Photovoltaics and the Epoch of Renewable Energy

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NEW YORK TIMES, THURSDAY, FEBRUARY 27, 2003

From a White House Roof, Solar Power Proclaims Gains

By LISA GUERNSEY

THE White House may be occupied by an admin-

When light photons hit the silicon atoms, electrons break free, creating a direct current. An inverter turns the electricity into an alternating current that can be fed into the White House power grid.

power bills and government subsidies for the use of alternative energy.

Glenn Hamer, executive director of the Solar En-

Still, solar power makes up only 1 percent of the total energy generated in the United States, according to Mr. Hamer of the industries association

Evergreen Solar

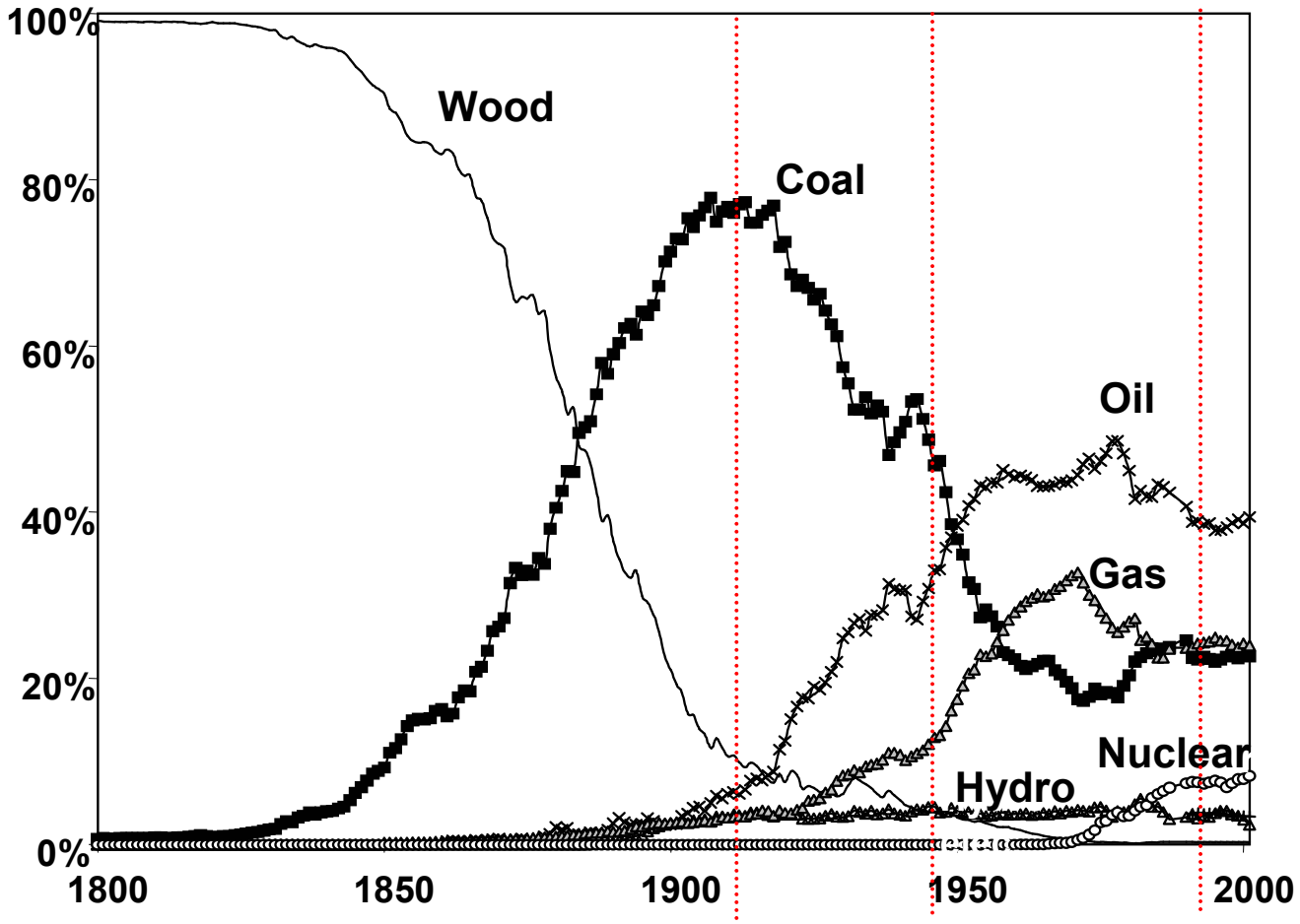
THE INSTALLATION

Bruce Newell of Evergreen Solar installing solar-cell panels on the roof of a maintenance shed at the southwest corner of the White House grounds.

THE PANELS

Each panel contains 36 cells connected by conductive strips or bus bars.

U.S. Historical Energy Use



British Navy converts to oil

WW II and aftermath

Gulf War 1

The Prize Daniel Yergin

The Players

- **Oil**
  - US oil production peaked in 1972 (Hubbert's peak)
  - Large Saudi fields are now yielding 30+% water
- **Coal**
  - Lots of it
  - Twice as much CO_2 per kW-h as Gas, 50% more than oil; can only rely on it if sequestration is practical and stable
- **Gas**
  - Candidate "transition" fuel, but will have same supply issues as oil (just delayed).
- **Nuclear**
  - Extraordinary challenges in disposal, proliferation, and defense against terrorist action.

Renewable Energy is Vital to our Nation and the World because:

- Fossil fuels are a finite resource.
- Our nation is dependent for survival on regimes that we would otherwise shun.
- Global warming is potentially devastating to ecology and economics.
- Nuclear electricity is very difficult to separate from Nuclear proliferation.

Current Energy Use: United States

- The U.S. uses approx. 100 Quads of energy per year. (1 Quad = 10^{15} BTU). 100 Quads ~ 100 Exajoules (1 Exajoule = 10^{18} Joule).
- The average power consumption of the U.S. is 3.3×10^{12} W.
- The average per capita power consumption in the U.S. is 13 kW.
  - We don't get to use all of this. For example, the 1.6 kW of electricity that each of us uses required 5 kW of heat energy (5 of 13).

Renewable Energy Sources

- Hydroelectricity
- Biomass
- Photovoltaics (PV) Solar to electricity
- Wind

Photovoltaics and Wind are complimentary in availability

Wind is more economical today, PV has the larger potential

Magnitude of Solar Resource

500 years worth of fossil energy = Amount of solar energy hitting the Earth in 500;

- Hours
- Days
- Months
- Years

Magnitude of Solar Resource

- At our latitude, the solar flux at mid-day on a clear day is 1000 W/m^2.
  - The average Including night and clouds is 200 W/m^2.
- The average solar power incident on Continental US is 1600. x 10^{12} W.
  - This is 500X the average power consumption in the U.S. (3.3 x 10^{12} W).

- If we cover 2% of the Continental US with 10% efficient PV systems, we would make all the energy we need*.
- For perspective:
  - 1.5% of the Continental US is covered with roads.
  - 40% is used to make food (20% crops, 20% grazing)

* Past 5% of total energy storage is needed

Rural electrification

- Drivers:
  - 2 billion people without electricity world-wide

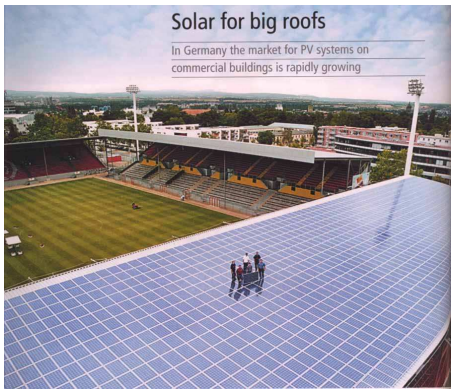
- Applications:
  - Solar home systems
  - Village power
  - Water pumping
  - Telecommunications

