Institute of Fundamental Studies (IFS), Kandy

Workshop on

Current Status and Future Trends in Thin Film Solar PV Technology

28-29 June 2012

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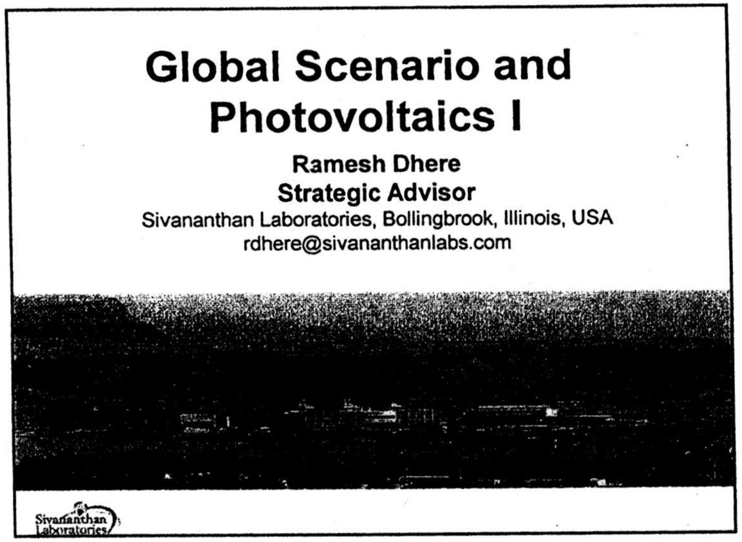
DA-1



Global Scenario and Photovoltaics I

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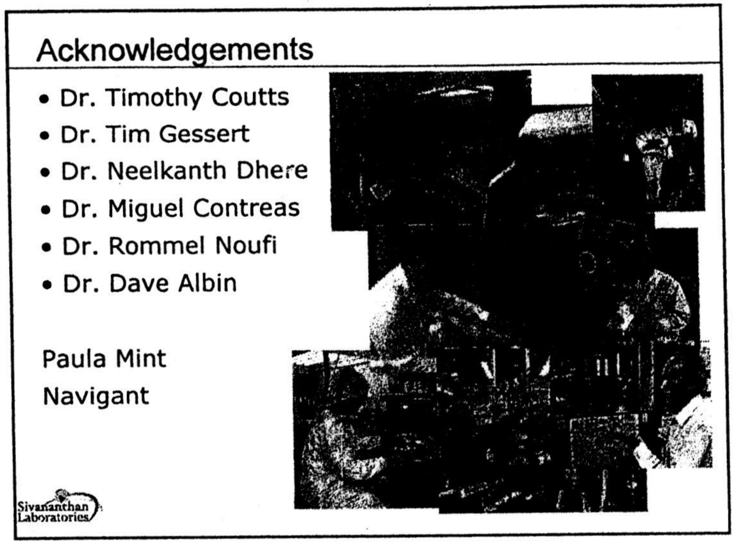

Acknowledgements

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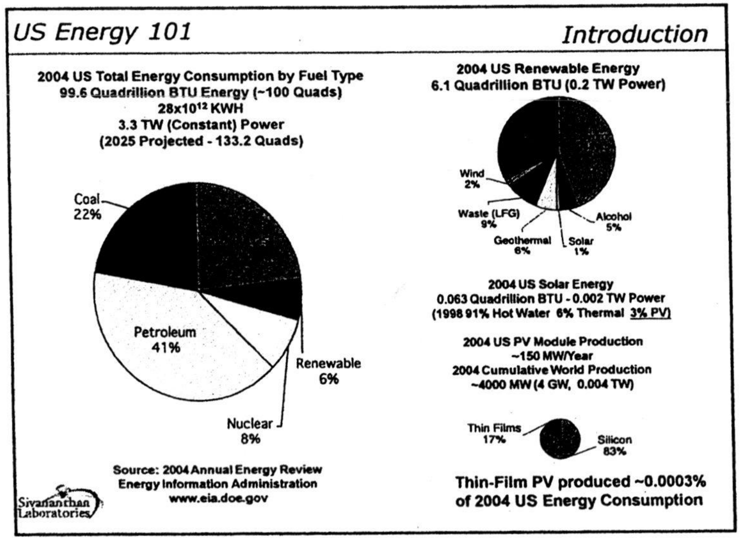
Navigant



US Energy 101 *Introduction*

2004 US Total Energy Consumption by Fuel Type
99.6 Quadrillion BTU Energy (~100 Quads)
28x10^{12} KWH
3.3 TW (Constant) Power
(2025 Projected - 133.2 Quads)

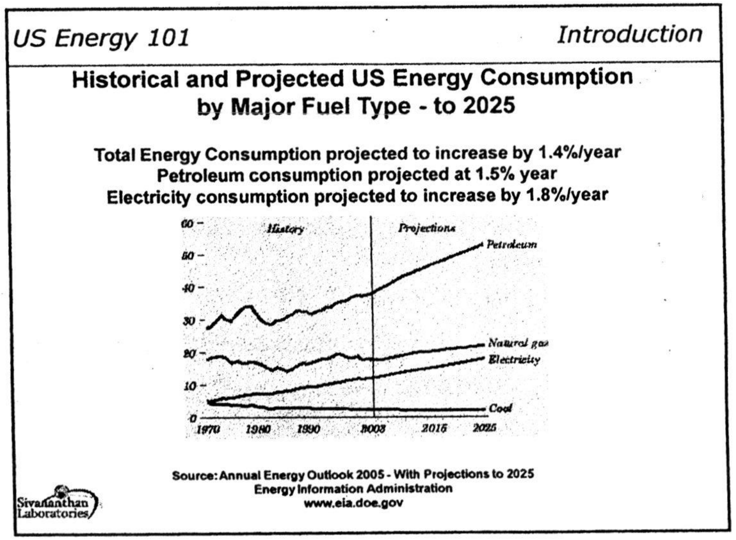
Source: 2004 Annual Energy Review
Energy Information Administration
www.eia.doe.gov

2004 US Renewable Energy
6.1 Quadrillion BTU (0.2 TW Power)

2004 US Solar Energy
0.063 Quadrillion BTU - 0.002 TW Power
(1998 91% Hot Water 6% Thermal 3% PV)

2004 US PV Module Production
~150 MW/Year
2004 Cumulative World Production
~4000 MW (4 GW, 0.004 TW)

Thin-Film PV produced ~0.0003% of 2004 US Energy Consumption



US Energy 101 *Introduction*

Historical and Projected US Energy Consumption by Major Fuel Type - to 2025

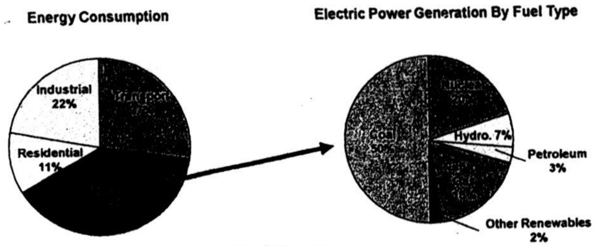
Total Energy Consumption projected to increase by 1.4%/year
Petroleum consumption projected at 1.5% year
Electricity consumption projected to increase by 1.8%/year

Source: Annual Energy Outlook 2005 - With Projections to 2025
Energy Information Administration
www.eia.doe.gov

US Energy Scene *Introduction*

US Energy Consumption by Sector (2004)

Electricity Sector is largest and coal generates most of electricity



The Dilemma:

The US needs to plan to double its electricity consumption in ~35 years (~1.8% growth)

- while acknowledging issues associated with burning more coal, natural gas, and petroleum

- and acknowledging issues associated with building more dams and nuclear power plants

Source: Energy Information Administration
www.eia.doe.gov

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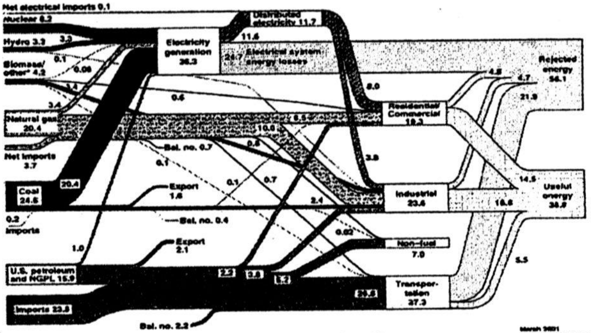
Basic Vocabulary *Introduction*

US Produced vs. End-Used Energy (Exajoules)

2/3-3/4 of US produced electricity is ultimately "Rejected"

BIPV application embodies very low rejection factor, so 10% is much higher



Source: Production and end-use data from Energy Information Administration, Annual Energy Review 1999
*Biomass/other includes wood and waste, geothermal, solar, and wind.

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Global Energy Scenario

Natural Gas -23%, Coal – 25%, Oil – 37%

Nuclear – 6%, Hydro – 3%, Renewable – 5%

Projected Energy Consumption Growth by 2050:

India – 31%, China – 146%, Middle East – 170%

Energy Consumption Distribution:

China – 20%, BRIC – 50%, US – 19%, ROW- 31%.

Energy Demand expected to double by 2050

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Environmental Impact

Percentage of CO_2 in ambient has increased rapidly in past 100 years.

To stabilize level we need to replace carbon based sources. Require 13000 GW of reneable energy production by 2050 i.e. 1GW/day.

Present PV production – 30 GW/year.

Big challenge and tremendous opportunity for growth:

$ 26 to 50 Trillion Dollar Market

Requires mix of technologies – PV, CSP, Wind

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Issues to consider for Energy Planning

- Energy Independence
- Environmental Considerations
- Renewable Energy Sources – Sustainibility
- Use of local resources – Appropriate technology
- Economic Development

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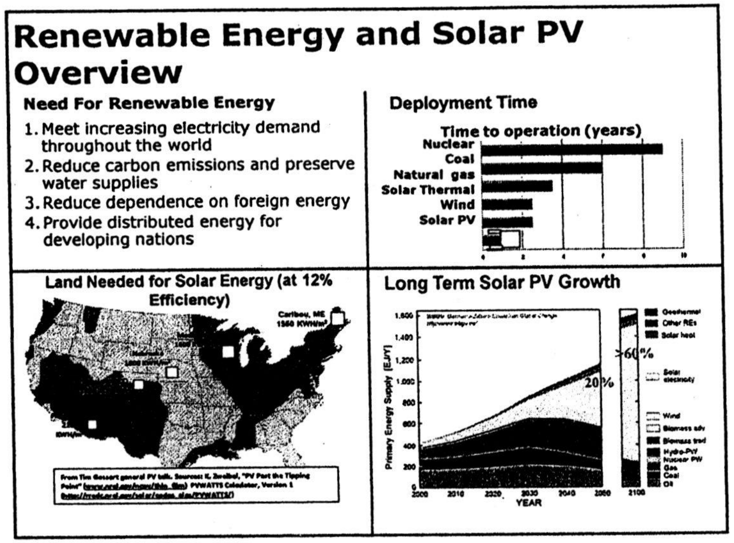

Renewable Energy and Solar PV Overview

Need For Renewable Energy

1. Meet increasing electricity demand throughout the world
2. Reduce carbon emissions and preserve water supplies
3. Reduce dependence on foreign energy
4. Provide distributed energy for developing nations

Deployment Time

Land Needed for Solar Energy (at 12% Efficiency)

From Tim Gessert general PV talk. Sources: K. Zweibel, "PV Part the Tipping Point" ([illegible]) PVWATTS Calculator, Version 1 ([illegible])

Long Term Solar PV Growth

Srilankan Context

Present Energy Mix:

- 2009 Statistics : Almost Equal use Hydropower and Thermal Power Stations for Electricity Generation.
- Great Progress in the development of Hydropower generation in last 50 years. Most of the resources already tapped.
- Future Energy Production Planning: Continue the same course (fossil fuels, coal) or consider renewable sources.

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Sustainibility

Energy Efficiency

Minimizing Waste-

- Use of CFCs already reducing energy for lighting
- With introduction of LED further reduction.
- Not only reduces consumption, minimizes heat from wasted energy, reduces A/C cost
- Architectural design to suit climate, use of smart windows, low E TCO coated glass to minimize heat

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Renewable Energy Sources

- Biofuels – transportation needs. Use of waste organic products. E.g. ARTI in India developing simple solutions using kitchen waste.
- Wind Energy – Island nation, more options to tap for optimal use.
- Tropical Climate – Ideal for solar cells.
- Photovoltaics and Wind energy compliment each other.

Photovoltaics

Advantages

- Modularity – Systems can be designed at any size without paying excessive penalty.
- Deployment – Systems can be installed in months, less time than alternative choices
- Maintenance – No moving parts, minimal breakdowns.

Disadvantage –

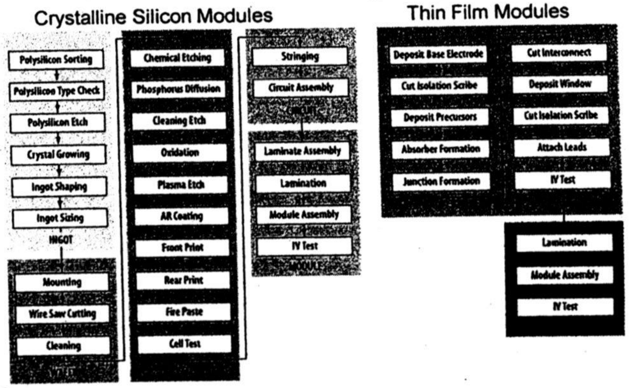
- Intermittent resource, need storage

Photovoltaics – Ideal for Srilanka

- Ideal for tropical climate
- Allows opportunity for use of highly literate population
- Reduce importation cost, energy independence and environmental benefits through reduction in greenhouse gases
- Use hydropower as storage – unique Srilankan advantage. Power on demand.
- PV and Wind complimentary sources
- Strategic Location – access to key markets

PV Technologies- Crystalline vs Thin Film

Module Manufacturing Sequence



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Silicon Based PV

- Most of Present PV manufacturing
- Energy intensive processing – Si production, purification, crystal growth.
- Rapid Reduction in cost in last 3 years through vertical integration
- China advantage:
  - ☐ Scaling (over 50% of world production)
  - ☐ Supply Chain Clustering
  - ☐ Large scale Government subsidies
  - ☐ Top 3 Chinese Companies project cost at \$ 0.6/W_p

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Thin Film PV

- Lowest Cost production
- Room for further cost reduction through either high rate processing for CIGS and higher performance for CdTe technology
- Simplified Processing Techniques
- Lower Energy Input
- Scope for vertical integration – module to systems for total installed cost reduction

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Srilanka PV Development

- Development of Workforce in all areas of PV
- Thin film module manufacturing – Trained workforce incentive to domestic or global manufacturers
- Coordinated effort to develop expertise from cell to system
- Use domestic market as training ground to build systems for different applications
- Cost reduction through vertical integration – Offer full solution from planning to turn-key systems
- Tap international markets – Demo functioning system under tropical conditions, Full service from building to servicing/maintaining the PV systems

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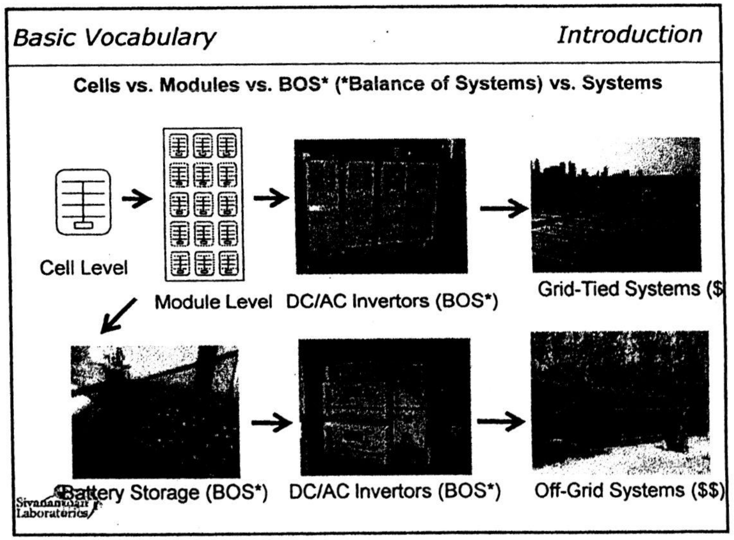

Basic Vocabulary *Introduction*

Cells vs. Modules vs. BOS* (*Balance of Systems) vs. Systems

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Substrate Device Structure

- Most commonly used. Used for CIGS, CZTS etc
- Allows freedom to chose substrates, enables flexible device architecture
- Junction formation is one of the last fabrication steps thus allows optimization of device performance
- Allows efficient use of anti-reflection coatings to minimize losses

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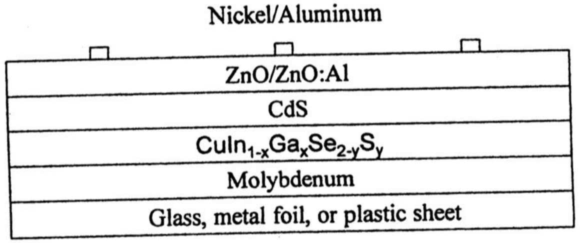

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Superstrate structure

Simplifies manufacturing- Glass/TCO can be sourced from vendors. Reduces capital cost .

