in H$_2$Se or Se vapor
- •Chemical deposition
- •Electrochemically

Ultra-high Performance III-V Solar Cells

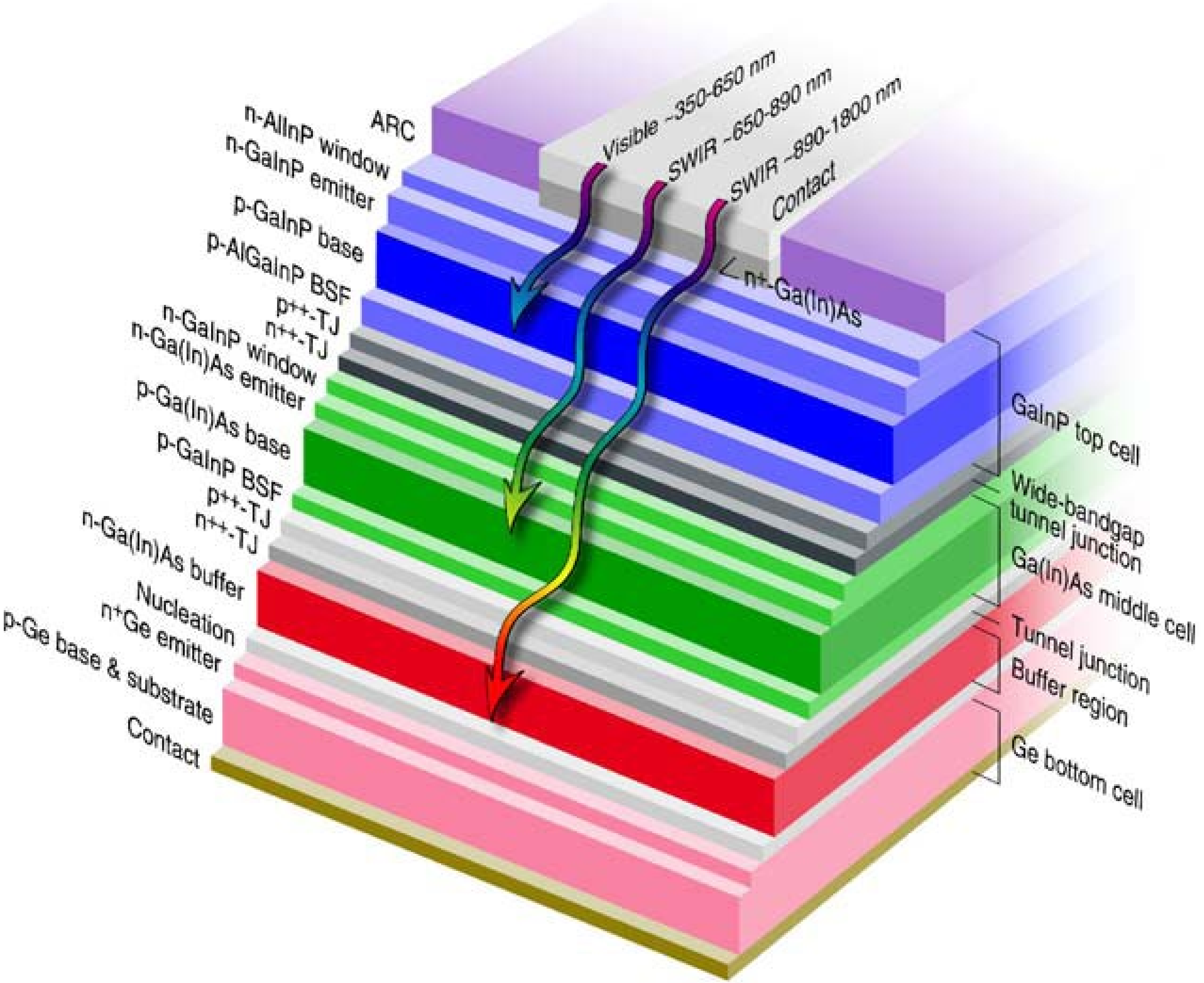


Spectrolab
GaInP/gaInAs/ Ge Cell

V_{oc} = 3.089 V
J_{sc} = 3.377 A/cm^2
FF = 88.24%
V_{mp} = 2.749 V

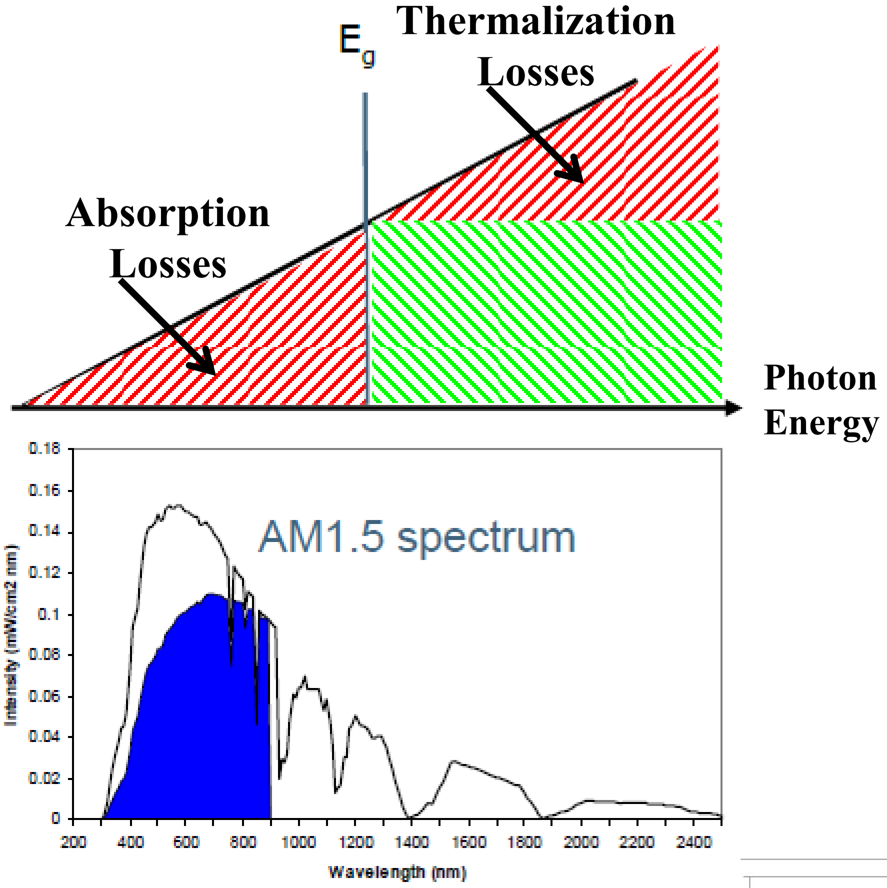
Efficiency = 39.0% ± 2.3%

236 suns (23.6 W/cm^2) intensity
0.2691 cm^2 aperture area
25 ± 1°C, AM1.5D, low-AOD spectrum



Why Use a Tandem Solar Cell?