Wireless power

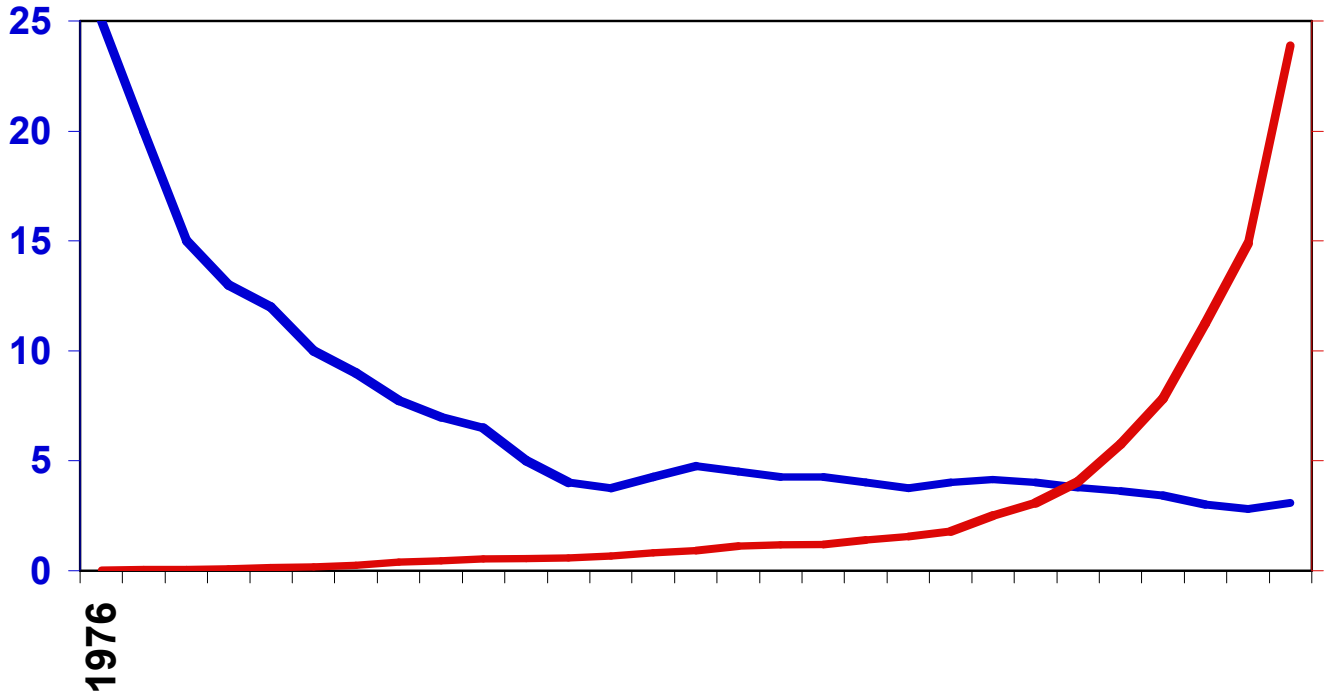
- Drivers:
  - Lowest cost for remote requirements
  - Power line extension cost $10,000 to $30,000 per mile
- Applications:
  - Telecommunications
  - Vacation homes
  - Irrigation
  - Billboard and street lighting
  - Instrumentation, traffic signals

On-grid Market

- Drivers:
  - Reduce Peaking Loads
  - Government subsidies
  - Environmental orientation
- Applications:
  - Residential
  - Commercial / industrial
  - Cover the land