Optical stack with right order of refractive indices minimizes reflectance losses. No need for AR coating.

Allows the freedom to fabricate the ohmic contact to CdTe, which is most difficult fabrication step.

Integrated module- minimizes production cost.

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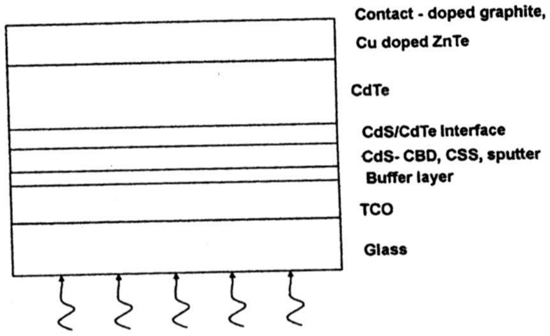

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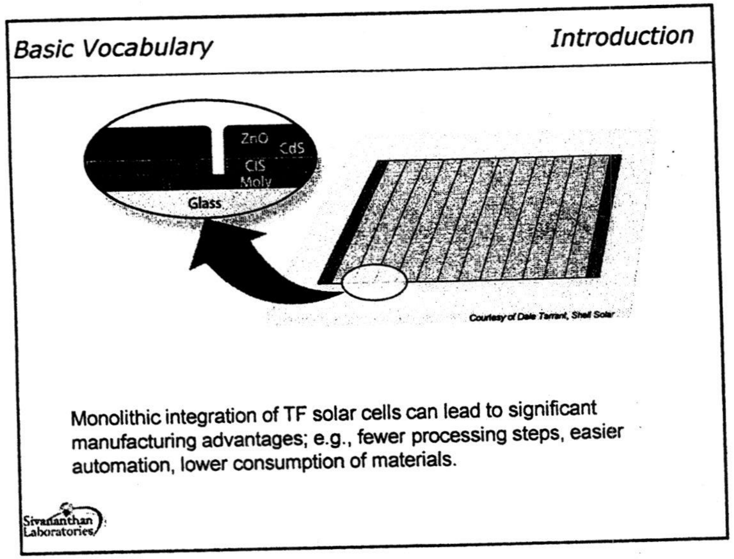

Basic Vocabulary *Introduction*

Courtesy of Dale Tarrant, Shell Solar

Monolithic integration of TF solar cells can lead to significant manufacturing advantages; e.g., fewer processing steps, easier automation, lower consumption of materials.

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Basic Vocabulary *Introduction*

Making Sense of PV Technology
(What's all this about anyway?)

Cells vs. Modules vs. BOS vs. Systems?

Thin Film PV vs. Crystalline PV?

Rigid PV vs. Flexible PV?

Supply-Chain Materials?

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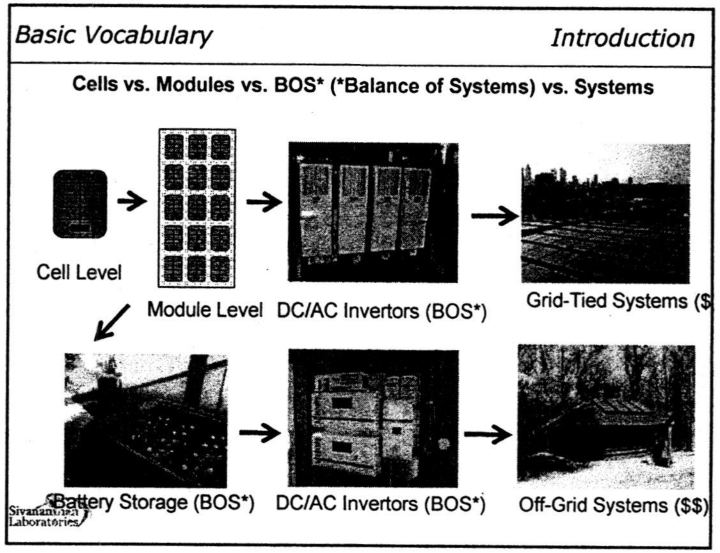

Basic Vocabulary *Introduction*

Cells vs. Modules vs. BOS* (*Balance of Systems) vs. Systems

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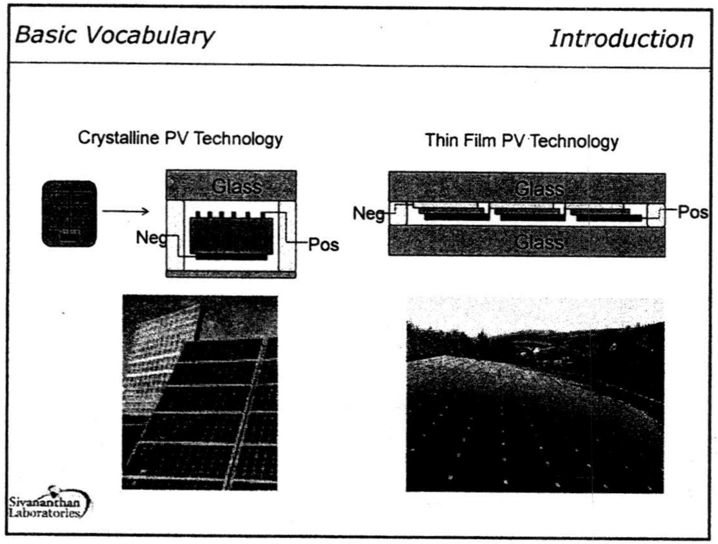

Basic Vocabulary *Introduction*

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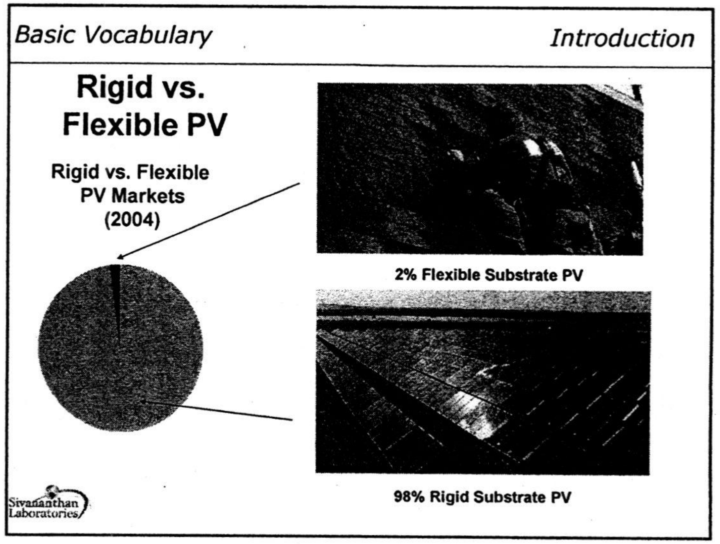

Basic Vocabulary *Introduction*

Rigid vs. Flexible PV

Rigid vs. Flexible PV Markets (2004)

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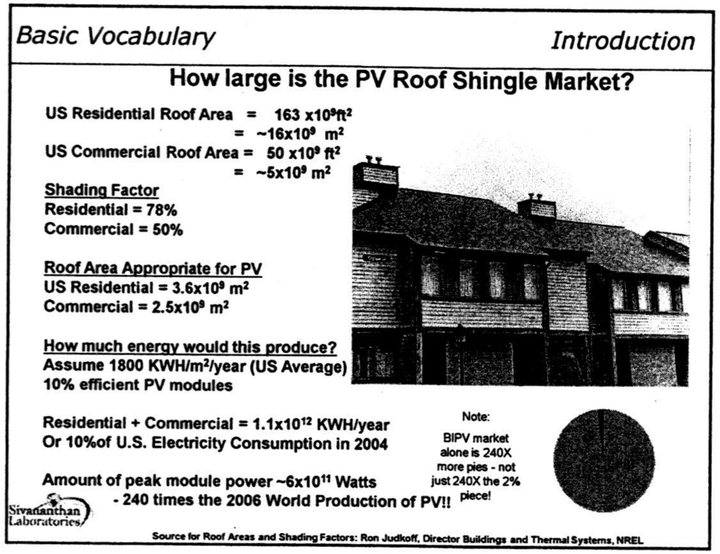

Basic Vocabulary *Introduction*

How large is the PV Roof Shingle Market?

US Residential Roof Area = 163 x10^9ft^2
= ~16x10^9 m^2
US Commercial Roof Area = 50 x10^9 ft^2
= ~5x10^9 m^2

Shading Factor
Residential = 78%
Commercial = 50%

Roof Area Appropriate for PV
US Residential = 3.6x10^9 m^2
Commercial = 2.5x10^9 m^2

How much energy would this produce?
Assume 1800 KWH/m^2/year (US Average)
10% efficient PV modules

Residential + Commercial = 1.1x10^{12} KWH/year
Or 10%of U.S. Electricity Consumption in 2004

Amount of peak module power ~6x10^{11} Watts
- 240 times the 2006 World Production of PV!!

Note:
BIPV market alone is 240X more pies - not just 240X the 2% piece!

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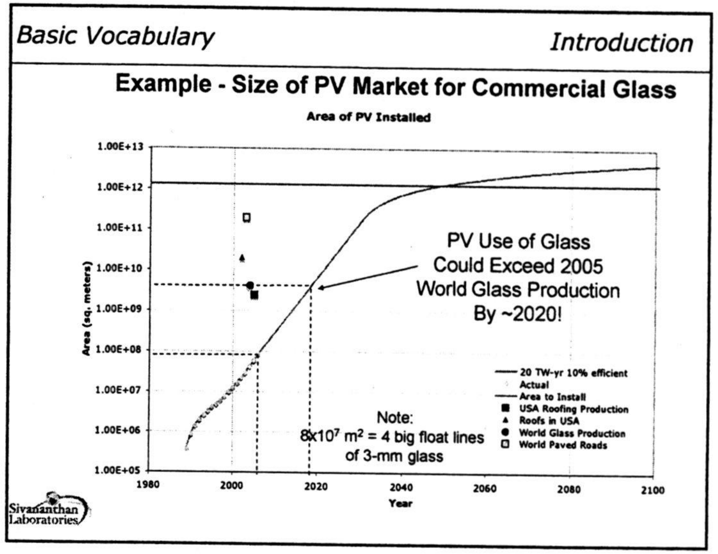
Source for Roof Areas and Shading Factors: Ron Judkoff, Director Buildings and Thermal Systems, NREL



Basic Vocabulary *Introduction*

Example - Size of PV Market for Commercial Glass

PV Use of Glass Could Exceed 2005 World Glass Production By ~2020!

Note:
8x10^7 m^2 = 4 big float lines of 3-mm glass

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Basic Vocabulary *Introduction*

Some Thin-Film CIGS, CdTe, and a-Si PV Companies

(Black - Rigid, Red - Flexible, Blue – Multiple/Undecided)

CIS

Shell Solar, CA
Global Solar Energy, AZ
Energy Photovoltaics, NJ
ISET, CA
Ascent (ITN/ES), CO
NanoSolar Inc., CA
DayStar Technologies, NY/CA
MiaSole, CA
HelioVolt, Tx
Solyndra, CA
SoloPower, CA

Wurth Solar, Germany
SULFURCELL, Germany
CIS Solartechnik, Germany
Solarion, Germany
Solibro, Sweden
CISEL, France
Showa Shell, Japan
Honda, Japan

CdTe

First Solar, OH
Solar Fields, OH/Calyxo (Germany)
AVA TECH, CO
Primestar Solar, CO
WK Solar Group, OH

CANRON, NY (and Canada)
Solexant, CA
Antec Solar, Germany
Arendi, Italy
Advanced Solar Power, China

a-Si

Uni-Solar, MI
EPV - MA
Iowa Thin Films, IA

Mitshubishi Heavy Ind. - Japan
Kaneka - Japan

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Environmental Discussion for Thin Film PV

Energy Balance

You're going to use more energy making PV than you'll generate!

- Slow PV Growth – Historical View
  - A PV module must make more energy than it took to make the module
- High PV Growth – What we have now
  - The generating capacity of all the installed arrays must exceed that used to manufacture more arrays in the next time interval
  - The "Energy Pay Back Time" (EPBT) must be less than the production doubling time (DT). Otherwise PV manufacture will be a net consumer of energy
- High PV Growth and High Net Energy Production
  - The EPBT must be significantly less than the DT. Otherwise PV will not produce the new electricity needed in the next 35 years (~40 Quads)

DR-3

Environmental Discussion for Thin Film PV

Energy Balance

Energy Payback Time (EPBT) Considers Energy Consumed During:

Extracting, refining, and purifying raw materials
Production, associated materials, and transportation of modules
Installation, balance of systems (BOS) components, and use of modules
Module disposal or recycling

	Ribbon Si	Poly Si	Mono Si	Thin Films		
				a-Si	CIS	CdTe
Modeled Efficiency	11.5%[1]	13.2%[1] 14.0%[3]	14.0%[1]	6%[2]	10%[3]	9%[1] 8%[3]
EPBT (Years)[1]	1.7	2.2	2.7	-	-	1.1
EPBT (Years)[2]	-	2.1-3.7	-	1.1-3.0	-	-
EPBT (Years)[3]		5			2.5	1.7

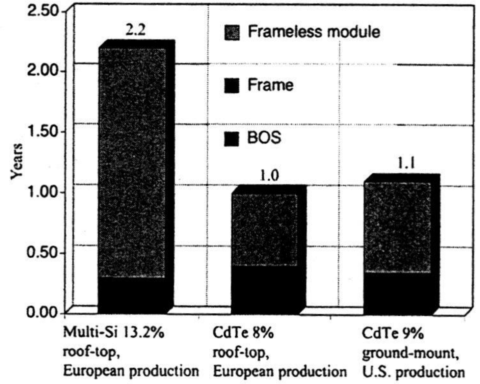
1. V. Fthenakis and H. Kim, Proc. 2006 European MRS Meeting, Nice France (6/06)
2. PV FAQs, U.S. Dept. Energy Pub. No. DOE/GO-102004-2040 (and internal references, 12/04).
3. M. Raugie et. al., 20th European PVSC, Barcelona, Spain (6/05)

Ref 1&3: www.nrel.gov/ncpv/thin_film/publications_news
Ref 2, www.nrel.gov/ncpv

Minerals Availability for Thin Film PV

Energy Balance

So what are the actual payback times?



V. Fthenakis and E. Alsema, PIP **14**, 275-280, 2006

Minerals Availability for Thin Film PV

Overview

Mineral Resource Considerations for Thin Films

(Si, a-Si, $CuInGaSe_2$, CdTe)

Technology	Material	World Production[a]	Materials Required[a,b]	% of Current Production	Annual Growth Needed (%)
Crystalline silicon	Purified silicon	25,000 MT/yr[b]	130,000 MT	520%	3.7%[c]
	Silver (grids/cell pads)	20,000 MT/yr	6,000 MT	30%	0.53%
Thin-film Cu (In, Ga) Se_2 alloys	Indium	250 MT/yr (byproduct)	400 MT	160%	2.0%[d]
	Selenium	2,200 MT/yr	800 MT	36%	0.6%[e]
	Gallium	150 MT/yr	70 MT	47%	0.9%[f]
Thin-film cadmium telluride	Tellurium	450 MT/yr (2,000 unused byproduct)	933 MT	38% (of total, including unused)	2.2%
	Cadmium	26,000 MT/yr (byproduct)	800 MT	3%	0.06%
Thin-film silicon	Germanium	270 MT/yr (3,200 unused byproduct)	40 MT	1% (of total including unused)	0.7%

[a] Necessary production for each type of PV technology to produce 20 GW/yr by 2050.
[b] Metric Tons
[c] Elemental silicon is not constrained by supply: current production is low because of low demand.
[d] Indium is a byproduct of zinc, which has been growing at 3%/yr for 50 years. Indium growth will probably exceed demand because of growth in zinc extraction. Indium production would only have to increase 2%/yr to keep pace with demand.
[e] Selenium is a byproduct of copper; an increase of only 0.16%/yr would keep pace with demand.
[f] Gallium is not constrained by supply: current production is low because of low demand.

