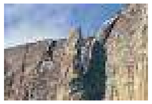

Vacuum Coating Process Issues for Photovoltaic Devices

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* (Written paper available on request)

Outline

Market requirements

Volume, cost

Available device technologies and structures

Amorphous silicon: cheap, stable materials

CdTe (not commercially viable due to Cd)

Cu(In,Ga)Se$_2$*: high efficiency (15% on foil)*

Inorganic/organic hybrid

Organic

Others (e.g. Spheral Solar)

Critical coating issues

Deposition rates

Equipment cost

Availability of small-scale equipment

Photovoltaic requirements

Market needs:

- <$1/W module cost (*minimum)*
- <$0.50/W module cost (preferred)
  (Corresponds to $2/W installed cost to customer)
- >15 year lifetime
  (The longer the better, but frequency of re-roofing may dominate)
- >7% efficiency
  (10-15 preferred for some applications)

Existing solutions:

c-Si:

- ~$2.50-$3.00/W, with limited potential for decrease
- >25 years (contact and system limited)
- >15% efficiency (SunPower claims 20%)
- Rigid, heavy

System issues

From $/m^2 to $/W: Peak solar intensity is ~1000 W/m^2

E.g., at 7% efficiency, $35/m^2 = $0.50/W

Add profit margin, installation costs, etc.: ⟶ $2/W, which corresponds to ~8¢/kWh

Photovoltaic modules are more than one layer of material...

- Metal electrode
- Transparent electrode
- Encapsulation
- Series interconnection
- Current collectors
- Module integration

Lowering the cost of just one layer does not solve the problem

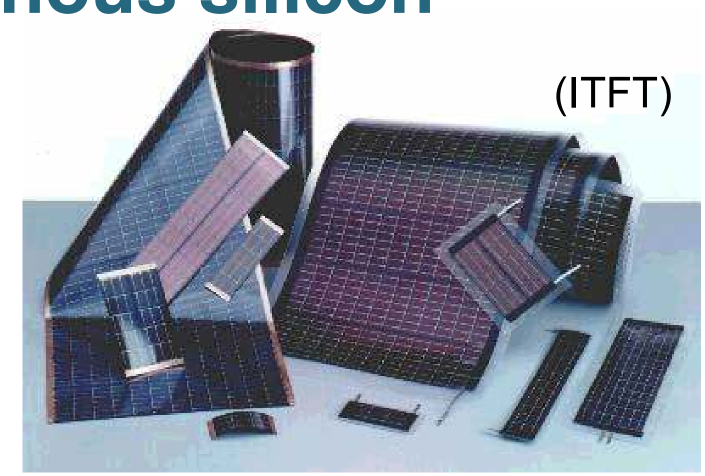
Encapsulation materials are expensive (fluoropolymers): ~$8/m^2 or more

Relatively high conductivity needed in TCO ⇒ thick film (~1 micron)

See J.R. Sheats, *J. Mater. Res.* **19,** 1974-1989 (2004); "Manufacturing and Commercialization Issues for Organic Electronics" for a discussion of costs of various thin film processes in the context of electronic devices

Amorphous silicon

TCO: 1-2 microns
p^+ Si: ~15 nm
i-Si: ~400 nm
n^+ Si: ~25 nm
Al: 0.5 – 1 micron
Substrate



- Deposition rate: conventionally ~0.1 nm/s (Si) and 1-10 (ZnO)
  Costs per film will be several $/m²
- Light-induced degradation 7 $\rightarrow$ 5%; eliminated by microcrystalline
  Still in R&D stage

Recent work (Eindhoven) up to 10 nm/s for nearly same quality (B.A. Korevaar, et al., *MRS Proc.*, 2003?)

- Netherlands' group (commercialized by Shell/Akzo Nobel) projects that they will achieve the magic \$0.50/W_p and \$35/m^2 with a tandem a-Si structure, using APCVD for F:SnO_2 on Al foil, which is etched away after lamination of plastic to top of finished cell.