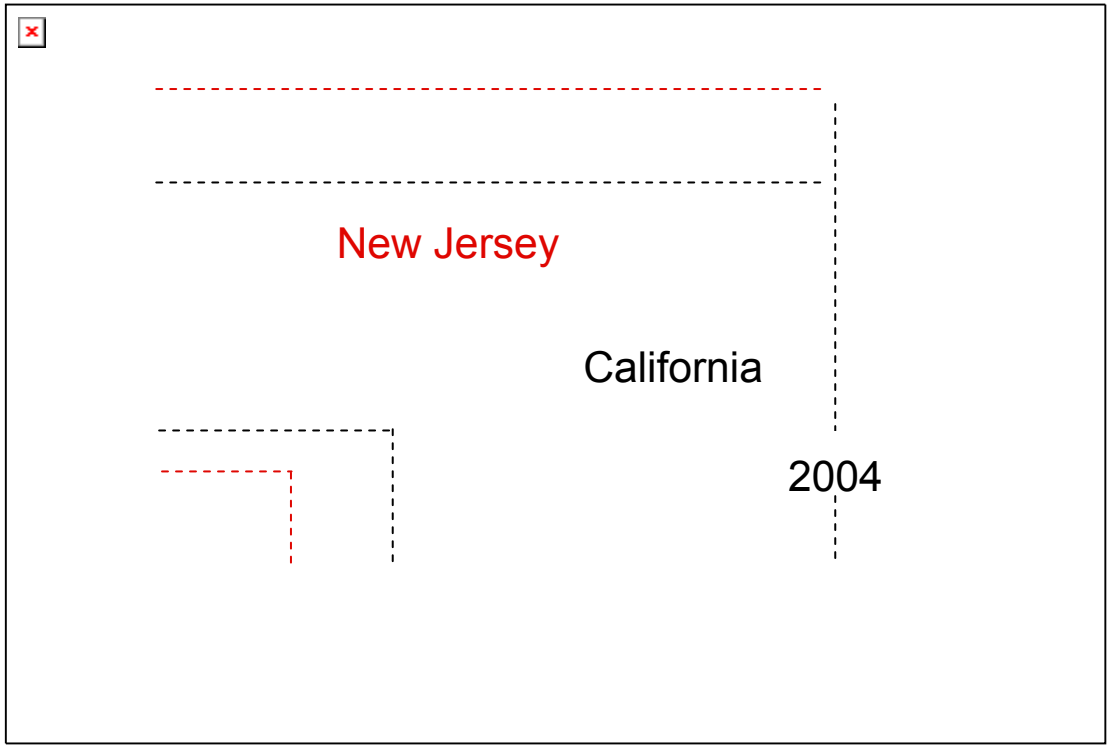
Declining Prices Build Markets



Price NOT adjusted for inflation

Shipments CAGR 2000-2005 > 35%

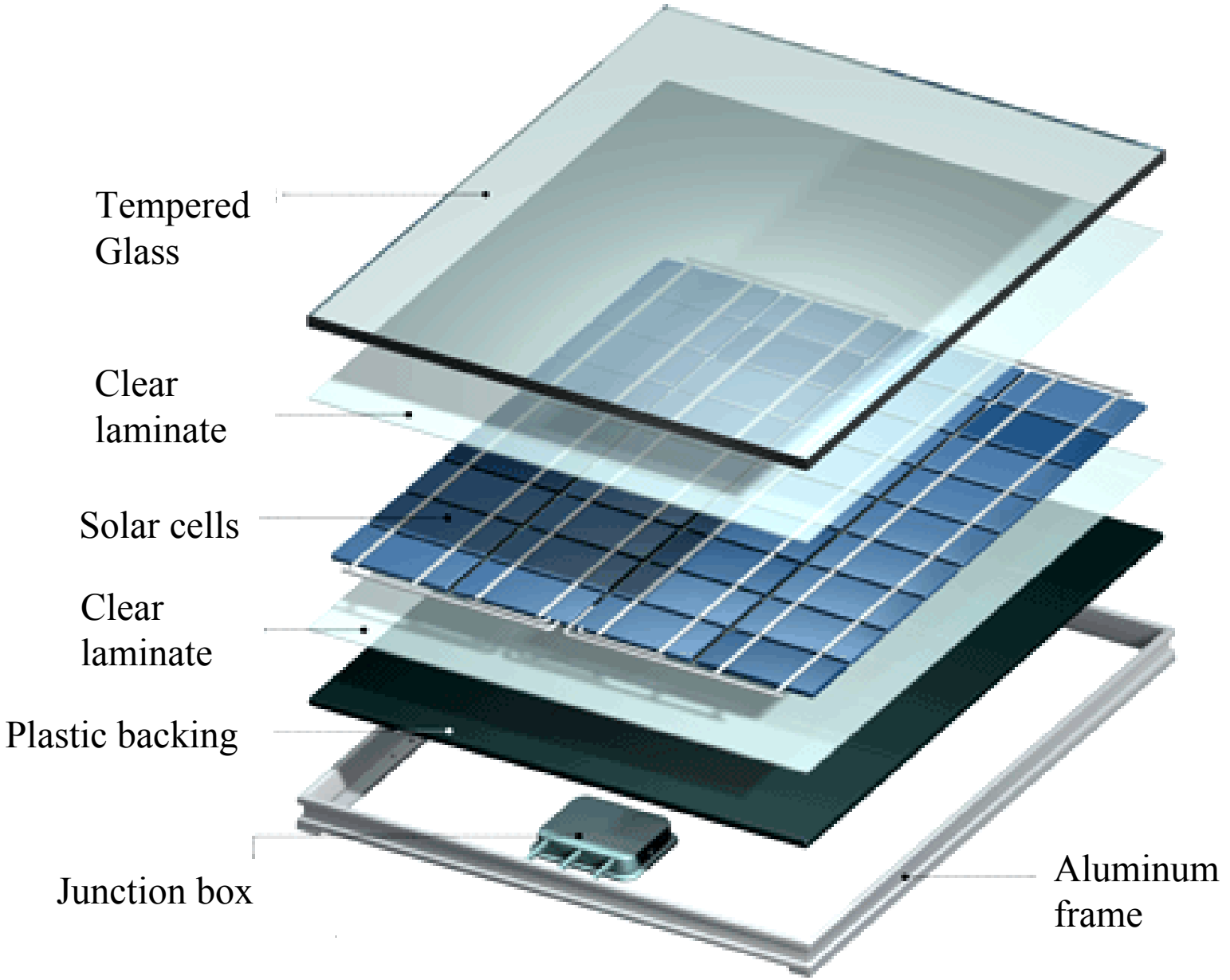
Cost Model



- Assumptions
  - –20 year system life
  - –6% interest rate
  - –No subsidies

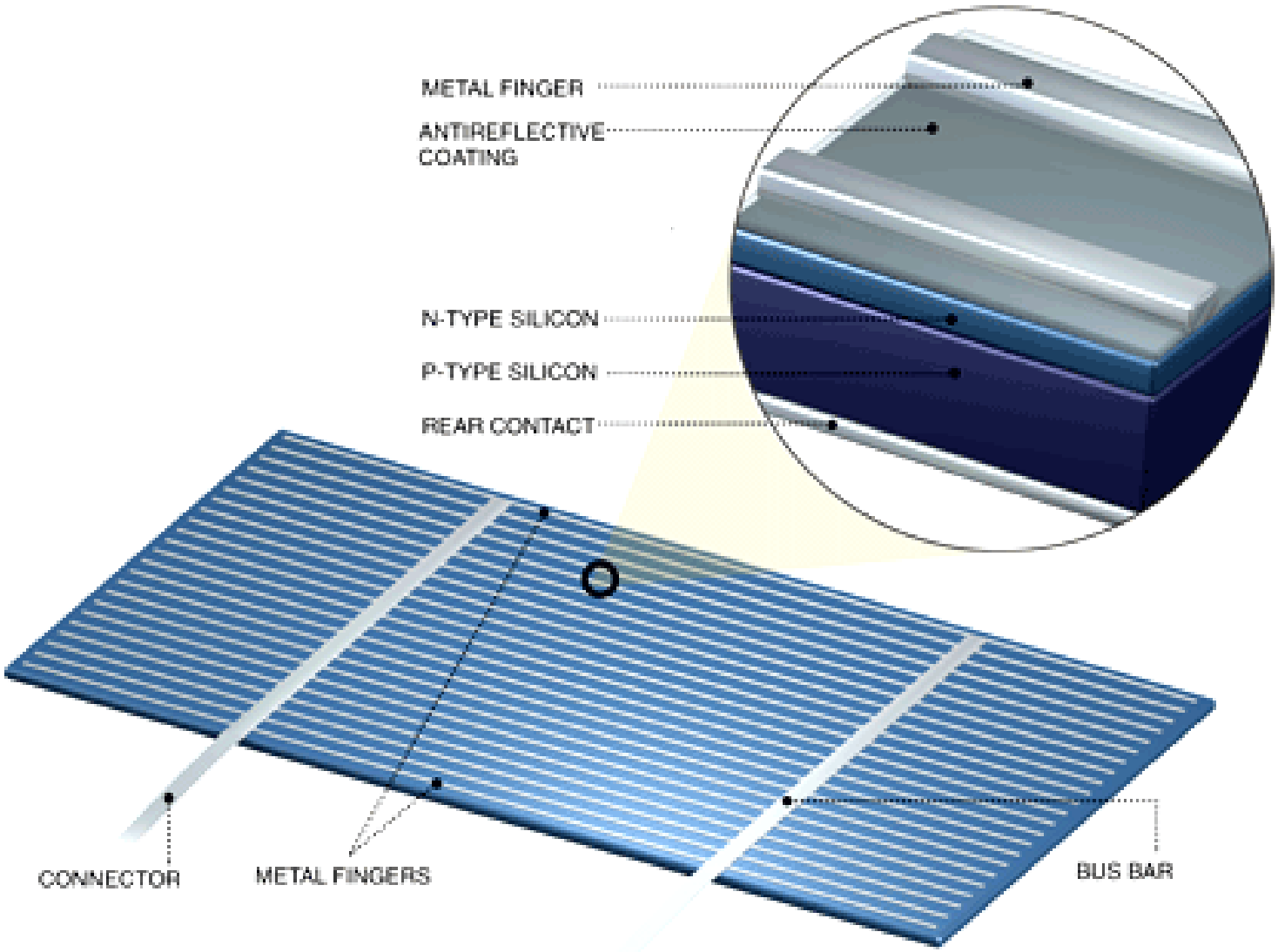
Must improve performance/cost by between and factor of 3 and 6