Source: PV FAQs, DOE/GO-102004-1834 (1/04), www.nrel.gov/ncpv

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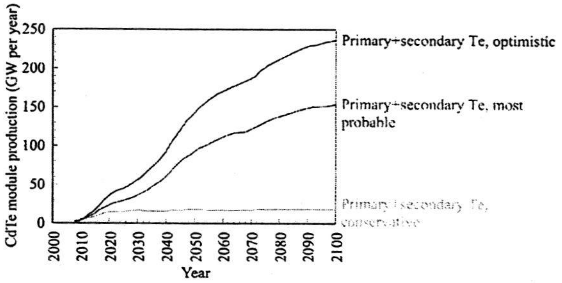
Environmental Discussion for Thin Film PV

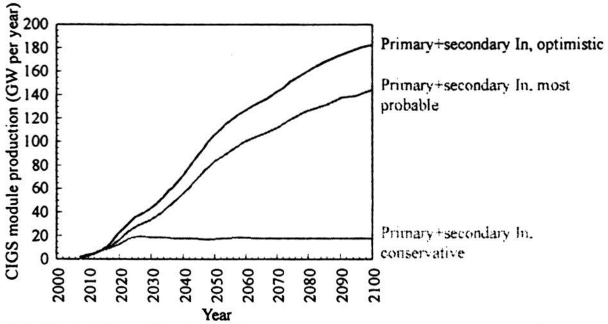
Overview

Sustainable CdTe module expansion



V. Fthenakis, Sustainability of photovoltaics: The case for thin-film solar cells,
Renewable and Sustainable Energy Reviews, 13, 2746-2750, (2009)

Sustainable CIGS module expansion



Presented by Timothy J. Coutts at The 16th Sede Boqer Symposium on Solar Electricity Production, February 14-16, 2010

V. Fthenakis, Sustainability of photovoltaics: The case for thin-film solar cells,
Renewable and Sustainable Energy Reviews, 13, 2746-2750, (2009)

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Environmental Discussion for Thin Film PV

Overview

Summary Comments on Minerals Availability

- The supply of tellurium (and indium) has been dictated by demand, not availability
- The level of understanding of these "mineral streams" is not as high as other minerals that have had a longer demand history
  - We are not very far up "Hubbert's Curve" on these commodities
- New/Alternative directions:
  - In – This group III element could be replaced by II-IV combinations such as Zn:Sn to form a different quaternary alloys (Kesterites = $Cu(Zn_xSn_{1-x})Se_2$ or $Cu(Zn_xSn_{1-x})S_2$)
  - Te – In addition to Zn ores, Te appears to associated also with volcanic activity, which suggests a new sources entirely

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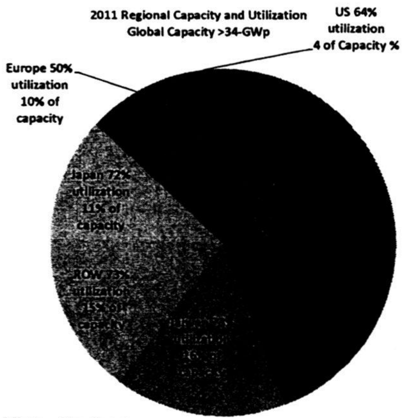
Global Manufacturing Capacity and Utilization



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Present status

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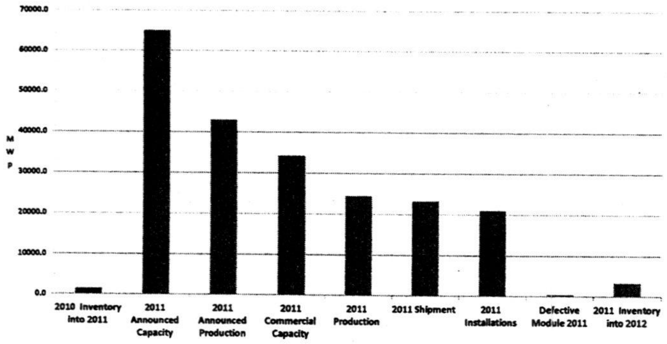
2011 into 2012 Global Statistics



High levels of inventory and manufacturing capacity will haunt the PV industry throughout 2012, And the inventory is continuing to build

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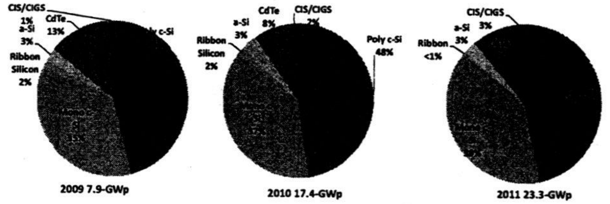


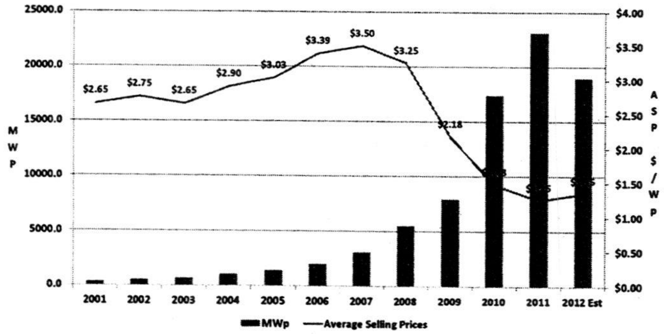
Challenging times for thin film manufacturers who must compete with artificially low prices for c-Si.

Price is the ONLY competitive factor currently.

Paula Mints, Navigant

Average Module Prices – Thin film modules have to be cheaper than Si due to area penalty

The range for modules to first buyer s $0.50/Wp to $3.35/Wp
The range for modules to second buyer from distributors is $1.15/Wp to $1.80/Wp
Reselling of inventory is averaging $1.05/Wp



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Future Projections

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Cost Projections

C- Si - at present \$1.25-1.50/W_p

Projected to go down to \$0.60/W_p

For further cost reduction to \$ 1/Wp for system cost, need to reduce production cost and improve performance for all technologies.

- Si - Poly Si, Thin Si, HIT cells.
- III-V - Multi-junction, concentrators.
- Thin films - a-Si, Polycrystalline thin films

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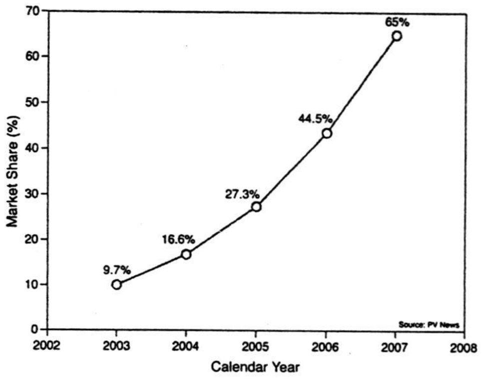
Why is Thin-Film PV Important? *Introduction*

Thin Film PV Market Share – USA



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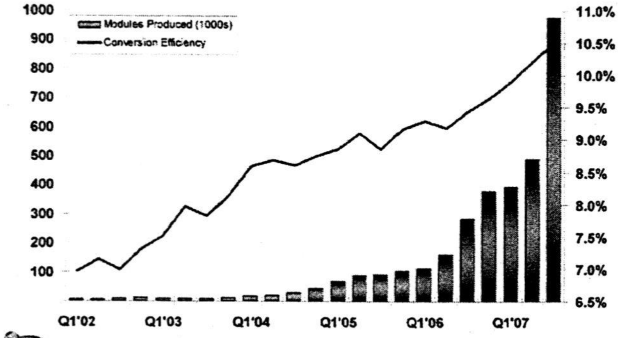
Why is Thin-Film PV Important? *Introduction*

Conversion Efficiencies & Module Shipments



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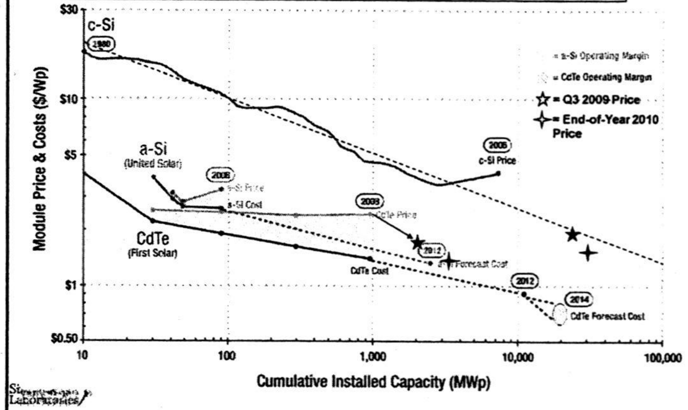
Why is Thin-Film PV Important? *Introduction*

How Much Does/Will Thin-Film PV Cost?



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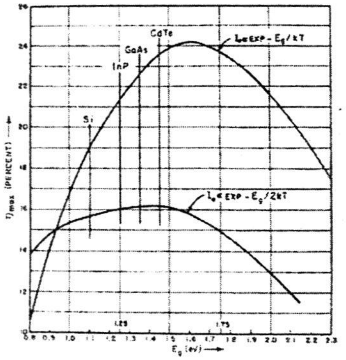

Efficiency vs band gap for different A values

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Overview

Conclusions

- Significant potential exists for new Thin film PV products to improve performance and reduce cost
- Thin-film products will compete in different segments
  - Flexible products for niche BIPV
  - Rigid products for utility scale
- Issues include:
  - Reducing EPBT further (<< 6 months?)
  - Increasing reproducible cell efficiency to 20% or greater
  - Keeping ahead of competing technologies in cost
- The rapid market penetration is forcing answers to questions few people have asked or even understand!
  - Will cost of Te remain high so that module recycling is profitable?

Electrical Prperties

Ramesh G. Dhere
Strategic Advisor, Sivananthan Laboratories,
Bollingbrook, Illinois, USA

Overview ***Thin-Film Technologies***

Why Thin-Film PV?

Average Need US Home - 5 kW$_p$
Present grid-tied PV system price - \$3-4/W$_p$ (with tax incentives)
PV system ~\$15K-\$20K
Utility cost - \$1000/year, cost balance in 15-20 years
Need to reduce cost to \$ 1/W$_p$ (=\$0.5 for PV module +\$0.5 BOS)

- c-Si - ~\$1/W$_p$ (Present Cost and Price)
- Projected to go down to <\$0.7/W$_p$
- Need Modules at \$0.5/W$_p$ (Price)
- Reduce production cost and/or improve performance
  - Si - Poly Si, Thin Si
  - III-V - Multi-junction, concentrators
  - Thin films - a-Si, Polycrystalline thin films

Overview ***Thin-Film Technologies***

Crystalline vs. Thin Film PV

Crystalline PV Technologies

- Lattice-matched substrates, slow growth, thermal equilibrium. Very few defects = high performance
- \$/Watt = Expensive Process/Higher Performance

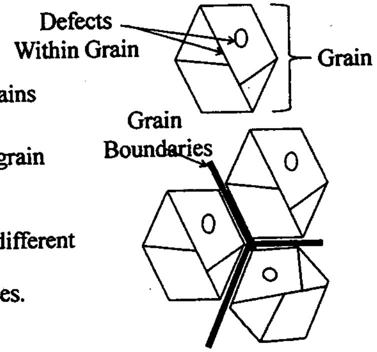
Thin-Film PV Technologies

- Economic considerations dominate
- High throughput, inexpensive substrates
- Produces lots of defects that limit device performance
- \$/Watt = Cheaper Process/Lower Performance

Overview ***Thin-Film Technologies***

Issues to to Consider in Thin-Film PV

- Substrates
- Grains
  - Defects within the grains
- Grain Boundaries
  - Electrical activity at grain boundaries and other structural defects.
- Interaction between the different layers of the device and properties of the interfaces.



D1-2

Substrates for Thin Film Growth

Some Considerations:
- Softening Point
- Thermal coefficient of Expansion
- Out Diffusion
- Cleaning

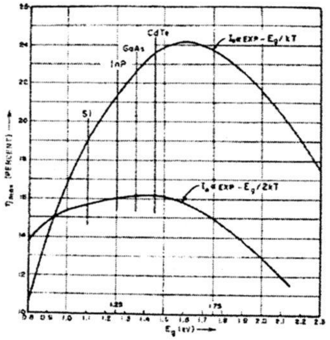
Glass type	Coeff. of Thermal Exp	Softening point (C)	Strain Point (C)
Sodalime	9.35×10^{-6}/C	696	473
Borosilicate	5.2×10^{-6}/C	815	640

Growth of thin films

Deposition Processes for Thin Films
- Primary Goal - High rate, good quality, low cost
- Vacuum Processes
  - r.f and d.c. magnetron sputtering
  - Sublimation (evaporation)
- Chemical Vapor Processes
  - LP CVD, PECVDE
- Atmospheric Pressure Processes
  - ED, CBD, Spray Deposition, Various Printing

Growth of thin films (Cont)

Thin-Film PV Candidate Materials
- III-V (InP, GaAs)
  - II-IV-V (ZnSnP, ZnGeAs)
- II-VI (CdTe)
  - I-II-VI (Cu_2S)
  - I-III-VI (CIS)
- Significant problems with III-V
  - Active grain boundaries?
  - Passivation of GB not successful
  - Best poly devices ~10%
- Better luck with II-VI
  - Benign grain boundaries
  - Tend to be columnar grains
  - Poly II-VI materials often better than crystal



Grain Boundaries

Grain Boundaries

- Regions of high defects
- Controlling factor of film
- Coherent twins (OK)
- Low-angle GB (Problem)
- High-angle GB (Bad)

TEM cross section view of a CdTe solar cell

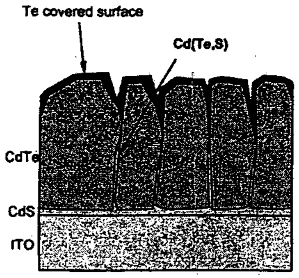
D1-3

Overview *Thin-Film Technologies*

Grain Boundaries (Cont)

Grain Boundaries (GBs)

- GBs can be regions of depletion, inversion, or accumulation
- Modification of GB
  - Neutralization by adding impurities
  - Capping with an insulator
  - Place GB in the junction
- In thin-film PV, we do not yet know how to control the influence of GB.
- Most GB optimization is experimentally determined.



Overview *Thin-Film Technologies*

Impact of Grains and Grain Boundaries on Device Performance

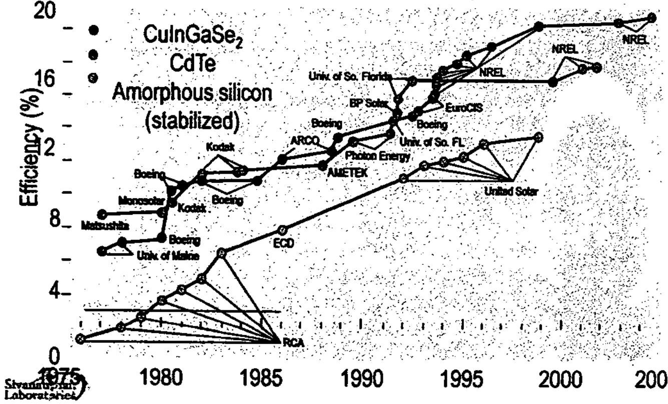
In General:

Recombination at GBs does not significantly limit current collection
High defect density at interface does not limit voltage (though high recombination current / low lifetime)

Reasons for this will be explained in following section

Champion Cell Efficiencies *Thin-Film Technologies*

The Best One-of-a-Kind Laboratory Cell Efficiencies for Thin Films (Standard Conditions)



Some CIGS-alloy, CdTe, & a-Si Laboratory Cells

	Area (cm^2)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Eff* (%)	Comment
CIGSe	0.410	697	35.1	79.52	20.0	CIGSe/CdS, NREL, 3-Stage
CIGSe	0.402	670	35.1	78.78	18.5	CIGSe/ZnS, Nakada et. al.
CIGS	0.409	830	20.9	69.13	12.0	CIGS/CdS, FSEC
CIAS	-	621	36.0	75.50	16.9	CIAS/CdS, IEC, 1.15 eV
CdTe	1.03	845	25.9	75.51	16.7	CTO/ZTO/CdS/CdTe, NREL, CSS
CdTe	-	-	-	-	17.3	First Solar VTD ???
CdTe	0.814	814	23.25	73:25	14.3	SLG,FTO/TO/CdS/CdTe, EPIR, CSS
a-Si	-	-	-	72.25	12.1	

***NREL Confirmed Efficiencies**

4-19

Champion Module Efficiencies **Thin-Film Technologies**

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Miasole	CIGS	9762	13.6-13.8	-	4/10
Global Solar	CIGS	8390	10.2*	88.9	8/02
First Solar	CdTe	6623	14.3*		8/08
Wurth Solar	CIGS	6500	13.0	84.6	6/04
United Solar	a-Si	4519	7.9*	35.7	6/97
Shell Solar	CIGSS	3626	12.8*	46.5	3/03
Showa Shell	CIGS	3459	13.5	-	8/02

*Module Efficiencies Measured at NREL

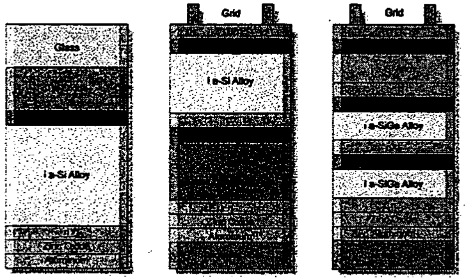
Comparing Thin Film Technologies **Thin-Film Technologies**

Comparison of Three Thin-Film PV Technologies Indicating Present Strengths of Each Technology

	Demonstrated Efficiency	Perceived Production Advantage	Perceived Materials Abundance/ Low Toxicity
a-Si			Strength
CdTe		Strength	
CIS	Strength		