Roll-to-roll amorphous silicon activity

Unisolar (stainless steel): S. Guha, et al., *Prog. Photovoltaics: Res. Appl.* **8**, 141 (2000)

Iowa Thin Film Technologies (PI): D. Grimmer, et al., *Int. J. Solar Energy* **18**, 205 (1996)

VHF Technologies (PI)

Sanyo (stainless steel)

❑ **Akzo Nobel/Shell** (Al/polymer): R.E.I. Schropp, et al., *MRS Proc.* **557**, 713 (1999); Flexible Displays and Electronics Conference, San Francisco, May 2004

o **Fuji Electric** (unspecified polymer): Y. Ichikawa, et al., *MRS Proc*. **557**, 703 (1999)

o **Teijin Ltd.** (PET): M. Yano, et al., *Thin Solid Films*,**146,** 75-81 (1987)

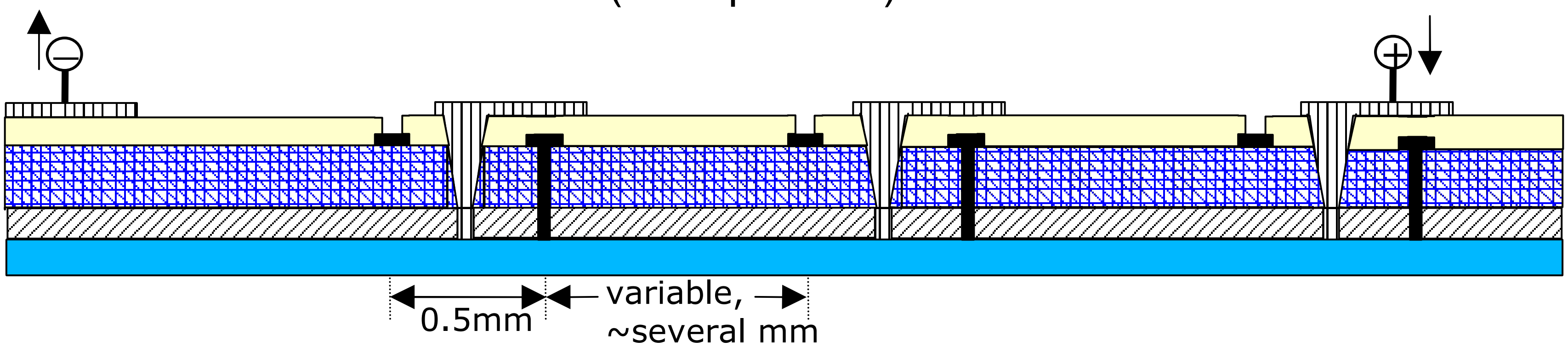
None of these companies is selling at a price below crystalline Si

❑ (pilot phase)

o (not in production)

Series interconnection

(ITFT process)



Prebake, surface prime, and metallization of web

Semiconductor coating

Laser scribe for isolation

Screen printing of insulator ink

Deposition of transparent conductor

Screen printing of conducting ink (metal)

Laser scribe of opens in transparent conductor

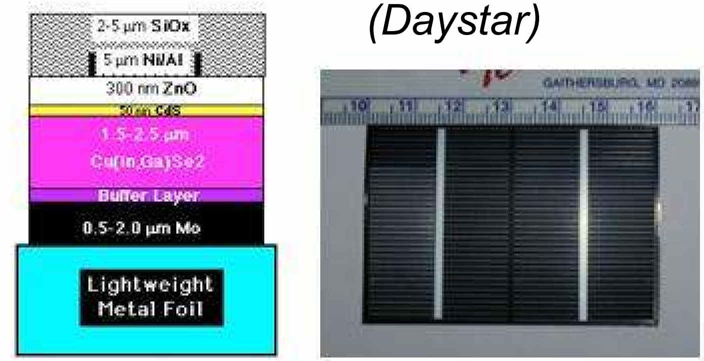
Laser welding of conducting ink metal to bottom metal

[Slitting, busbar attachment, and encapsulation]

CIGS

TCO: 0.3 – 1 micron
CdS: 50 nm
CIGS: 1.5 – 2.5 microns
Mo: 0.5 - 1 micron
Diffusion barrier
Substrate

(Daystar)



Thin-Film Space Solar Cell Schematic & Photograph

- High temperature (>450 – 500 C) anneal for up to 30 min. required
  - ⇒*only metal foil (though PI has been used)*
  - *Diffusion barrier required to prevent contamination from substrate*
- Very difficult to control stoichiometry of ternary/quaternary semiconductor
- Relatively thick layers compared to a-Si, and expensive materials

Recent work (ISET: www.isetinc.com) on nanoparticle "inks":
V.K. Kapur, et al., *Proc. Third World Conf. Photovoltaic Energy Conv., Osaka, Japan (2003):* 8% efficiency on PI

V.K. Kapur, et al., *29th IEEE Photovoltaic Spec. Conf., New Orleans, LA* (2002): 10% efficiency on Mo foil
Lab-scale work only (no roll-to-roll fabrication)

Roll-to-roll activity in CIGS

❖Global Solar (www.globalsolar.com); Evaporation/sputtering
NREL NCPV and Solar Program Review Meeting 2003: NREL CD-520-33586