Detail of Solar Panel

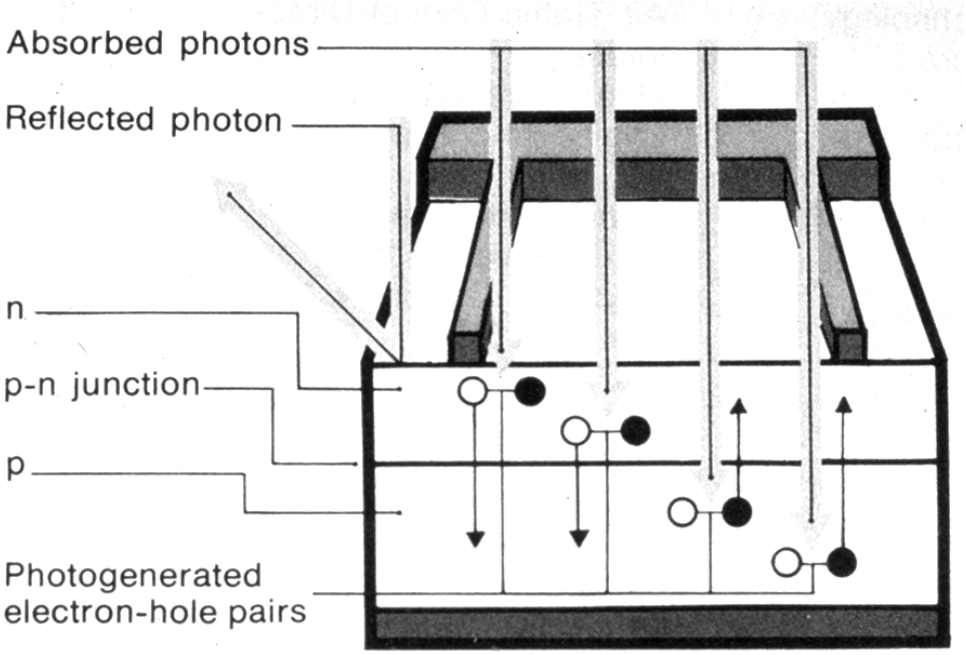


Lamination of Modules

Detail of Solar Cell

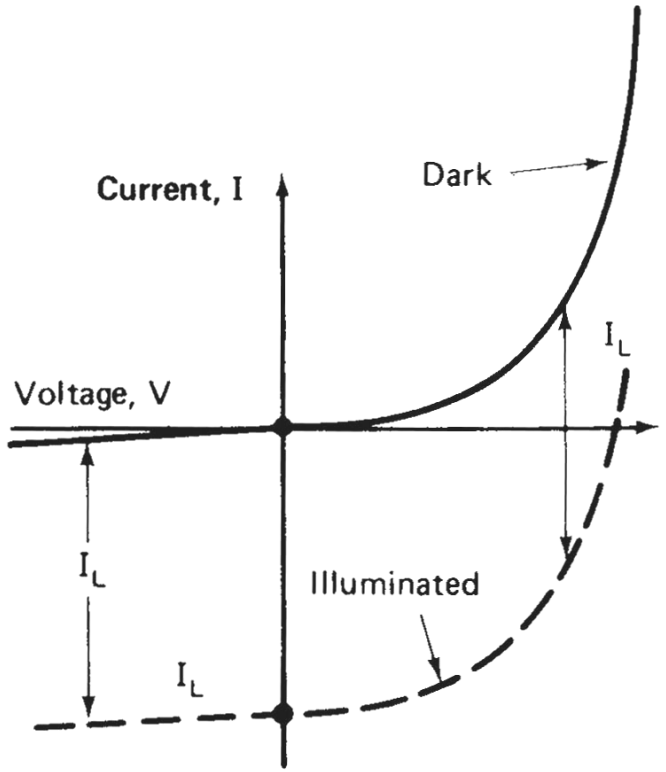


What Does a Solar Cell Do ?



● Electron: negative charge carrier

○ Hole: positive charge carrier



Crystalline Silicon; Where is the cost?

Technology steps

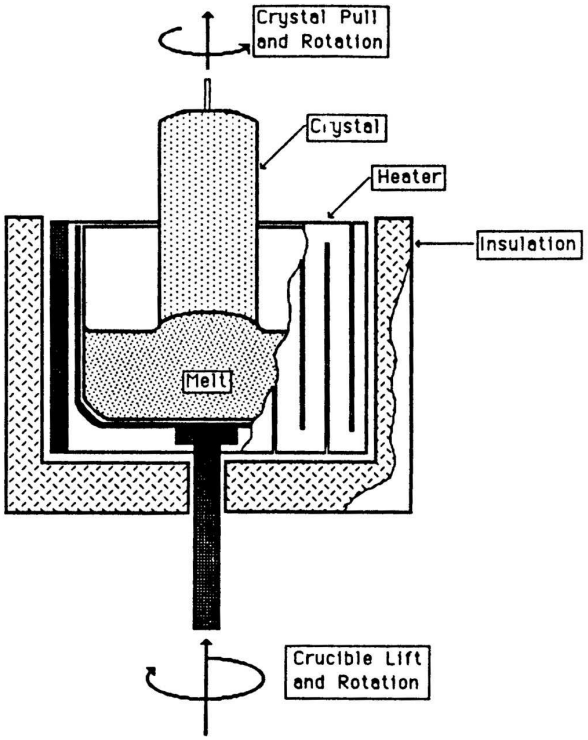
- Produce Wafers (40%)
- Fabricate Cells (30%)
- Interconnect and laminate - module (30%)

Producing wafers is the most expensive of the 3 steps

AND Cell fab and Module Fab have many steps

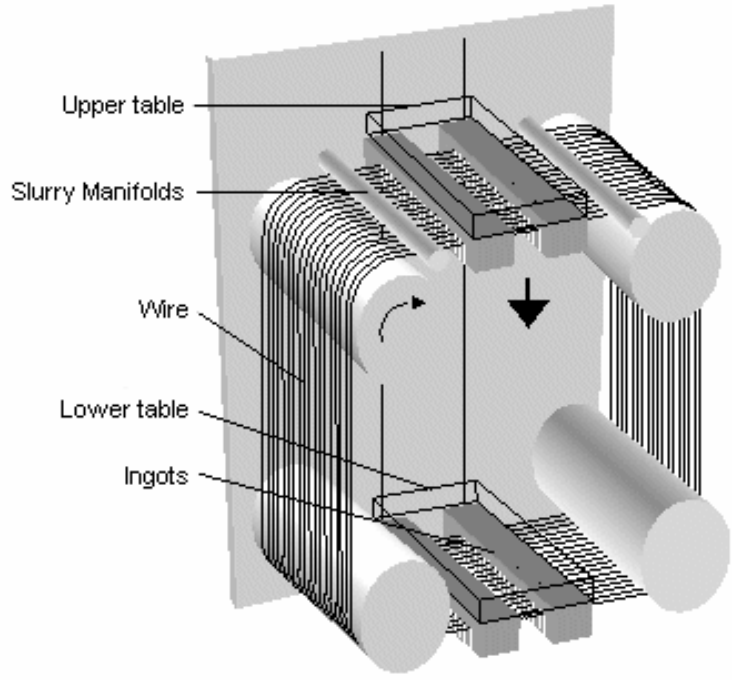
So, if you are going to work on one step - work on wafers