Amorphous Si Basics **Thin-Film Technologies**

Amorphous Si
Thin-film Solar Cells



Amorphous Si Basics **Thin-Film Technologies**

Crystalline Si vs. a-Si vs. a-Si:H

Crystalline Si is an indirect band gap semiconductor with $E_g = 1.1$ eV

Disordered Si (amorphous Si) changes nature of absorption $E_g = 1.7$ e

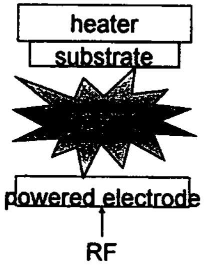
a-Si without H (e.g., sputtered from Si) contains unsaturated dangling bonds

Defect density ~10^{19} cm^{-3}
Essentially useless for PV applications

H in a-Si (5-20%, from decomposition of SiH_4) saturates dangling bonds

Defect density reduced to 10^{15} - 10^{16} cm^{-3}

Plasma-Enhanced (PE)CVD



- Pressure 0.3 - 2 Torr
- Elect. gap 1 - 3 cm
- Sub. Temp. 150 - 300° C
- RF Power 5 - 25 mW/cm²
- H_2:SiH_4 to get μc-Si formation ~ 30:1
- Dep. Rate ~3 Å/sec typical
- Also called Glow Discharge

Figure courtesy Brent Nelson, NREL

Doping and Simple Devices

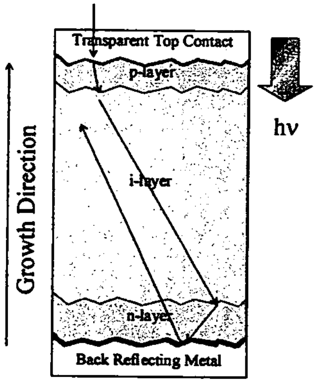
Typical undoped a-Si:H is typically intrinsic or slightly n-type
Contains impurities (O, N, and C) at 10^{18}-10^{19} cm^{-3}
Reduction of these impurities to 10^{15} range does not improve devices

Luckily - Extrinsic doping just like crystalline or polycrystallline Si:
Boron (p-type) and Phosphorus (n-type)

Unfortunately - Doping decreases electrical quality (reduces carrier lifetime)
Cannot use doped layers for absorber layers
Use and intrinsic (i-layer) for high-performance devices

Dave Carlson patented n-i-p device 1972

Typical a-Si:H Solar Cell (Single-Junction)



- p-layer
  - 80 - 200 Å
  - wide bandgap (a-SiC:H or μc-Si:H)
  - boron doped
- i-layer
  - 2000 - 5000 Å
  - 1.68 - 1.75 eV
- n-layer
  - 200 - 400 Å
  - phosphorous doped

Companies Making nip a-Si single junction : EPV, BP Solar (closed thin-film)

Figure courtesy Brent Nelson, NREL

Stability

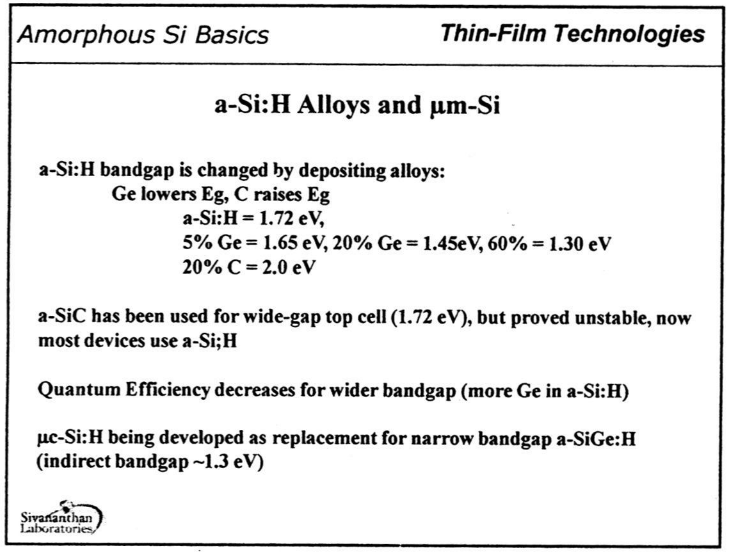
1977 - Staebler and Wronski noted significant changes in optoelectronic properties of a-Si:H when material was exposed to light that were reversible on annealing at 150° C for a few hours. This is now known as the Stabeler-Wronski effect (SWE)

Thiner i-layers reduce SWE, but this provides less light absorption

Understanding

It appears that the high electric field in thin i-layer reduces the SWE
SWE effect may be due to multiple causes
Work is still being done

D-9



Amorphous Si Basics ***Thin-Film Technologies***

a-Si:H Alloys and μm-Si

a-Si:H bandgap is changed by depositing alloys:
Ge lowers Eg, C raises Eg
a-Si:H = 1.72 eV,
5% Ge = 1.65 eV, 20% Ge = 1.45eV, 60% = 1.30 eV
20% C = 2.0 eV

a-SiC has been used for wide-gap top cell (1.72 eV), but proved unstable, now most devices use a-Si;H

Quantum Efficiency decreases for wider bandgap (more Ge in a-Si:H)

μc-Si:H being developed as replacement for narrow bandgap a-SiGe:H (indirect bandgap ~1.3 eV)

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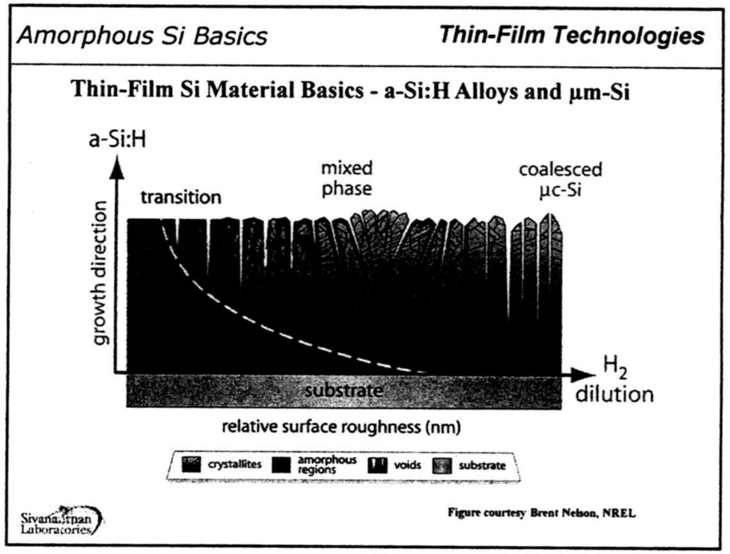

Amorphous Si Basics ***Thin-Film Technologies***

Thin-Film Si Material Basics - a-Si:H Alloys and μm-Si

Figure courtesy Brent Nelson, NREL

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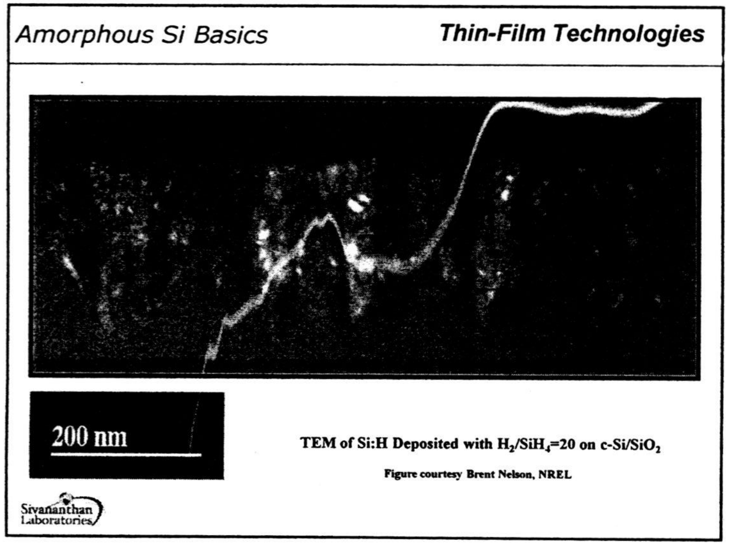

Amorphous Si Basics ***Thin-Film Technologies***

TEM of Si:H Deposited with H_2/SiH_4=20 on c-Si/SiO$_2$

Figure courtesy Brent Nelson, NREL

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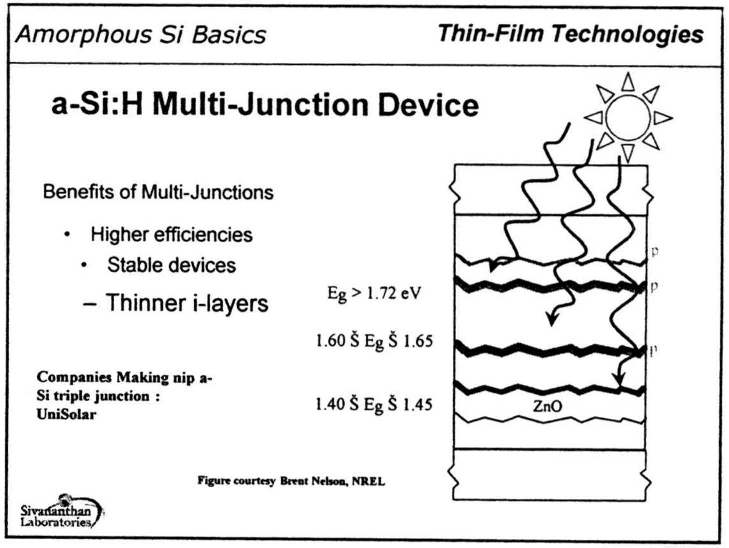

Amorphous Si Basics ***Thin-Film Technologies***

a-Si:H Multi-Junction Device

Benefits of Multi-Junctions

- Higher efficiencies
  - Stable devices
  - Thinner i-layers

Companies Making nip a-Si triple junction : UniSolar

Figure courtesy Brent Nelson, NREL

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A1-7

Amorphous Si Basics ***Thin-Film Technologies***

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Understanding

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Amorphous Si Basics ***Thin-Film Technologies***

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µc-Si:H being developed as replacement for narrow bandgap a-SiGe:H (indirect bandgap ~1.3 eV)

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Amorphous Si Basics ***Thin-Film Technologies***

Thin-Film Si Material Basics - a-Si:H Alloys and µm-Si

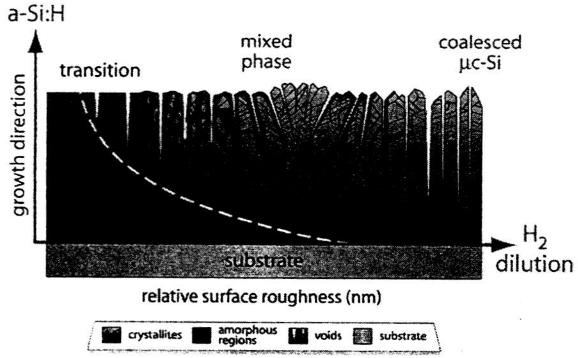

Figure courtesy Brent Nelson, NREL

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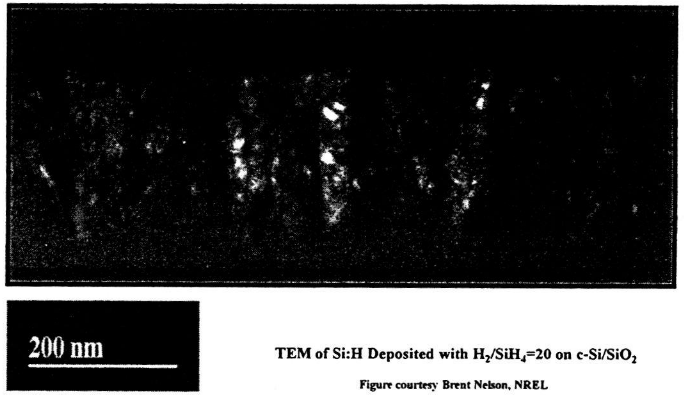
Amorphous Si Basics ***Thin-Film Technologies***



TEM of Si:H Deposited with H_2/SiH_4=20 on c-Si/SiO_2

Figure courtesy Brent Nelson, NREL

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8-9

Amorphous Si Basics **Thin-Film Technologies**

a-Si:H Multi-Junction Device

Benefits of Multi-Junctions

- Higher efficiencies
  - Stable devices
    - Thinner i-layers

Companies Making nip a-Si triple junction :
UniSolar

Eg > 1.72 eV

1.60 Š Eg Š 1.65

1.40 Š Eg Š 1.45

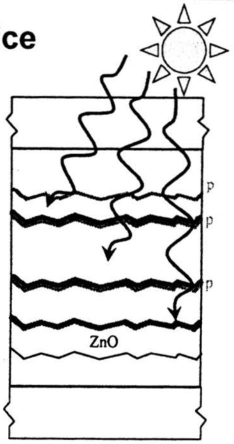

Figure courtesy Brent Nelson, NREL

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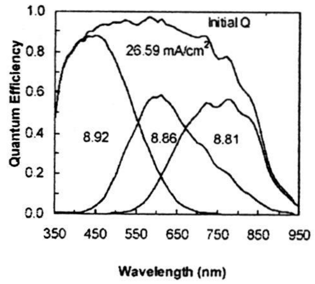
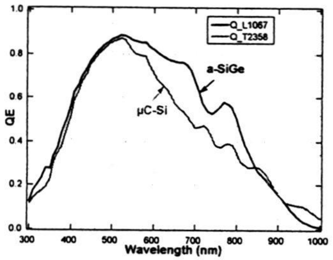
Amorphous Si Basics **Thin-Film Technologies**

Thin-Film Si Material Basics - a-Si:H Alloys

Research is proceeding on improving the quality of the wide-gap alloys



UniSolar Triple-Junction Device. Number indicate current density from Individual junctions



NREL Single-junction devices
(Recent results suggest µm-Si as good as a-SiGe:H)

Figurse courtesy Brent Nelson, NREL

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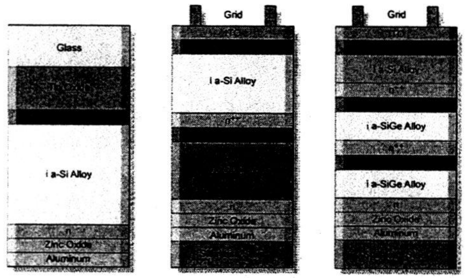
Amorphous Si Basics **Thin-Film Technologies**

Review Amorphous Si Thin-film Solar Cells
(What Have We Learned?)



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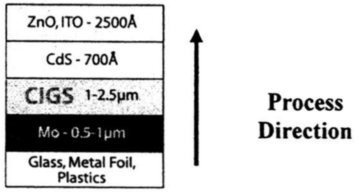
CIGS Basics **Thin-Film Technologies**

$CuInSe_2$-Alloy (CIGS)
Thin-film Solar Cells



ZnO, ITO - 2500Å
CdS - 700Å
CIGS 1-2.5µm
Mo - 0.5-1µm
Glass, Metal Foil, Plastics

Process Direction

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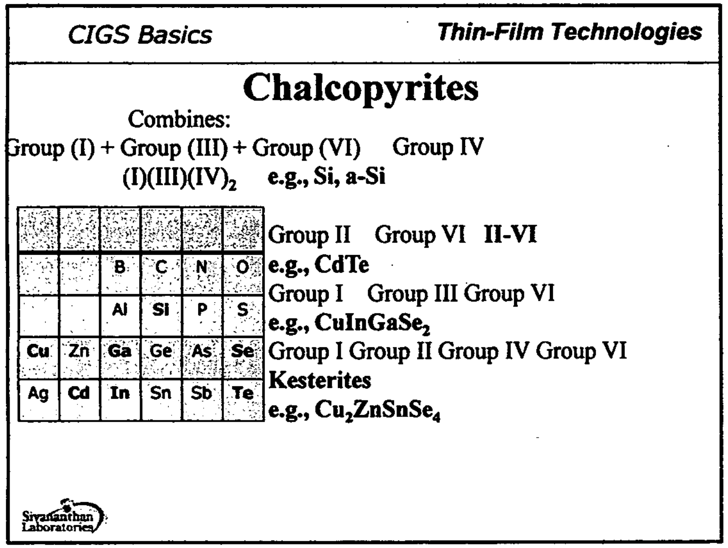


CIGS Basics ***Thin-Film Technologies***

Chalcopyrites

Combines:

Group (I) + Group (III) + Group (VI) Group IV

(I)(III)(IV)$_2$ **e.g., Si, a-Si**

		B	C	N	O
		Al	Si	P	S
Cu	Zn	Ga	Ge	As	Se
Ag	Cd	In	Sn	Sb	Te

Group II Group VI **II-VI**

e.g., CdTe

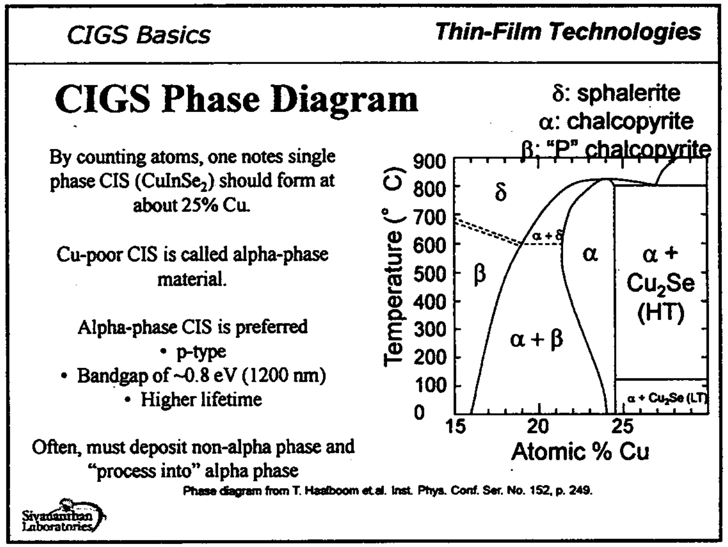
Group I Group III Group VI

e.g., $CuInGaSe_2$

Group I Group II Group IV Group VI

Kesterites

e.g., $Cu_2ZnSnSe_4$



CIGS Basics ***Thin-Film Technologies***

CIGS Phase Diagram

δ: sphalerite
α: chalcopyrite
β: "P" chalcopyrite

By counting atoms, one notes single phase CIS ($CuInSe_2$) should form at about 25% Cu.