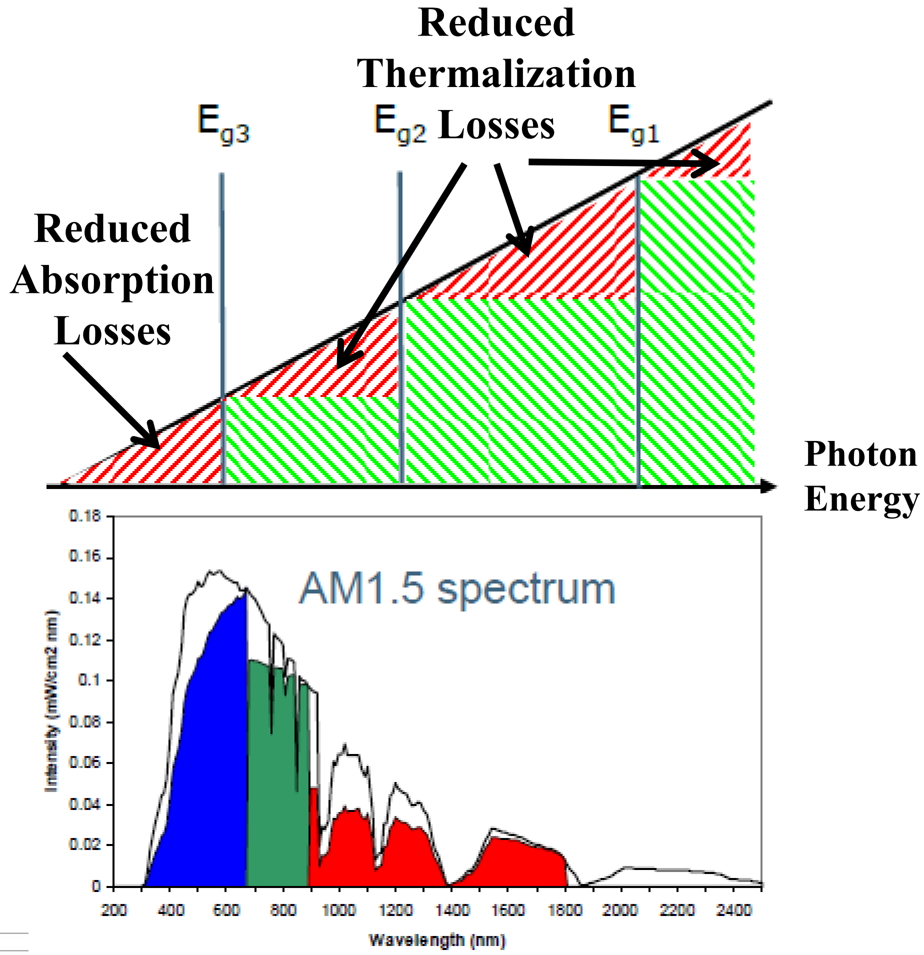
Single Junction



Thermalization Losses

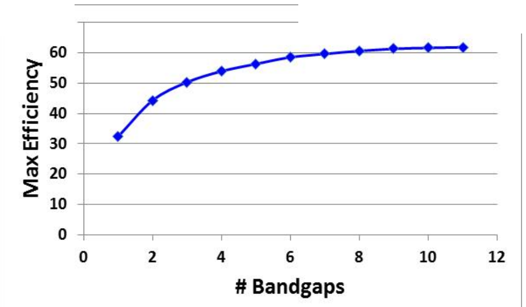
Absorption Losses

Multiple Junctions

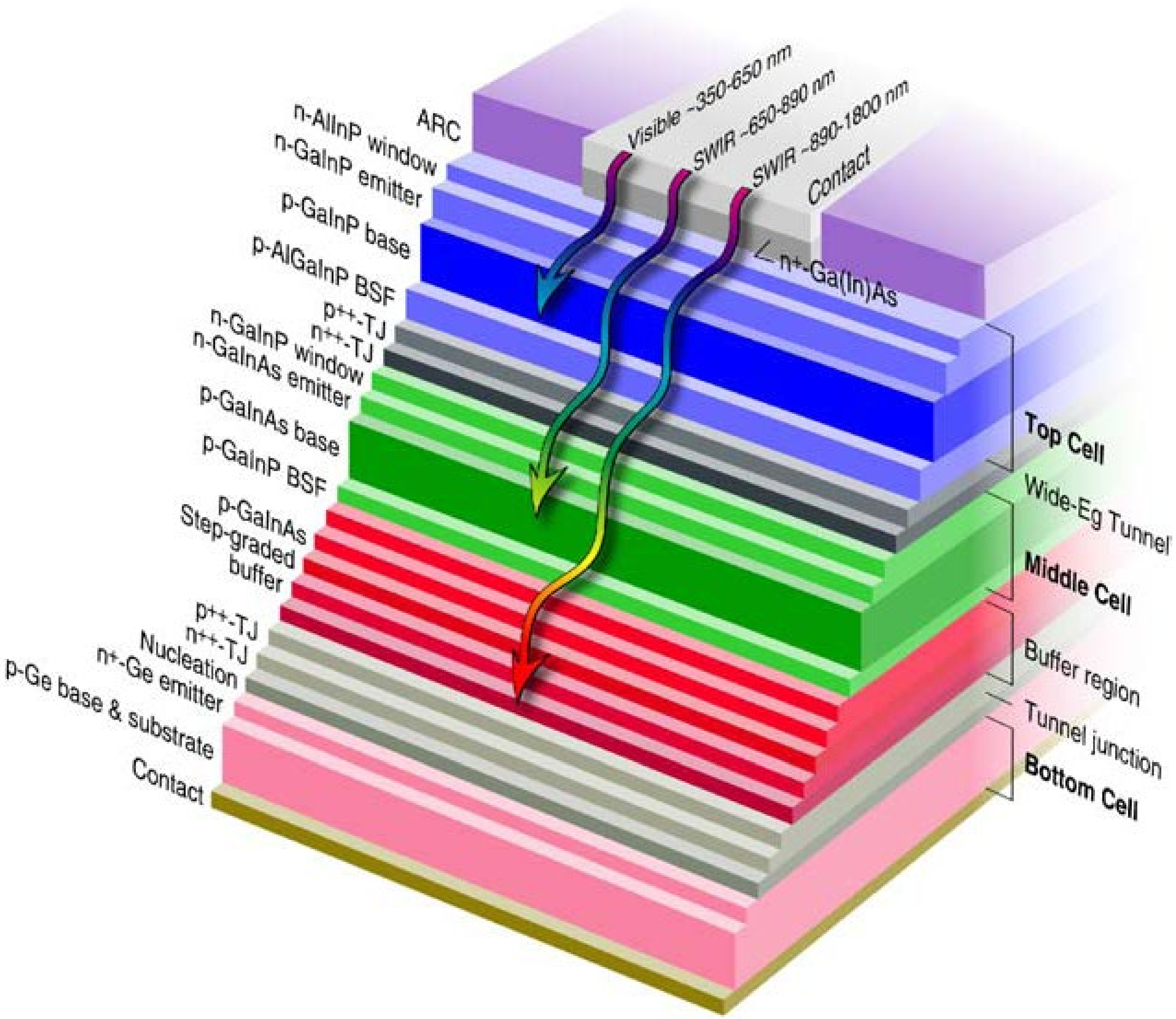


Reduced Thermalization Losses