Mono-crystalline Wafers - Czochralski

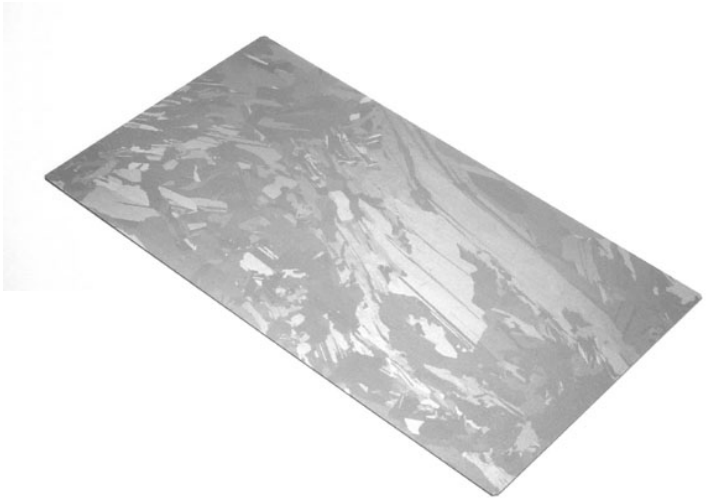


Cylindrical Ingots must be ground and sawn into wafers

Wire Saws



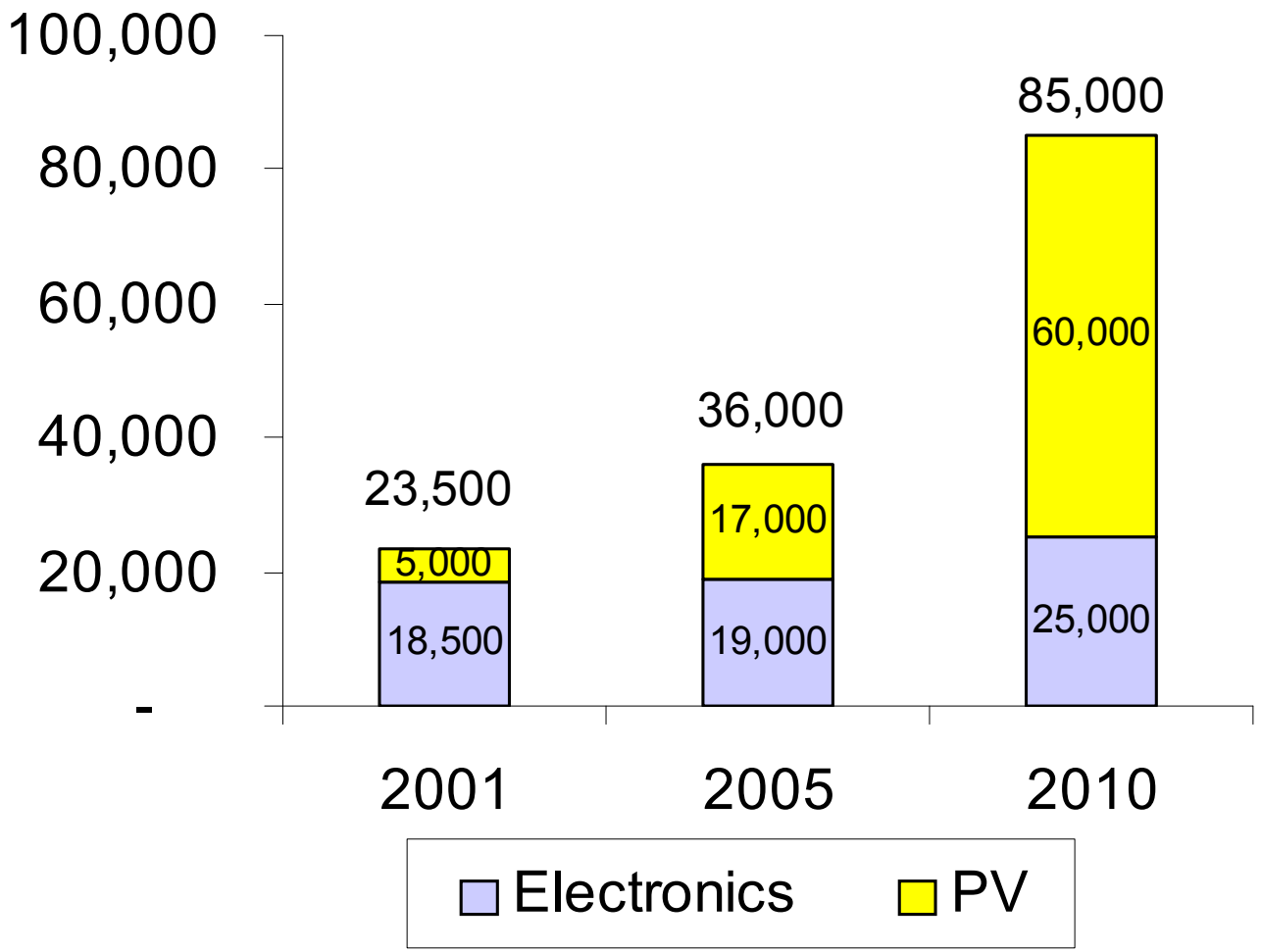
Cast Ingots - Multicrystalline Silicon



Cast Ingots must STILL be ground, sawn up and then etched

High purity Si usage

(Metric tons – rough estimate)

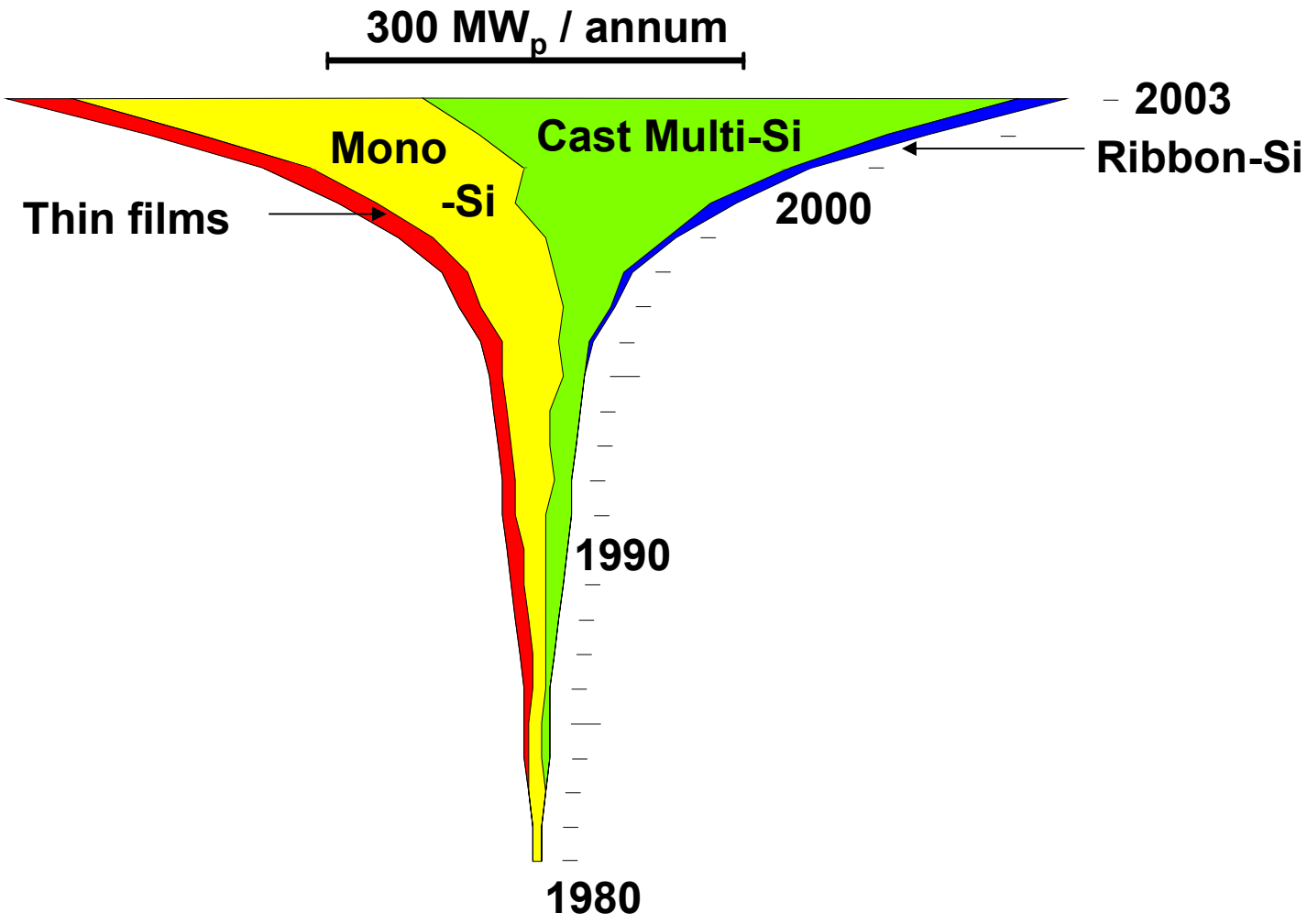


Note: “Usage” includes material used from production, from inventories and from recycling. “Usage” is gross usage, including loss.

Energy Payback - Poly Silicon

	Cast-Multi today	String Ribbon today	Future?
Energy cost poly	250 kW-hr/kg	250 kW-hr/kg	150 kW-hr/kg
thickness wafer	500 μ	200 μ	150 μ
efficiency of module	0.14	0.13	0.16
insolation	0.2	0.2	0.2
Years of operation for payback	1.2 yr	0.5 yr	0.2 yr