Solarion (http://www.solarion-gmbh.de/): IBAD
Ion beam assisted deposition

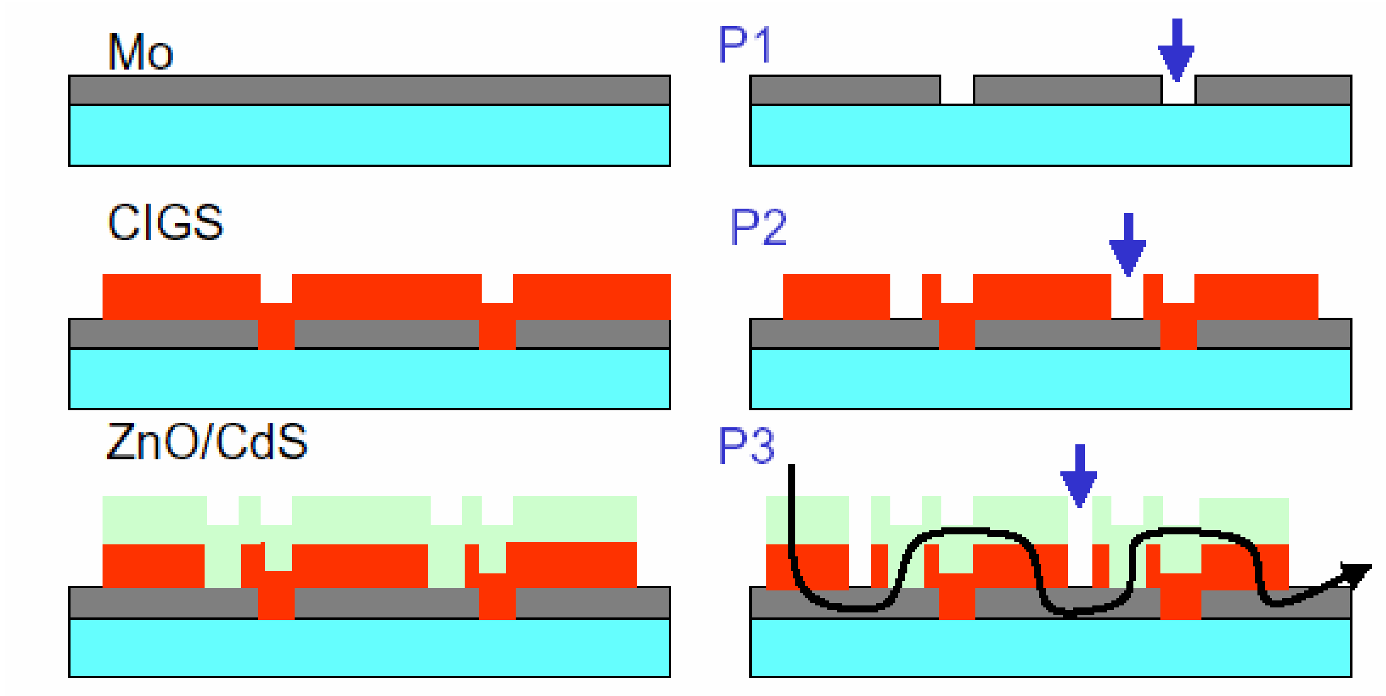
Miasole (http://www.miasole.com/start.asp): Sputtering
Cylindrical magnetrons
Claims up to 1 m/min.web speed (projected)

In pilot line development
R&D on in-line system; R2R projected for 2005

Critical issues for roll-to-roll CIGS processing:

- Long anneals
- Selenization (at high temperature)
- Stoichiometry control
- Thick films: web speeds of a few cm to a few inches/min. (NEDO, Univ. Del.)