Cu-poor CIS is called alpha-phase material.

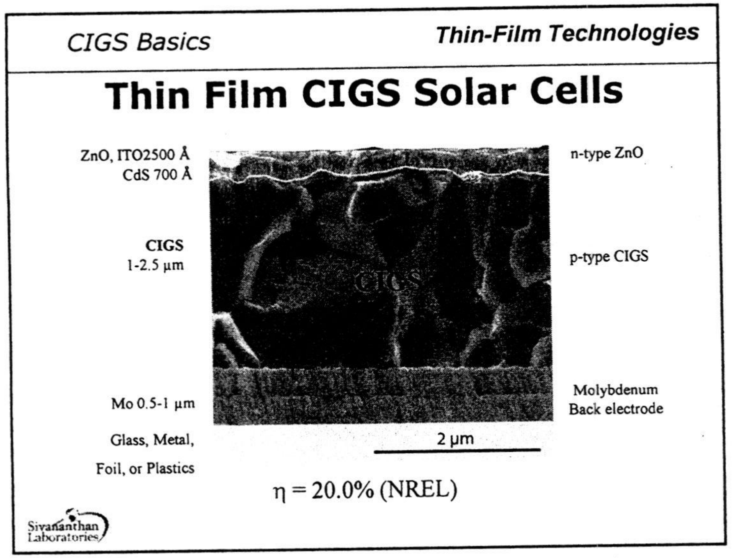
Alpha-phase CIS is preferred

- p-type
- Bandgap of ~0.8 eV (1200 nm)
- Higher lifetime

Often, must deposit non-alpha phase and "process into" alpha phase

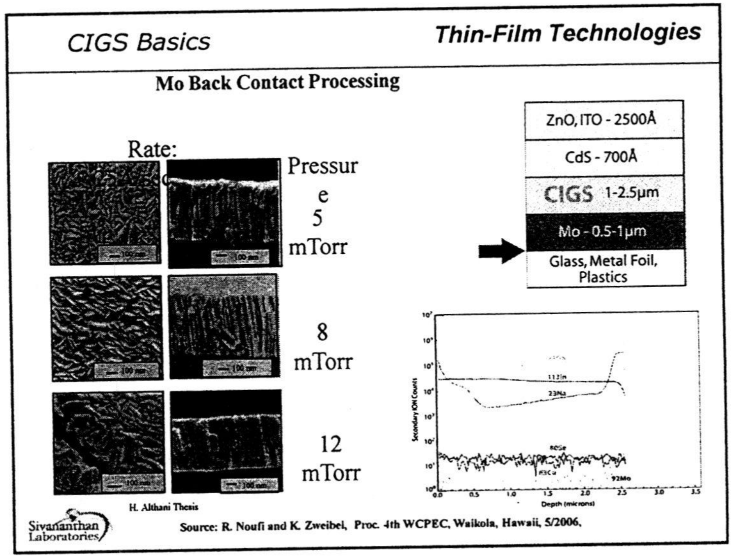
Phase diagram from T. Haalboom et.al. Inst. Phys. Conf. Ser. No. 152, p. 249.

D2-1



Thin Film CIGS Solar Cells

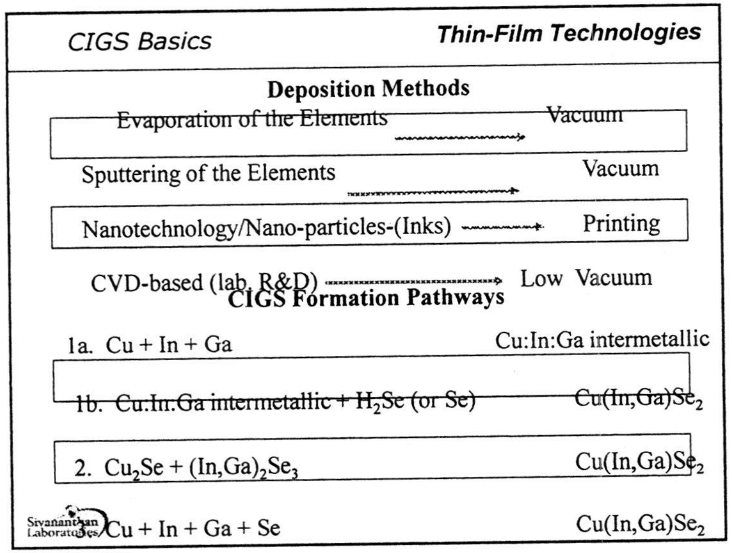
$\eta = 20.0\%$ (NREL)



Mo Back Contact Processing

H. Althani Thesis

Source: R. Noufi and K. Zweibel, Proc. 4th WCPEC, Waikola, Hawaii, 5/2006.



Deposition Methods

Evaporation of the Elements → Vacuum

Sputtering of the Elements → Vacuum

Nanotechnology/Nano-particles-(Inks) → Printing

CVD-based (lab, R&D) → Low Vacuum

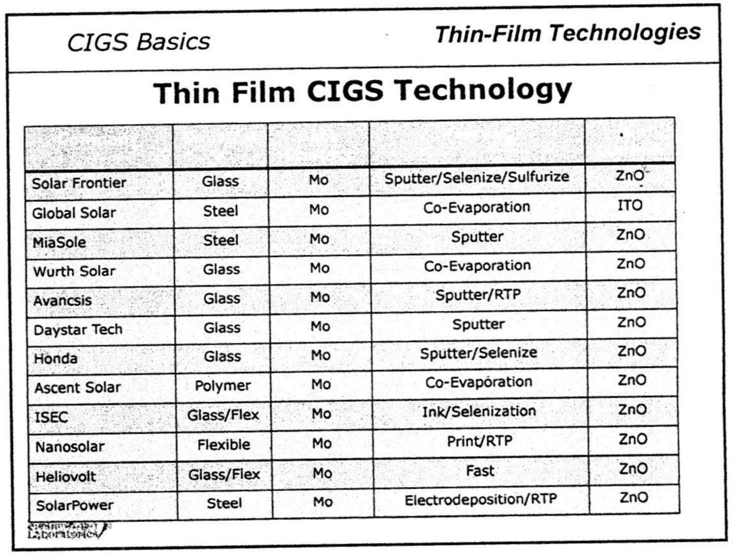
CIGS Formation Pathways

1a. Cu + In + Ga → Cu:In:Ga intermetallic

1b. Cu:In:Ga intermetallic + H_2Se (or Se) → $Cu(In,Ga)Se_2$

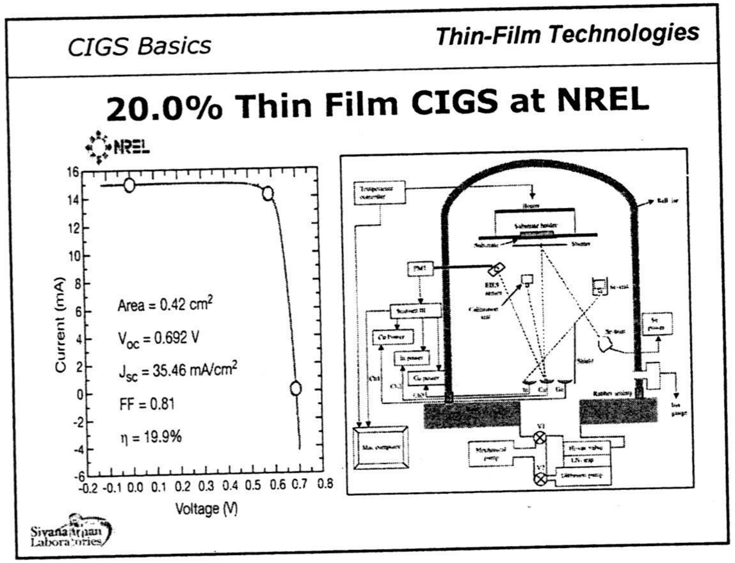
2. $Cu_2Se + (In,Ga)_2Se_3$ → $Cu(In,Ga)Se_2$

3. Cu + In + Ga + Se → $Cu(In,Ga)Se_2$



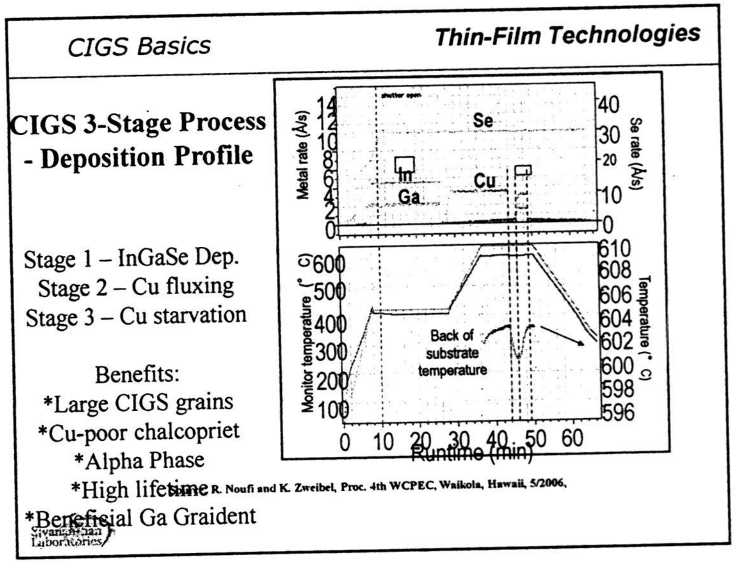
Thin Film CIGS Technology

Solar Frontier	Glass	Mo	Sputter/Selenize/Sulfurize	ZnO
Global Solar	Steel	Mo	Co-Evaporation	ITO
MiaSole	Steel	Mo	Sputter	ZnO
Wurth Solar	Glass	Mo	Co-Evaporation	ZnO
Avancsis	Glass	Mo	Sputter/RTP	ZnO
Daystar Tech	Glass	Mo	Sputter	ZnO
Honda	Glass	Mo	Sputter/Selenize	ZnO
Ascent Solar	Polymer	Mo	Co-Evaporation	ZnO
ISEC	Glass/Flex	Mo	Ink/Selenization	ZnO
Nanosolar	Flexible	Mo	Print/RTP	ZnO
Heliovolt	Glass/Flex	Mo	Fast	ZnO
SolarPower	Steel	Mo	Electrodeposition/RTP	ZnO



CIGS Basics **Thin-Film Technologies**

20.0% Thin Film CIGS at NREL



CIGS Basics **Thin-Film Technologies**

CIGS 3-Stage Process - Deposition Profile

Stage 1 – InGaSe Dep.
Stage 2 – Cu fluxing
Stage 3 – Cu starvation

Benefits:
*Large CIGS grains
*Cu-poor chalcopriet
*Alpha Phase
*High lifetime
*Beneficial Ga Graident

Source: R. Noufi and K. Zweibel, Proc. 4th WCPEC, Waikola, Hawaii, 5/2006,

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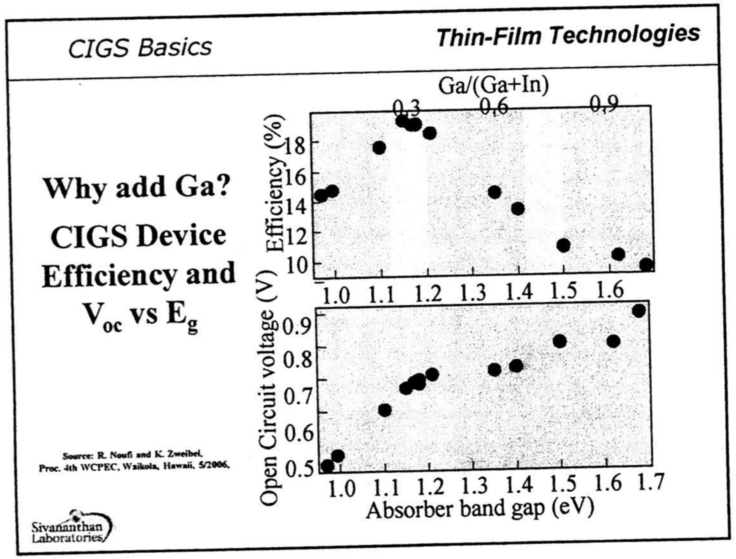

CIGS Basics **Thin-Film Technologies**

Why add Ga? CIGS Device Efficiency and V_{oc} vs E_g

Source: R. Noufi and K. Zweibel, Proc. 4th WCPEC, Waikola, Hawaii, 5/2006,

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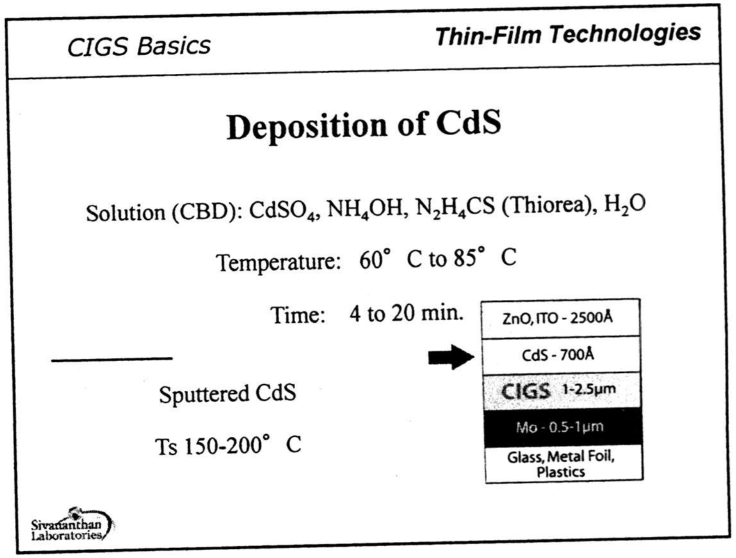

CIGS Basics **Thin-Film Technologies**

Deposition of CdS

Solution (CBD): $CdSO_4$, NH_4OH, N_2H_4CS (Thiorea), H_2O

Temperature: 60° C to 85° C

Time: 4 to 20 min.

Sputtered CdS

Ts 150-200° C

D57

CdTe Thin Film Solar Cells

Sivananthan Laboratories

CdTe

Advantages:

- Ideal band gap - 1.5 eV, direct gap semiconductor, requires only 2 μm thickness to absorb most of the spectrum.
- Simple binary system, can be prepared by many techniques. Properties favor formation of single phase material.
- Exists in both n and p type.
- CdS works as a good hetero-junction partner.

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Disadvantages:

- Difficult to dope p -type. Properties controlled by native defects in the material. In polycrystalline material, extrinsic dopants accumulate at the grain boundaries.
- Ohmic Contact - CdTe has high work function 5.8 eV. No suitable metals for forming ohmic contacts. Need to form intermediate layer to get tunneling contact.
- This requires use of inverted structure where CdTe contact formation is the last step.