Development of Global PV Market



Courtesy: ISE Fraunhofer

Shaped Crystal Growth - Ribbon Growth

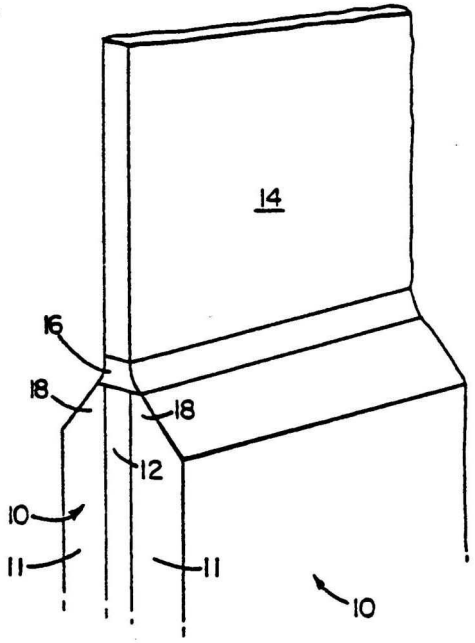


FIG. 1
PRIOR ART

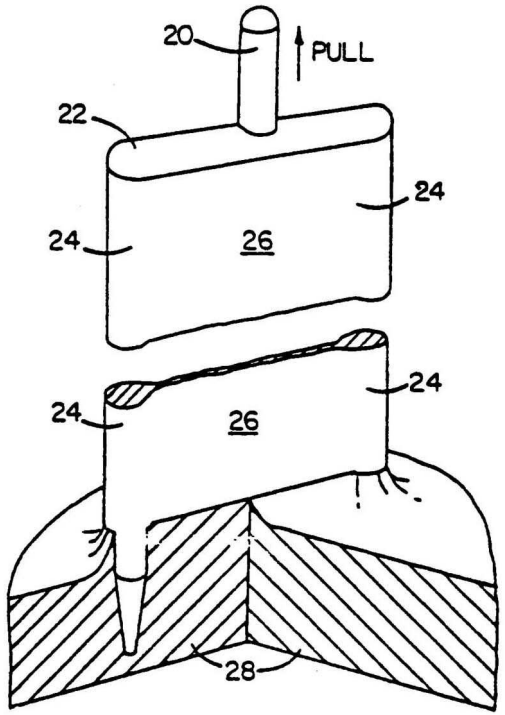


FIG. 2
PRIOR ART

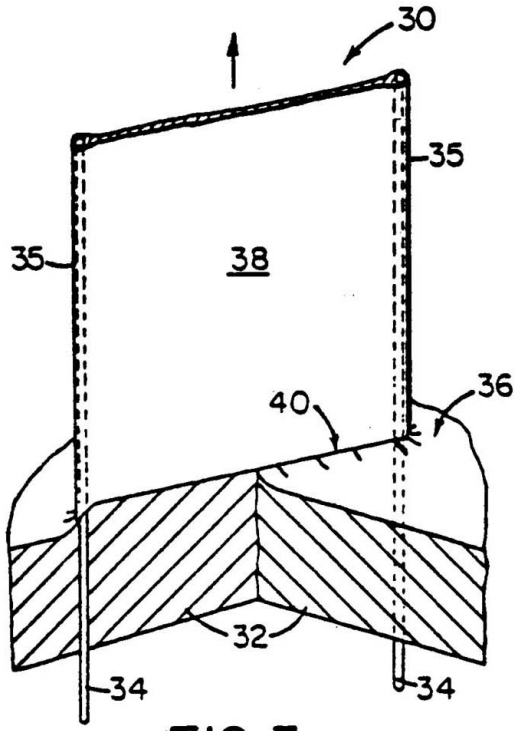
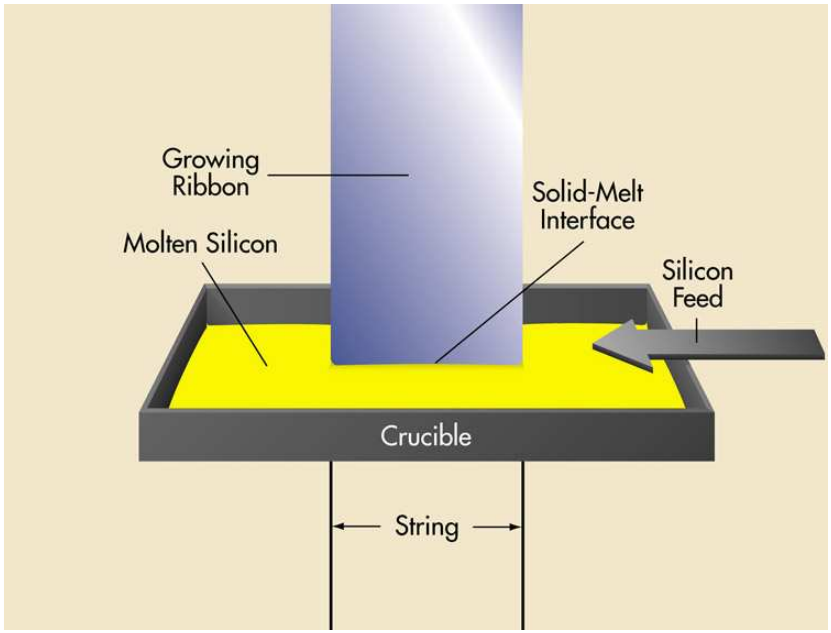
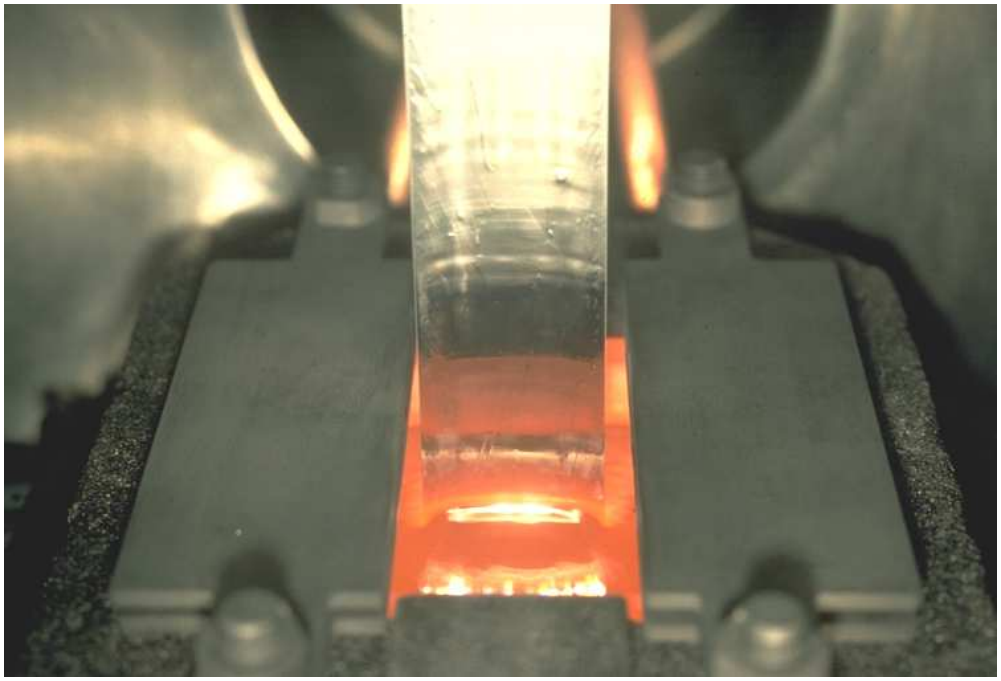


FIG. 3

String Ribbon

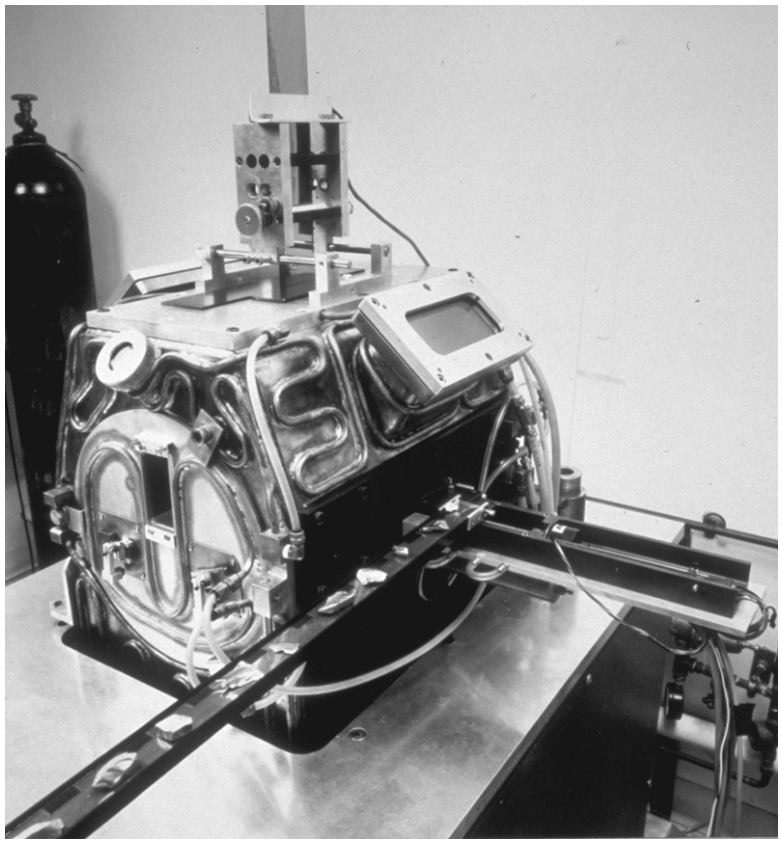
Think soap bubble, but continuous and with the bubble hardening