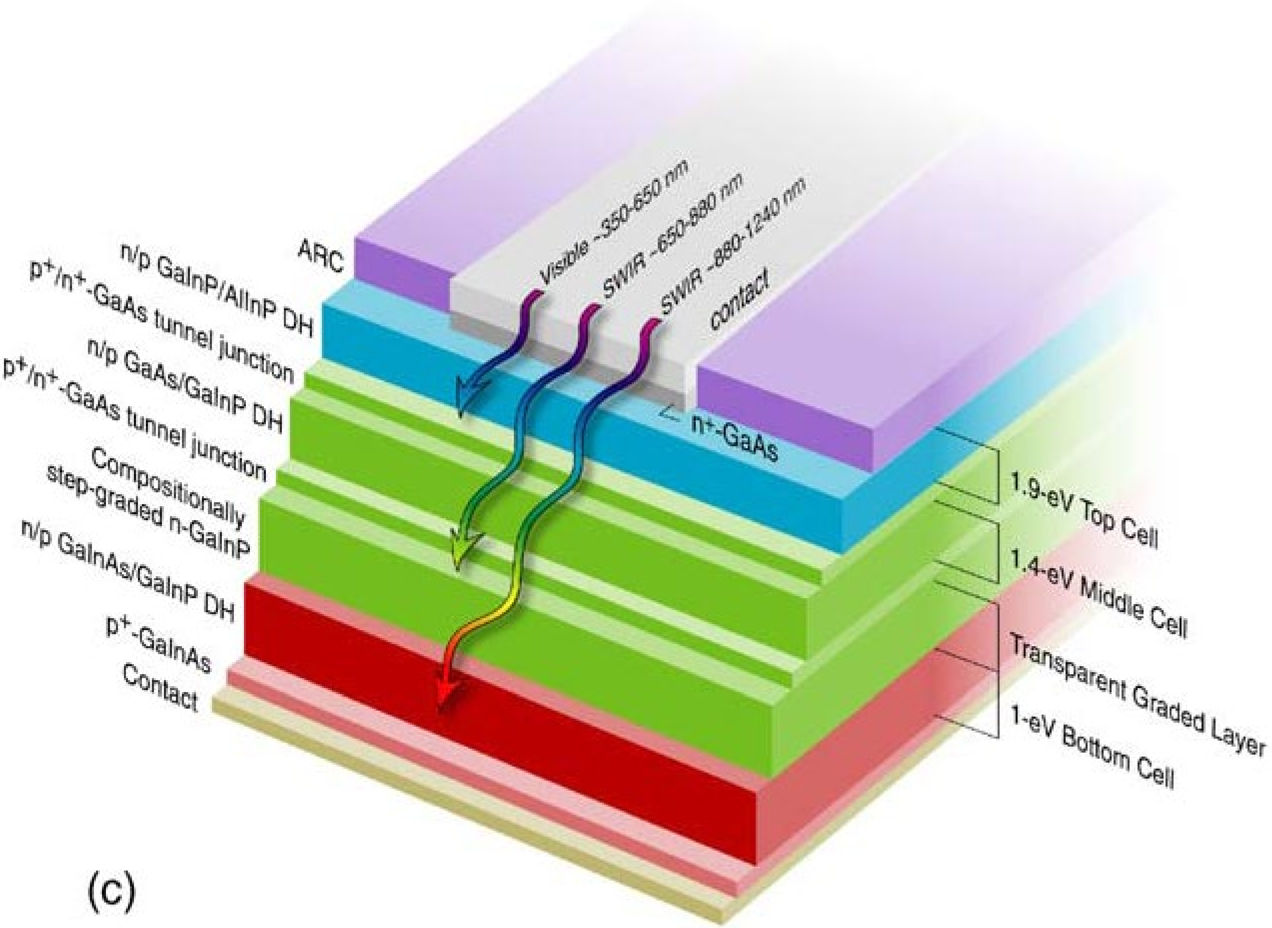
Reduced Absorption Losses



Ultra-high Performance III-V Solar Cells



Ultra-high Performance III-V Solar Cells



Ultra-high Performance III-V Solar Cells

See the additional III-V concentrator PV presentation from IMEC also on the lecture webpage. The topics and approaches currently being used are all covered in this lecture.

Watts=(Joule/second)➔(eV/second)
(eV/Second)/photon energy = #photons/sec = #ehps/sec
(#ehps/sec) x q =C/sec = Amps