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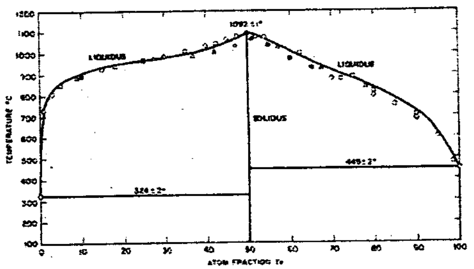
Phase Diagram for CdTe



From Semiconductors and Semimetals, vol. 13, CdTe, K Zanio, Academic Press, 1978

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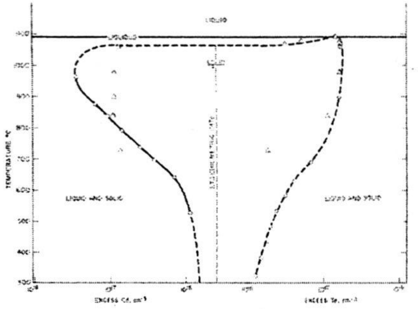
D3-2

CdTe Basics **Thin-Film Technologies**

Phase Diagram for CdTe



From Semiconductors and Semimetals, vol. 13, CdTe, K Zanio, Academic Press, 1978

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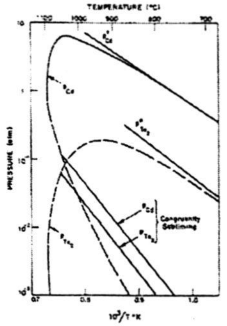
CdTe Basics **Thin-Film Technologies**

Vapor Pressure for CdTe



From Semiconductors and Semimetals, vol. 13, CdTe, K Zanio, Academic Press, 1978

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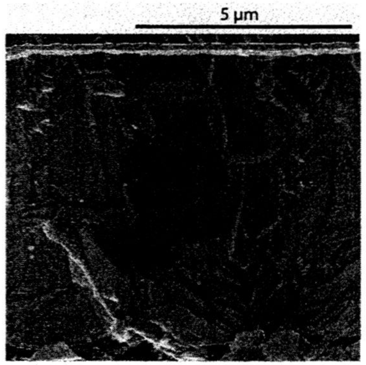
CdTe Basics **Thin-Film Technologies**

Thin Film CdTe Solar Cells

η = 16.5%
(NREL)



Glass

CdS
600-2000 Å

CdTe
2-8 µm

Cu-Containing Interface
(Paste, Pretreatments,
ZnTe:Cu) + Metals

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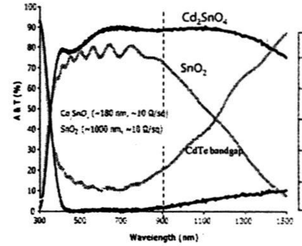
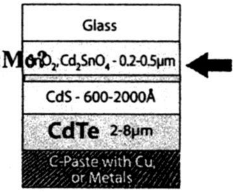
CdTe Basics **Thin-Film Technologies**

High Quality TCO



Sample	Cd_2SnO_4	SnO_2 ($SnCl_4$)	SnO_2 (TMT)
t (nm)	510	~1000	~1000
n (cm^{-3})	8.94×10^{20}	4.95×10^{20}	4.52×10^{20}
μ (cm$_2$/Vs)	54.5	15.4	42.0
Resistivity (Ω cm)	1.28×10^{-4}	8.18×10^{-4}	3.29×10^{-4}
R_s (Ω/sq)	2.6	8.6	3.3

lternate TCO Layers: In_2O_3:Sn/SnO, In_2O_3:Mo?



Glass
SnO_2, Cd_2SnO_4 - 0.2-0.5µm
CdS - 600-2000Å
CdTe 2-8µm
C-Paste with Cu, or Metals

TCO layer typically combined with
a "Buffer" layer between CdS and TCO

From X. Wu et. al, Proc. 28th Photovolt. Spec. Conf. pp. 470-474 (2000)

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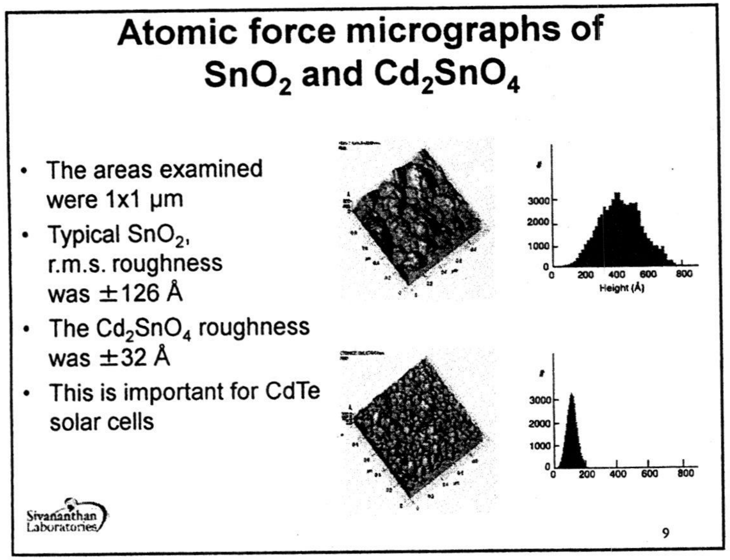

Atomic force micrographs of SnO_2 and Cd_2SnO_4

- The areas examined were 1x1 µm
- Typical SnO_2, r.m.s. roughness was ±126 Å
- The Cd_2SnO_4 roughness was ±32 Å
- This is important for CdTe solar cells

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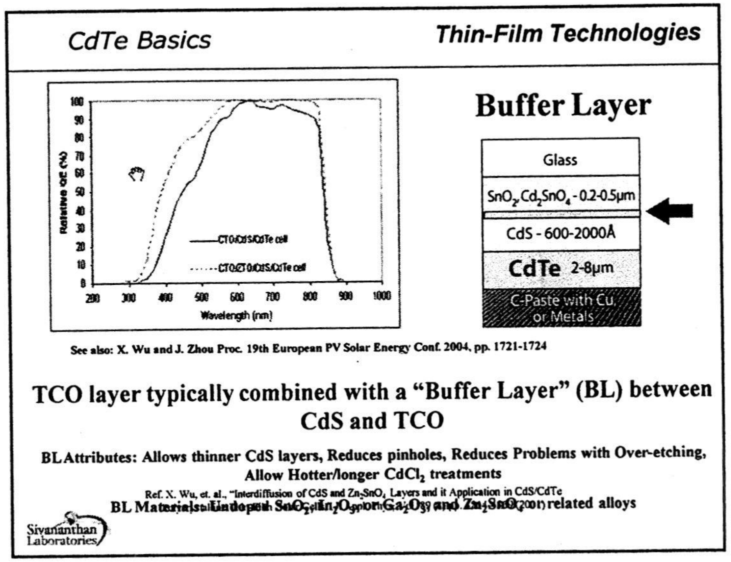

CdTe Basics **_Thin-Film Technologies_**

Buffer Layer

See also: X. Wu and J. Zhou Proc. 19th European PV Solar Energy Conf. 2004, pp. 1721-1724

TCO layer typically combined with a "Buffer Layer" (BL) between CdS and TCO

BL Attributes: Allows thinner CdS layers, Reduces pinholes, Reduces Problems with Over-etching, Allow Hotter/longer $CdCl_2$ treatments

Ref. X. Wu, et. al., "Interdiffusion of CdS and Zn_2SnO_4 Layers and it Application in CdS/CdTe

BL Materials: Undoped SnO_2, In_2O_3, or Ga_2O_3 and Zn_2SnO_4 or related alloys

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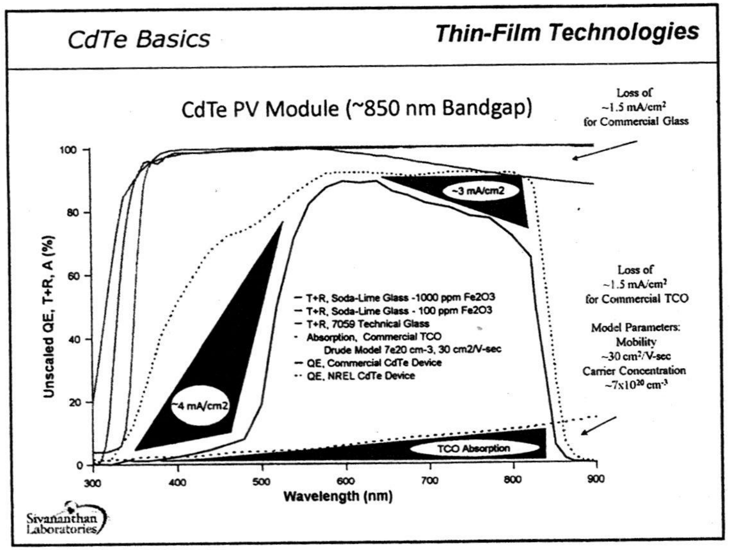

CdTe Basics **_Thin-Film Technologies_**

CdTe PV Module (~850 nm Bandgap)

Loss of ~1.5 mA/cm² for Commercial Glass

Loss of ~1.5 mA/cm² for Commercial TCO

Model Parameters:
Mobility
~30 cm²/V-sec
Carrier Concentration
~7x10²⁰ cm⁻³

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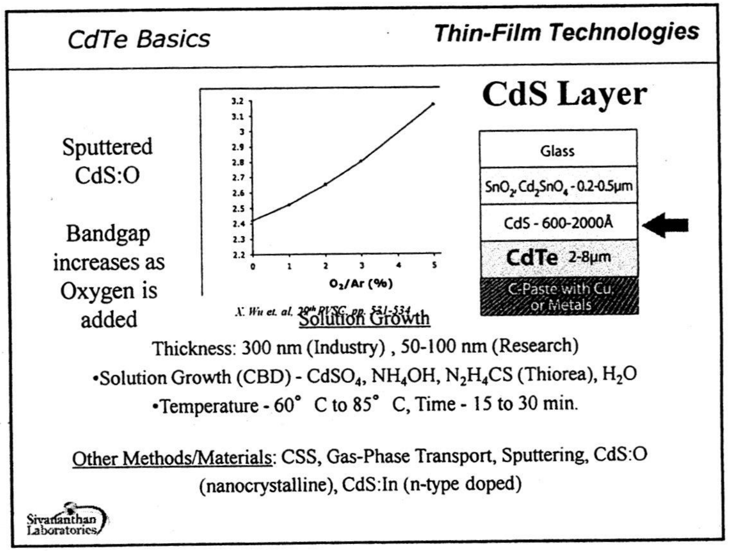

CdTe Basics **_Thin-Film Technologies_**

CdS Layer

Sputtered CdS:O

Bandgap increases as Oxygen is added

X. Wu et. al. 29^{th} PVSC, pp. 531-534

<u>Solution Growth</u>

Thickness: 300 nm (Industry) , 50-100 nm (Research)

•Solution Growth (CBD) - $CdSO_4$, NH_4OH, N_2H_4CS (Thiorea), H_2O

•Temperature - 60° C to 85° C, Time - 15 to 30 min.

<u>Other Methods/Materials</u>: CSS, Gas-Phase Transport, Sputtering, CdS:O (nanocrystalline), CdS:In (n-type doped)

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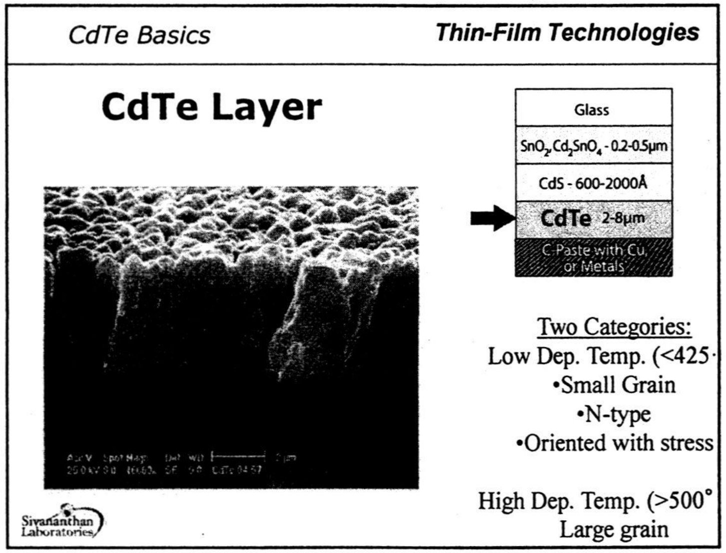
6-3-4



CdTe Basics **Thin-Film Technologies**

CdTe Layer

Two Categories:
Low Dep. Temp. (<425
- Small Grain
- N-type
- Oriented with stress

High Dep. Temp. (>500°
Large grain

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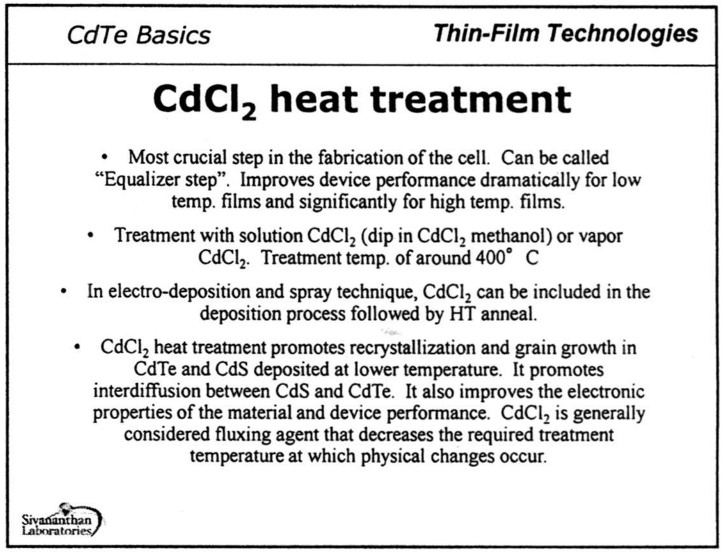

CdTe Basics **Thin-Film Technologies**

$CdCl_2$ heat treatment

- Most crucial step in the fabrication of the cell. Can be called "Equalizer step". Improves device performance dramatically for low temp. films and significantly for high temp. films.
- Treatment with solution $CdCl_2$ (dip in $CdCl_2$ methanol) or vapor $CdCl_2$. Treatment temp. of around 400° C
- In electro-deposition and spray technique, $CdCl_2$ can be included in the deposition process followed by HT anneal.
- $CdCl_2$ heat treatment promotes recrystallization and grain growth in CdTe and CdS deposited at lower temperature. It promotes interdiffusion between CdS and CdTe. It also improves the electronic properties of the material and device performance. $CdCl_2$ is generally considered fluxing agent that decreases the required treatment temperature at which physical changes occur.

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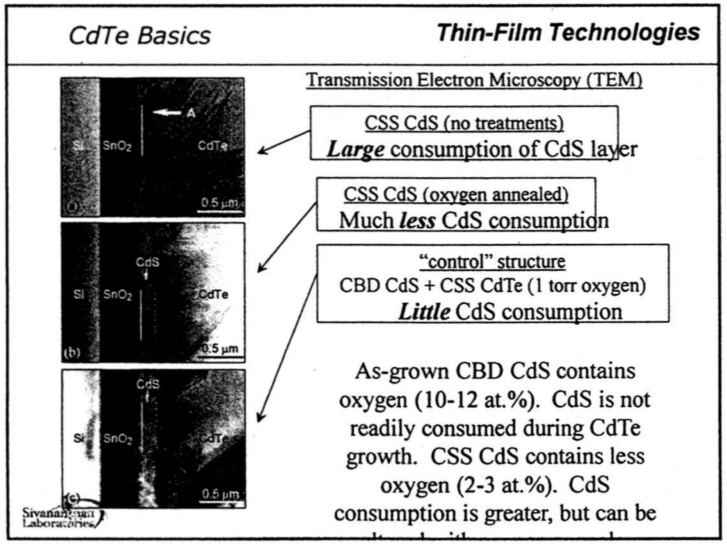

CdTe Basics **Thin-Film Technologies**

Transmission Electron Microscopy (TEM)

CSS CdS (no treatments)
Large consumption of CdS layer

CSS CdS (oxygen annealed)
Much ***less*** CdS consumption

"control" structure
CBD CdS + CSS CdTe (1 torr oxygen)
Little CdS consumption

As-grown CBD CdS contains oxygen (10-12 at.%). CdS is not readily consumed during CdTe growth. CSS CdS contains less oxygen (2-3 at.%). CdS consumption is greater, but can be

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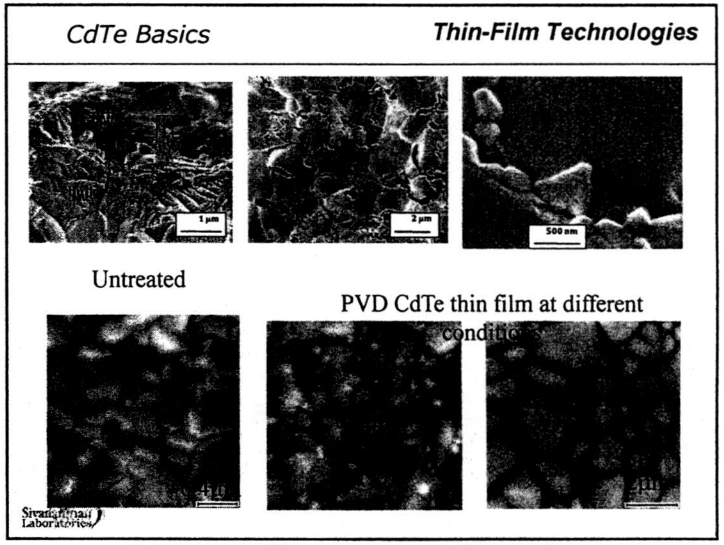