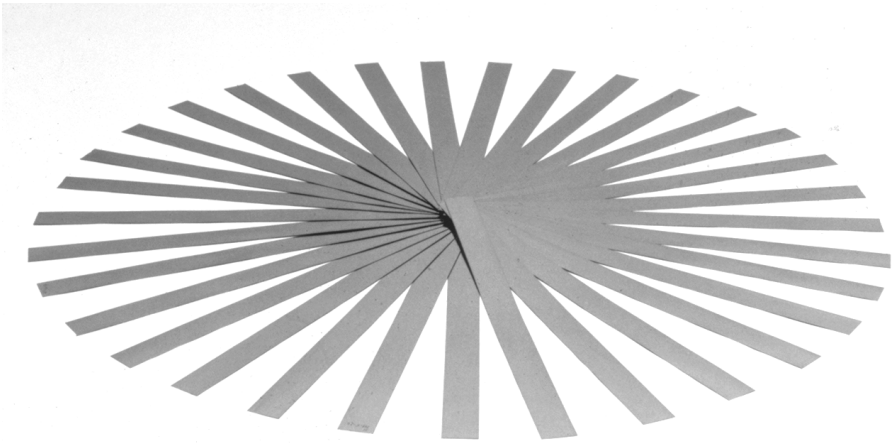


- No grinding sawing or etching
- Very stable process

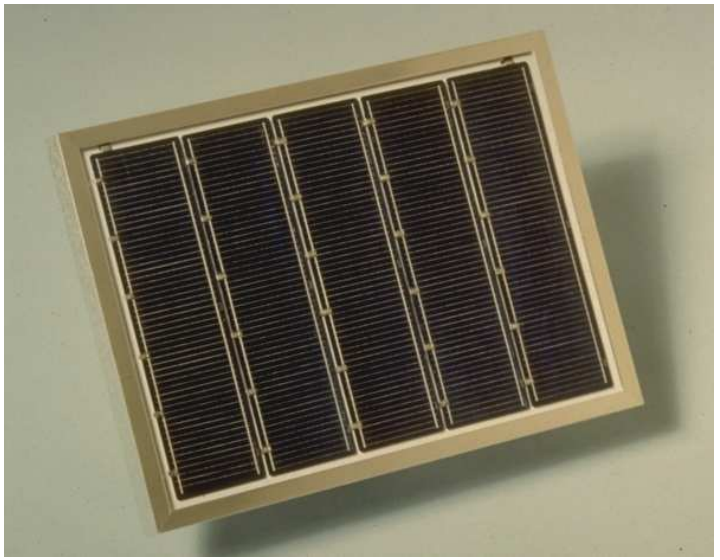
Milestone (1986) Continuous Growth



Chunks of silicon in, ribbon out



Portion of the ribbon grown during 100 hours of continuous operation (97% duty cycle).



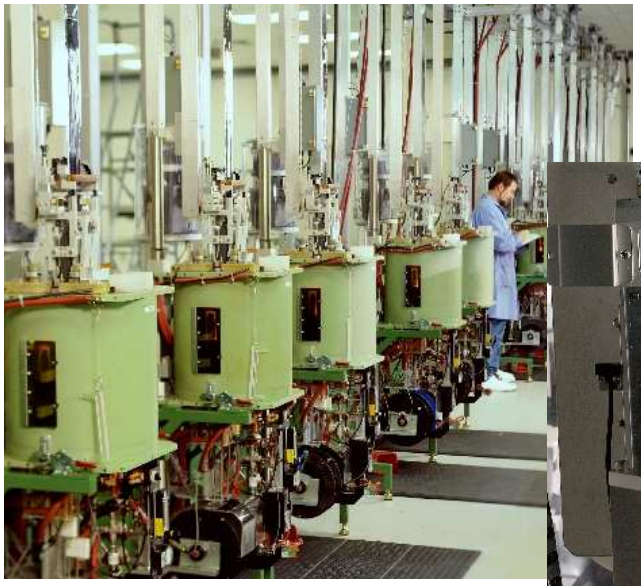
Panel. Ave Cell efficiency 12.5%

“End of the Road” (1986)

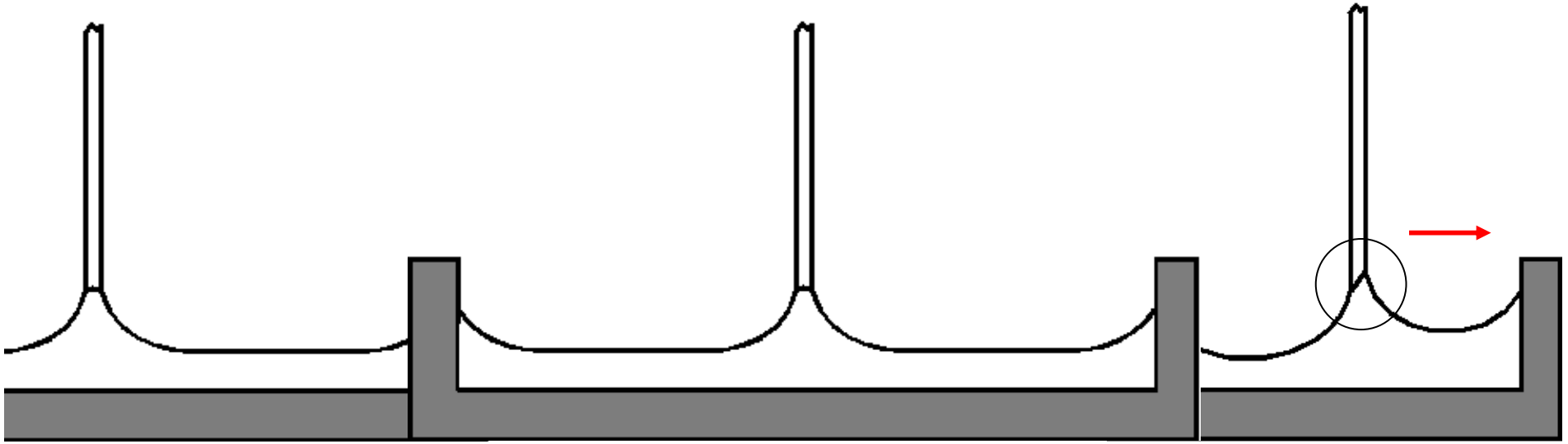
- Oil prices drop from $26 to $12/barrel in 3 weeks.
- Funding source (option to Solarex) dries up.

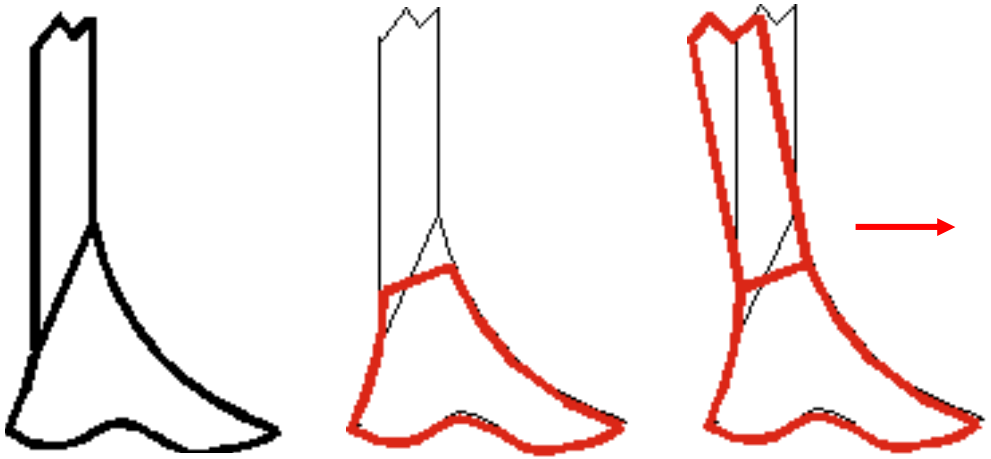
EVERGREEN SOLAR

- 120 Furnaces in operation.
- 15 MW annual production in Marlboro, MA
- 30 MW factory starting up in Freiburg Germany.