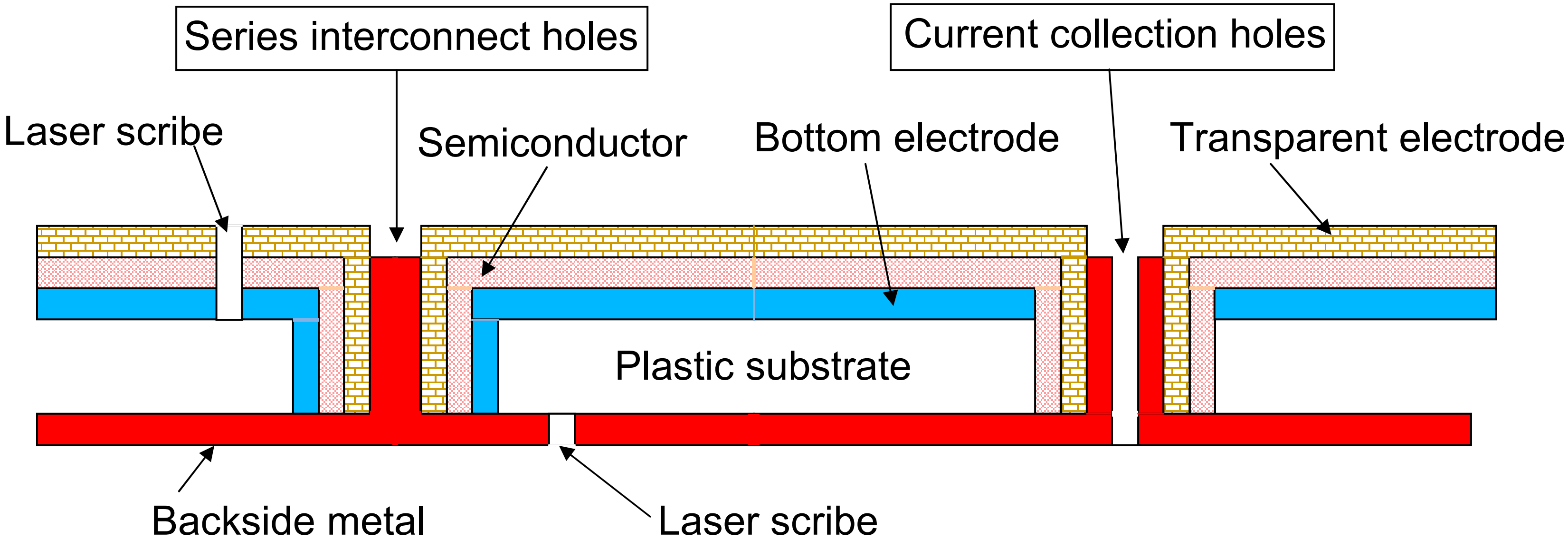
Series interconnect in CIGS



- Impossible to deposit all layers in a simple series
- Depth control required on laser etching

A unique roll-to-roll interconnection method

(Fuji Electric)



Process sequence:

1) Punch series interconnect holes
2) Deposit bottom electrode
3) Punch current collection holes
4) Deposit semiconductor
5) Deposit transparent electrode
6) Deposit backside metal
7) Laser scribes on both sides

Advantages:

- Minimal process control on laser etch
- No laser process until all depositions are finished
- Only one laser step

Only works with vacuum!

Organic and Hybrid Photovoltaics

- Konarka (www.konarkatech.com): dye-sensitized TiO_2
  (also owns rights to many all-organic patents)
- Nanosys (www.nanosysinc.com): CdTe nanotetrapods
  (with organic hole transport polymer)
- Numerous other licensees to ETH (Graetzel) technology
  (but none roll-to-roll)

For all-organic cells:

✗ Efficiency $\lesssim$ 3%; price < $1/W highly improbable
But, could go to $0.50/W or less at 5-10 %efficiency

? Lifetime: unproven but plausible in view of OLEDs

For dye-sensitized cells:

- Efficiency can be up to ~10%
  - Problems with sealing liquid containing cells
  - Stability of electrolyte

Cost implications for vacuum processing

Consider these two cost projections *(not yet demonstrated!)*:

- R2R a-Si solar cells (Utrecht et al.): **$35/m^2$**
  PECVD a-Si
  APCVD TCO (100 nm/sec)
  9 layers, 3 low-resolution patterning steps
- R2R silvered mirror (NREL): **$15/m2**
  2 µm IBAD Al_2O_3 (10-20 nm/sec)
  4 layers (*cf. C. Kennedy, et al., AIMCAL Proc., 2003)*

Though involving very different materials and structures, both processes have about the same cost/layer!

- a-Si appears to have a chance if the new high-rate CVD processes work
- CIGS is highly problematic due to thick layers and stringent stoichiometry control
- Organic/nanostructure approaches are still emerging

Other issues

- Cost of lowest-scale vacuum web coaters makes development difficult (solution coaters can be bought for $20k)
- Fractional utilization for expensive materials (e.g. indium) is poorer for vacuum deposition
- The opportunity at best lies with equipment suppliers, not with coaters

  E.g., ITO at $15-$20/m^2 cannot be sold to PV industry!
- Nevertheless, there will always* be a need for vacuum coating in PV (at minimum for the metal electrode)

  *(anyway for a long time...)

And the market is respectable:

2.6B m^2/yr, $400B (1996 consumption)

(assuming 10% efficiency and 25 year lifetime)

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