CdTe Basics **Thin-Film Technologies**

Untreated

PVD CdTe thin film at different conditio

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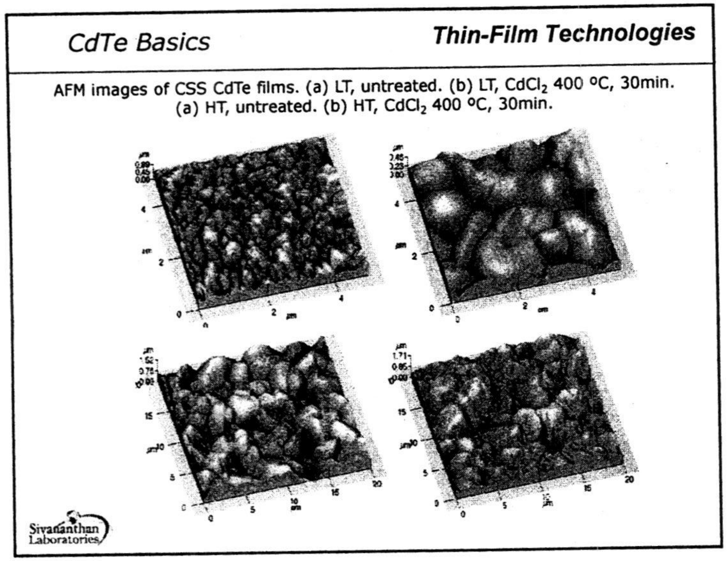
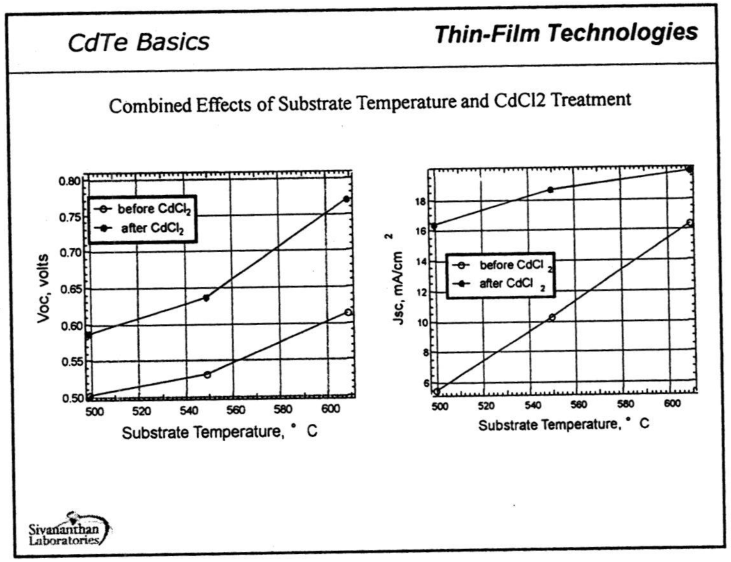
D3-5



CdTe Basics **Thin-Film Technologies**

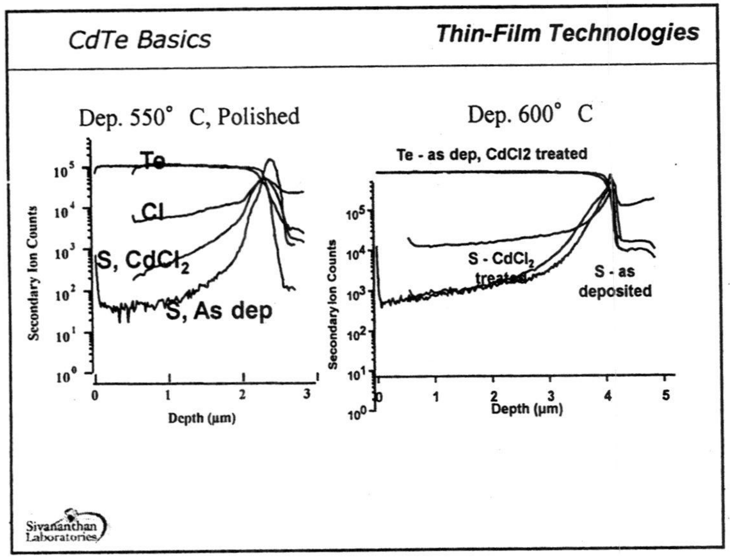
AFM images of CSS CdTe films. (a) LT, untreated. (b) LT, $CdCl_2$ 400 °C, 30min. (a) HT, untreated. (b) HT, $CdCl_2$ 400 °C, 30min.



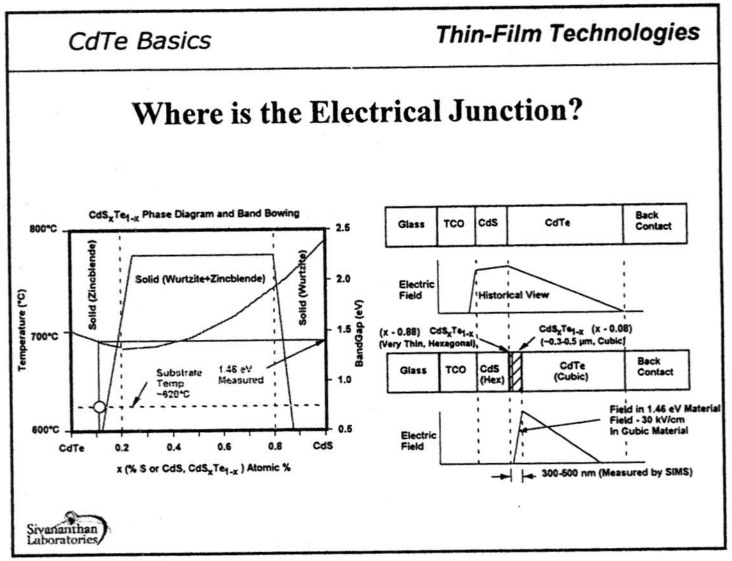
CdTe Basics **Thin-Film Technologies**

Combined Effects of Substrate Temperature and CdCl2 Treatment

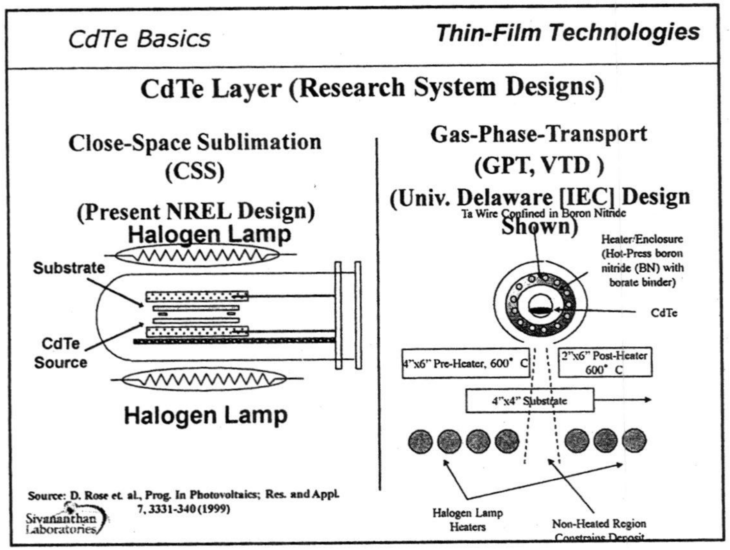
1-45



Where is the Electrical Junction?

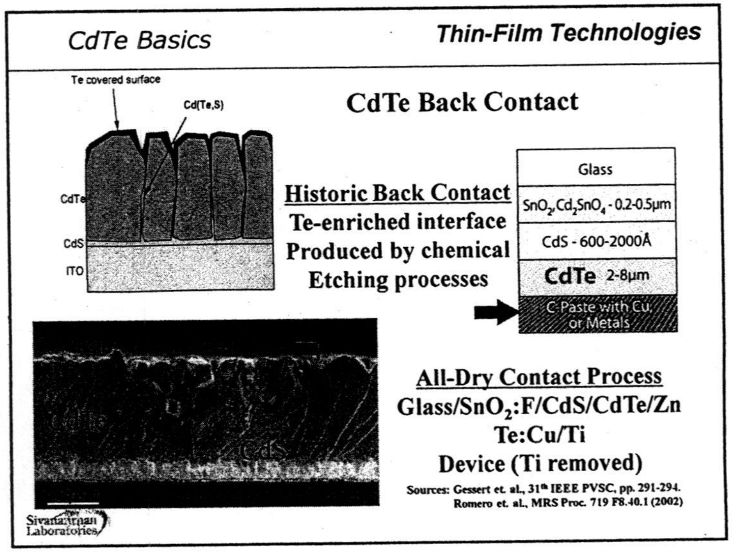


CdTe Layer (Research System Designs)



Source: D. Rose et. al., Prog. In Photovoltaics; Res. and Appl. 7, 3331-340 (1999)

CdTe Back Contact



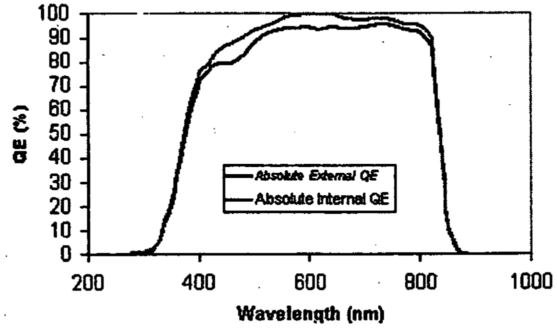
Historic Back Contact
Te-enriched interface
Produced by chemical
Etching processes

All-Dry Contact Process
Glass/SnO$_2$:F/CdS/CdTe/Zn
Te:Cu/Ti
Device (Ti removed)

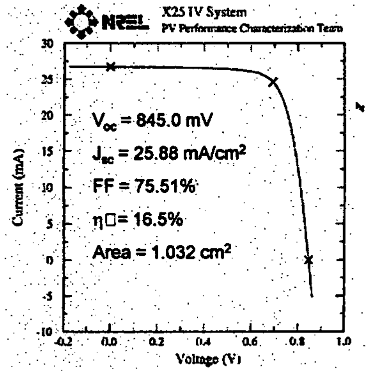
Sources: Gessert et. al., 31th IEEE PVSC, pp. 291-294.
Romero et. al., MRS Proc. 719 F8.40.1 (2002)

A4-2

Quantum Efficiency of a CTO/ZTO/CdS/CdTe Solar Cell



I-V Curve of a CTO/ZTO/CdS/CdTe Cell



V_{oc} = 845.0 mV

J_{sc} = 25.88 mA/cm^2

FF = 75.51%

η□= 16.5%

Area = 1.032 cm^2

Cell QE losses for 2 cases

	Thick CdS (250 nm) with commercial SnO_2	Thin CdS (80 nm) with CTO/ZTO
TCO	4.4 mA/cm^2	0.74 mA/cm^2
Reflection	1.7 mA/cm^2	1.19 mA/cm^2
CdS	5.8 mA/cm^2	1.4 mA/cm^2
Deep penetration	1.1 mA/cm^2	
J_{sc}	17.6 mA/cm^2	25.65 mA/cm^2
J_{max}	30.5 mA/cm^2	29.5 mA/cm^2
Losses	12.9 mA/cm^2	3.5 mA/cm^2

Efficiency loss mechanisms

Comparing CdTe devices with GaAs which has a similar bandgap:

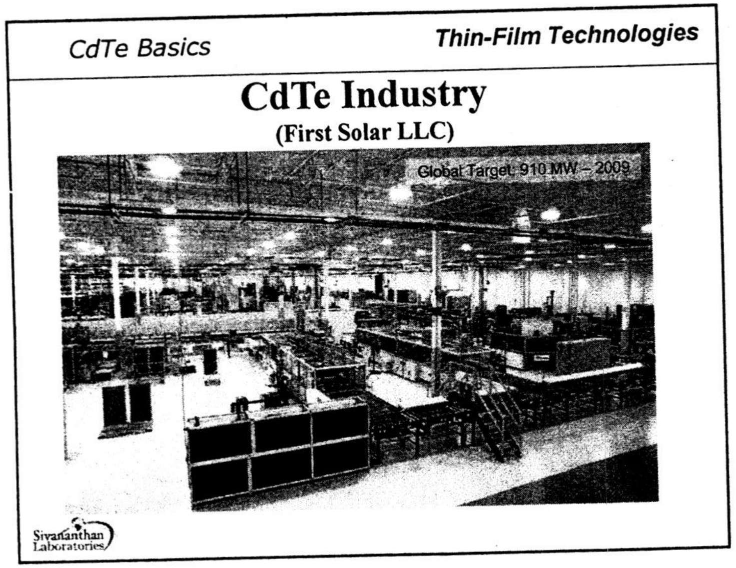
a) Difference in J_{sc} is minimal, the losses are well understood

b) Loss in Voc is ~ 200 mV. Due to a large diode quality factor (1 vs 1.9), the difference at V_{mp} is even more ~ 300 mV. Due to additional recombination losses, excess forward current for CdTe 2 orders of magnitude higher.

c) Of the 9.2 % efficiency difference, most of the losses attributed to poly-crystallinity.

d) In addition to the increased recombination, poly-crystallinity also results into non-uniformity resulting in further performance loss.

D4-3



CdTe Basics ***Thin-Film Technologies***

CdTe Industry

(First Solar LLC)

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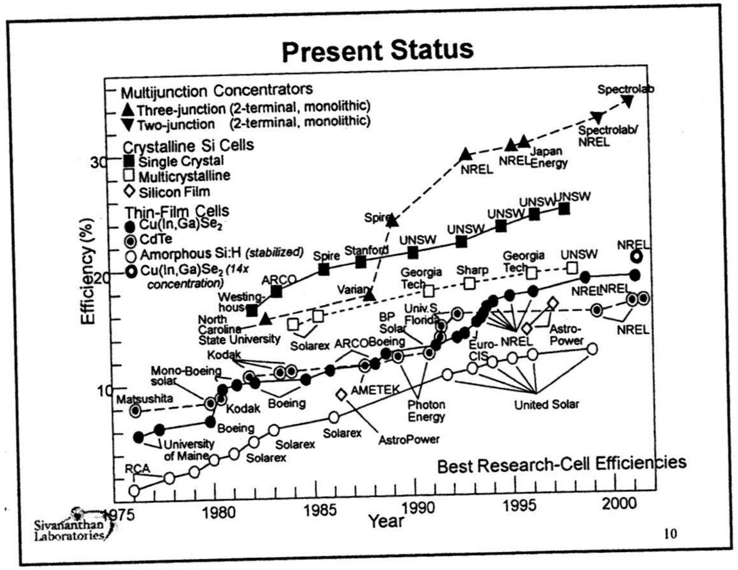

Present Status

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10

DB-1

Electrical Properties and Module Design

Ramesh G. Dhere
Strategic Advisor, Sivananthan Laboratories,
Bollingbrook, Illinois, USA

Sivananthan Laboratories

Device Analysis

Key device parameters for device performance

- Diffusion length – function of mobility (μ) and lifetime of the carriers. determines the collection efficiency of carriers, determines J_{sc}.
- Carrier density determines the resistivity and position of Fermi level of the semiconductor. Relevant for FF and V_{oc}.
- Lifetime (τ) of minority carriers is affected by the recombination which determines the dark current (J_0)of the diode. V_{oc} is function of the ratio of J_{sc}/J_0.

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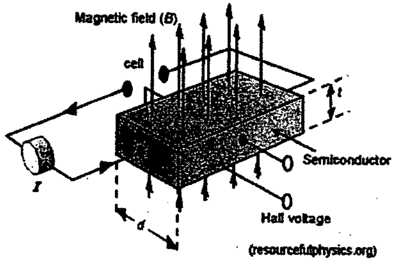
THE HALL EFFECT

- •Lorentz Force:
- •F = q[E + (v x B)]



(resourcefulphysics.org)

- •Hall voltage is produced by charge accumulation on sidewalls
- •Charge accumulation balances Lorentz Force
- •Charge accumulation increases resistance

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THE HALL EFFECT: SEMICONDUCTORS

What we can learn

- Sign of charge carrier
- Charge carrier density
- Charge carrier mobility
- Temperature dependence of mobility gives the indication of dominant scattering mechanism (important for thin film devices to optimize properties)

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AB-2

HALL VOLTAGE

For simple conductors

$$V_H = \frac{-IB}{ned} = R_H \frac{IB}{d}$$

Where n = carrier density, d = conductor length

- R_H is known as the Hall coefficient
- $V_H \propto B$ → Useful for measuring B-Fields

HALL COEFFICIENT

- Semiconductors have two charge carriers

$$R_H = \frac{-n\mu_e^2 + p\mu_h^2}{e(n\mu_e^2 + p\mu_h^2)^2}$$

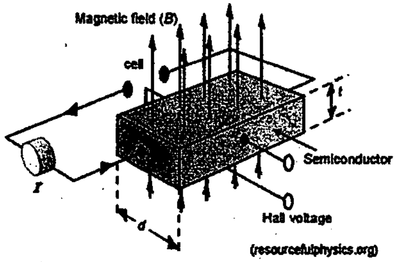
- However, for large magnetic fields

$$R_H = \frac{1}{(p-n)e}$$

- Enables us to determine the carrier density

THE HALL EFFECT

- Lorentz Force:
- F = q[E + (v x B)]



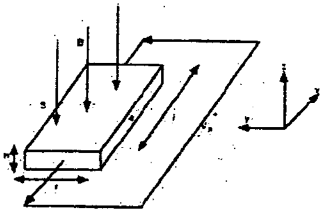
(resourcefulphysics.org)

- Hall voltage is produced by charge accumulation on sidewalls
- Charge accumulation balances Lorentz Force
- Charge accumulation increases resistance

THE HALL EFFECT: SEMICONDUCTORS

- **Why Semiconductors?**
  - Ideal number of charge carriers
  - Charge carriers increase with temperature

- **What we can learn**
  - Sign of charge carrier
  - Charge carrier density
  - Charge carrier mobility



HALL VOLTAGE

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HALL COEFFICIENT

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- However, for large magnetic fields

$$R_H = \frac{1}{(p-n)e}$$

- Enables us to determine the carrier density
- Combine with σ = neμ to determine n and μ

Temperature Dependence

☼ Temperature dependence of carrier mobility μ(T) dependent on the dominant scattering mechanism, thus *elastic scattering* with change in energy on scattering   kT described in terms of the average relaxation time between scattering events $\langle\tau_r(E)\rangle$ given by

$$\mu(T) = \frac{q\langle\tau_r(E)\rangle}{m^*_{cond}}$$

where m^*_{cond} is the conductivity effective mass.

Elastic Scattering

- Most important types of elastic scattering in semiconductors by acoustic lattice waves or acoustic phonons for which $\tau_r(E) \propto E^{-1/2}$ and the acoustic mobility proportional to $T^{-3/2}$ and by charged impurity scattering for which $\tau_r(E) \propto E^{3/2}$ and the impurity mobility proportional to $T^{+3/2}/N_I$ where N_I the charged impurity density.

DB-4

Grain Boundary Scattering

- In polycrystalline material, grain boundary potentials may influence overall mobility, introducing an apparent increase in overall mobility with temperature.
- The temperature dependence of mobility summarized in following figure.

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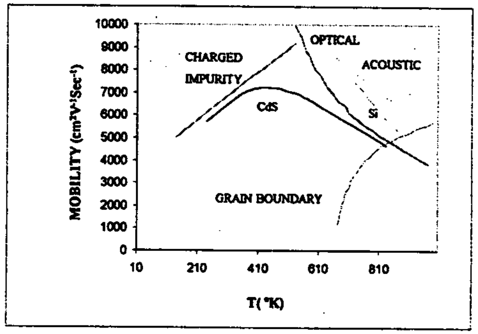
Mobility Variation



Total Mobility

☼ Several modes always present and the total mobility obtained by the addition of reciprocals,

$$\frac{1}{\mu}=\frac{1}{\mu_a}+\frac{1}{\mu_i}+\frac{1}{\mu_{gb}}$$

☼ The temperature dependence for one-carrier conductivity σ_n of an n-type material given by

$$\sigma_n = qN_c\mu_n(T)e^{[-\frac{(Ec-Ef)}{kT}]}$$

Arrhenius Conductivity Plot

- A straight-line plot of ln σ_n versus 1/T with a slope of $-(E_c - E_F)/kT$ *only* if all other temperature dependences cancel out such as in the simplest case of scattering of electrons by packets acoustic lattice wave or acoustic phonons for which the acoustic mobility proportional to $T^{-3/2}$ which just cancels the temperature dependence of N_c.

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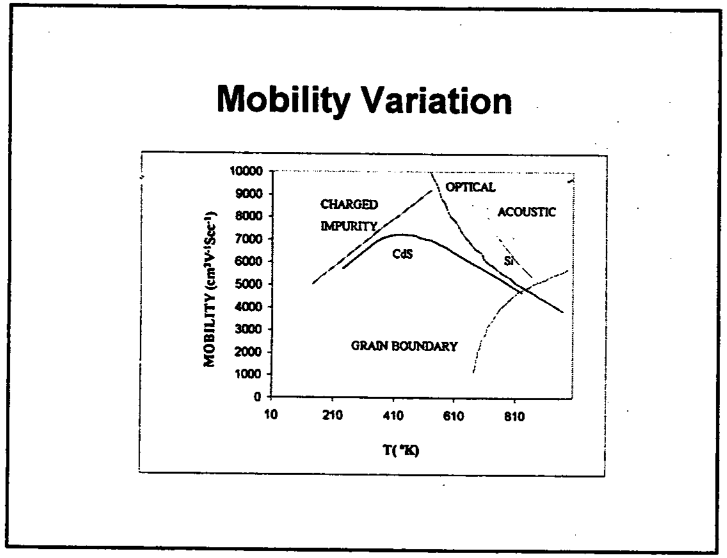
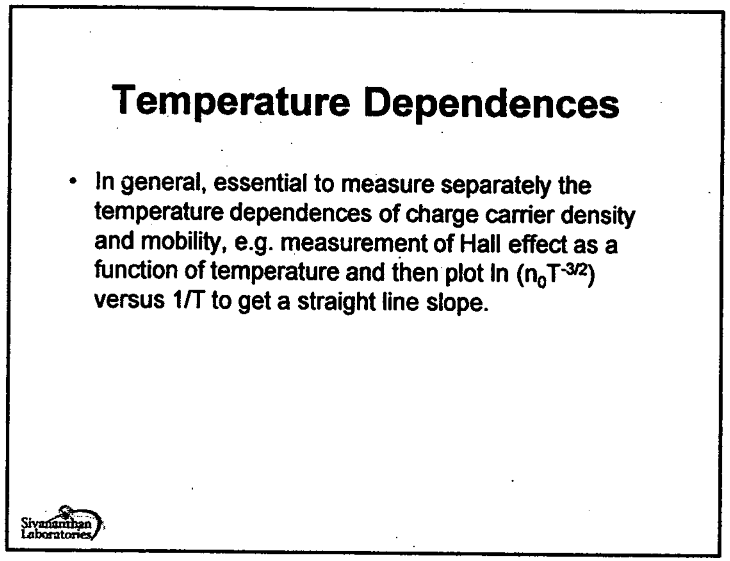
DB-5

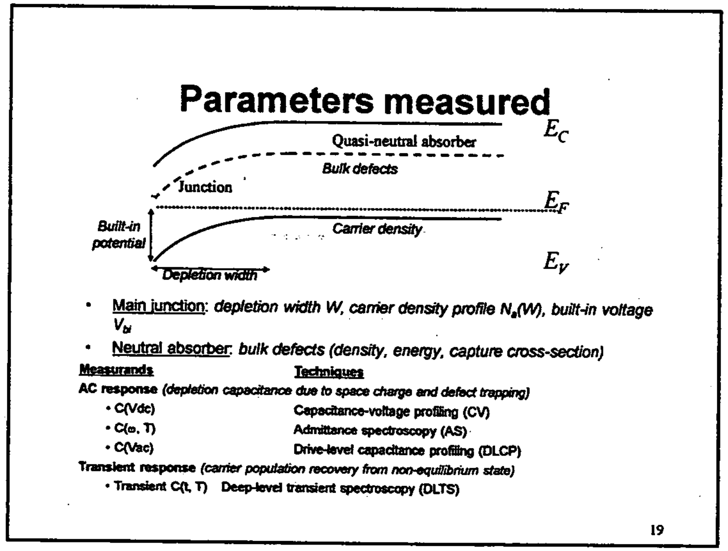


Mobility Variation



Temperature Dependences

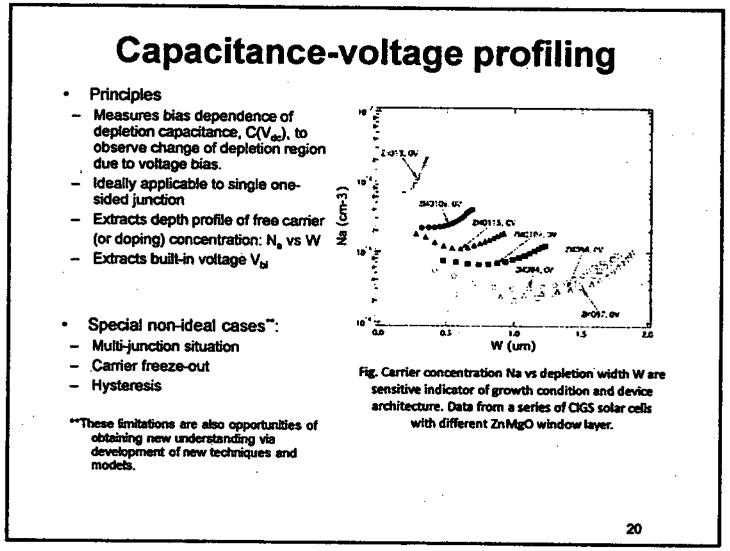
- In general, essential to measure separately the temperature dependences of charge carrier density and mobility, e.g. measurement of Hall effect as a function of temperature and then plot ln ($n_0T^{-3/2}$) versus 1/T to get a straight line slope.



Parameters measured

- Main junction: *depletion width W, carrier density profile $N_a(W)$, built-in voltage V_{bi}*
- Neutral absorber: *bulk defects (density, energy, capture cross-section)*

Measurands	**Techniques**
AC response *(depletion capacitance due to space charge and defect trapping)*	
• C(Vdc)	Capacitance-voltage profiling (CV)
• C(ω, T)	Admittance spectroscopy (AS)
• C(Vac)	Drive-level capacitance profiling (DLCP)
Transient response *(carrier population recovery from non-equilibrium state)*	
• Transient C(t, T)	Deep-level transient spectroscopy (DLTS)



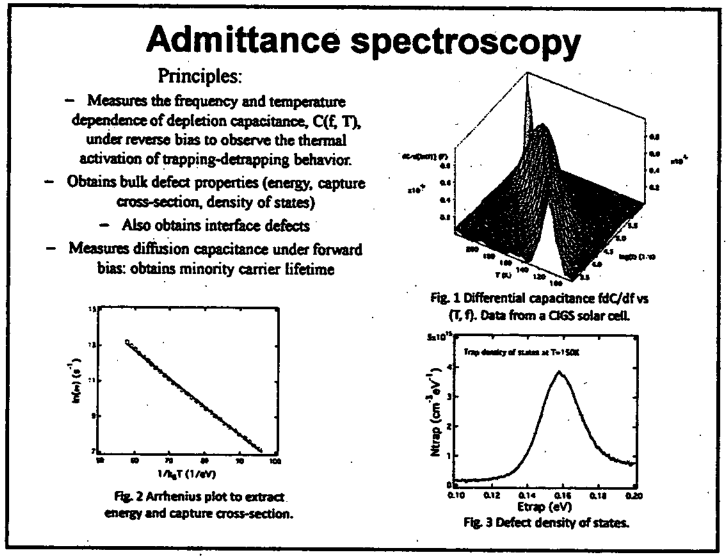
Capacitance-voltage profiling

- Principles
  - Measures bias dependence of depletion capacitance, $C(V_{dc})$, to observe change of depletion region due to voltage bias.
  - Ideally applicable to single one-sided junction
  - Extracts depth profile of free carrier (or doping) concentration: N_a vs W
  - Extracts built-in voltage V_{bi}
- Special non-ideal cases**:
  - Multi-junction situation
  - Carrier freeze-out
  - Hysteresis

**These limitations are also opportunities of obtaining new understanding via development of new techniques and models.

Fig. Carrier concentration Na vs depletion width W are sensitive indicator of growth condition and device architecture. Data from a series of CIGS solar cells with different ZnMgO window layer.

DR-6



Admittance spectroscopy

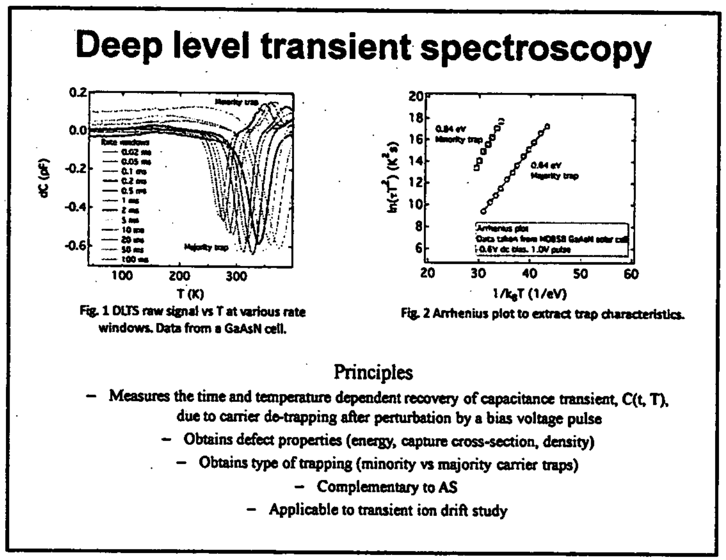
Principles:

- Measures the frequency and temperature dependence of depletion capacitance, C(f, T), under reverse bias to observe the thermal activation of trapping-detrapping behavior.
- Obtains bulk defect properties (energy, capture cross-section, density of states)
  - Also obtains interface defects
- Measures diffusion capacitance under forward bias: obtains minority carrier lifetime

Fig. 1 Differential capacitance fdC/df vs (T, f). Data from a CIGS solar cell.

Fig. 2 Arrhenius plot to extract energy and capture cross-section.

Fig. 3 Defect density of states.



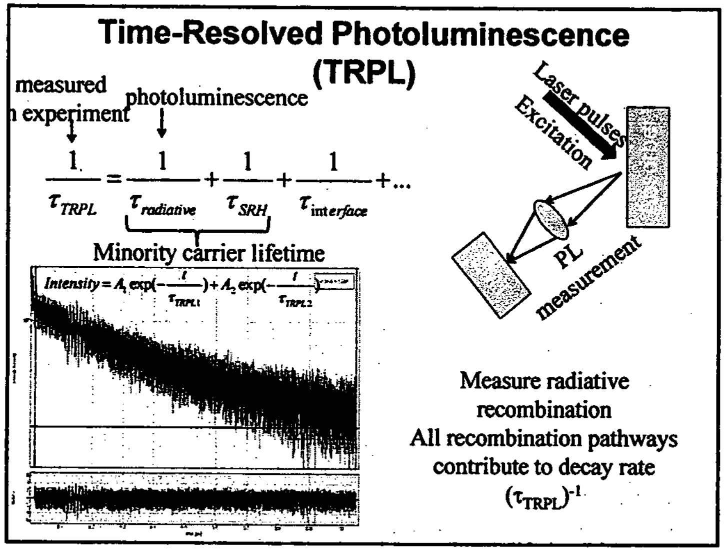
Deep level transient spectroscopy

Fig. 1 DLTS raw signal vs T at various rate windows. Data from a GaAsN cell.

Fig. 2 Arrhenius plot to extract trap characteristics.

Principles

- Measures the time and temperature dependent recovery of capacitance transient, C(t, T), due to carrier de-trapping after perturbation by a bias voltage pulse
  - Obtains defect properties (energy, capture cross-section, density)
  - Obtains type of trapping (minority vs majority carrier traps)
  - Complementary to AS
  - Applicable to transient ion drift study



Time-Resolved Photoluminescence (TRPL)

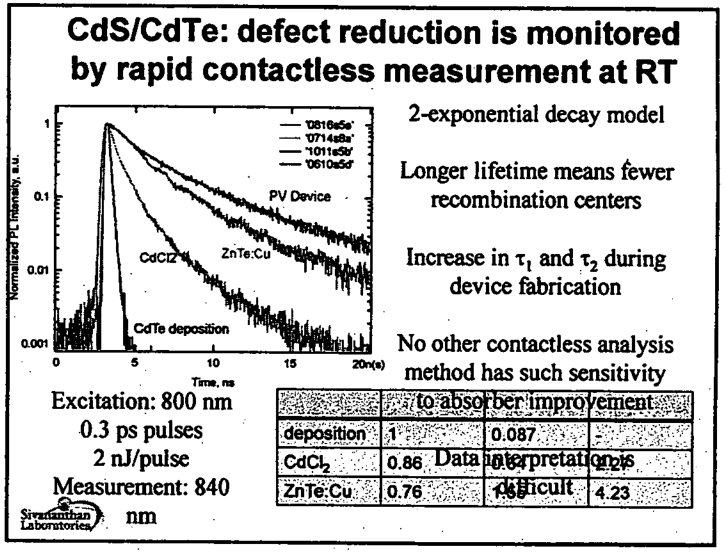
measured in experiment ↓ photoluminescence ↓

$$\frac{1}{\tau_{TRPL}}=\underbrace{\frac{1}{\tau_{radiative}}+\frac{1}{\tau_{SRH}}}_{\text{Minority carrier lifetime}}+\frac{1}{\tau_{interface}}+\ldots$$

$$Intensity=A_1\exp\left(-\frac{t}{\tau_{TRPL1}}\right)+A_2\exp\left(-\frac{t}{\tau_{TRPL2}}\right)$$

Measure radiative recombination

All recombination pathways contribute to decay rate $(\tau_{TRPL})^{-1}$



CdS/CdTe: defect reduction is monitored by rapid contactless measurement at RT

2-exponential decay model

Longer lifetime means fewer recombination centers

Increase in τ_1 and τ_2 during device fabrication

No other contactless analysis method has such sensitivity to absorber improvement

deposition	1	0.087	-
$CdCl_2$	0.86	0.64	2.27
ZnTe:Cu	0.76	1.65	4.23

Data interpretation is difficult

Excitation: 800 nm
0.3 ps pulses
2 nJ/pulse
Measurement: 840 nm

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