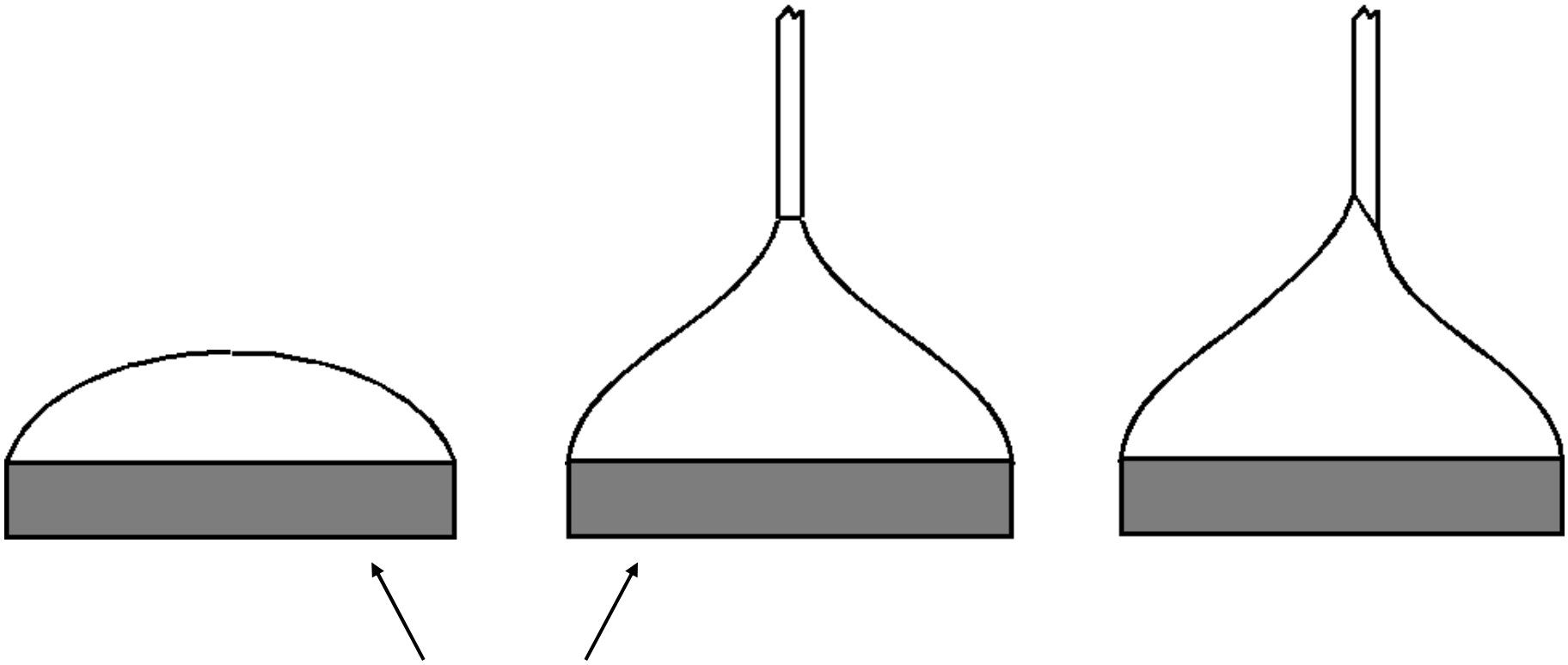


Reducing Crucible Width



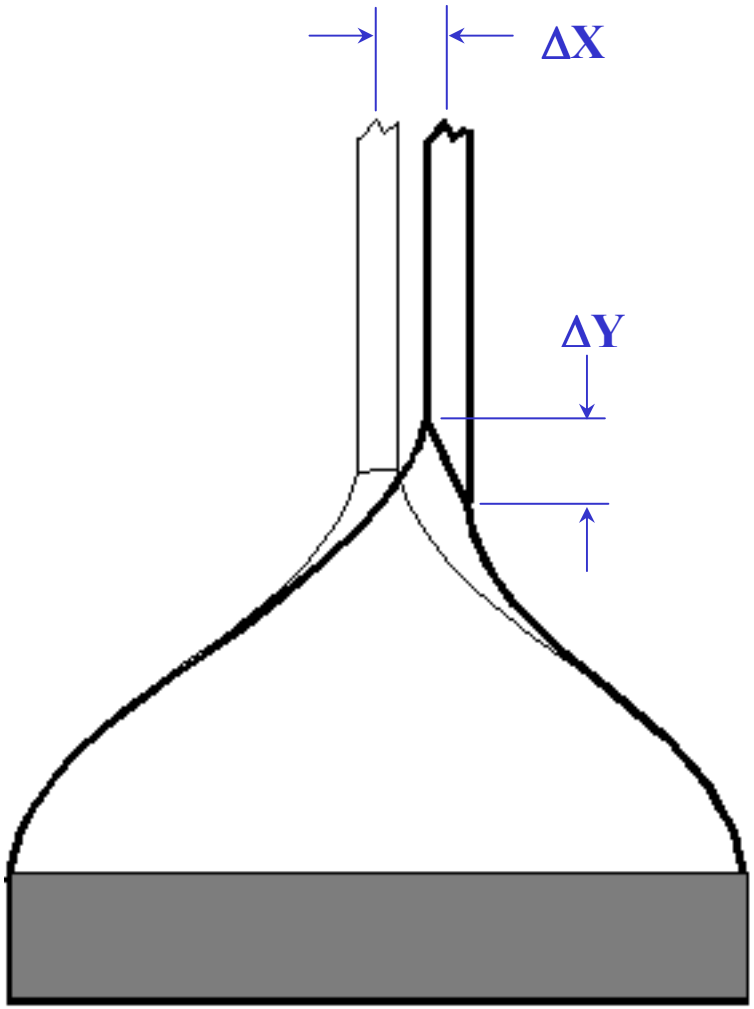


The Mesa Crucible



Mesa crucible

Flatness; Quantitative

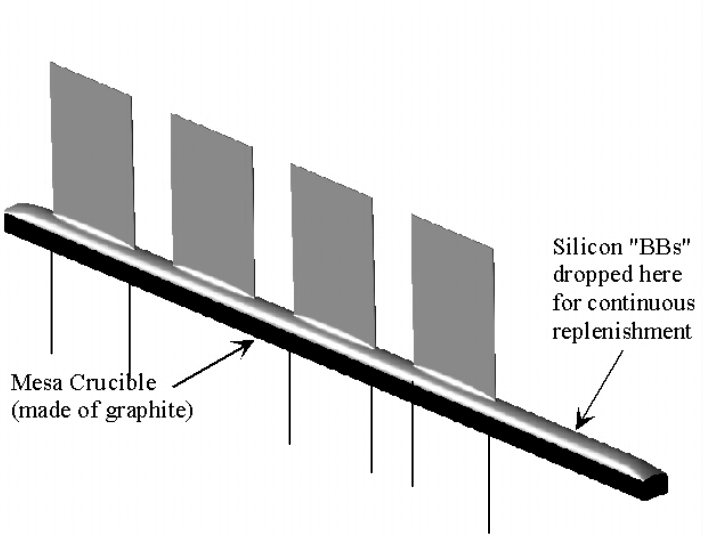


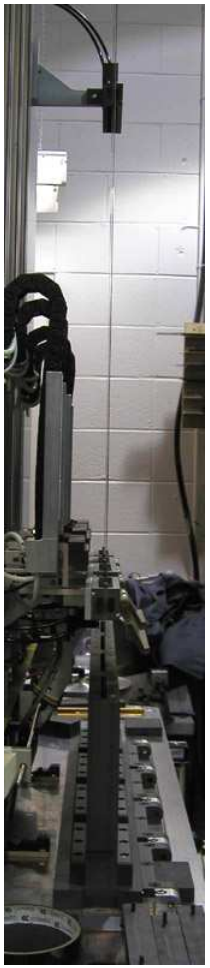
$$\text{Restoring Index} = \frac{\Delta Y}{\Delta X}$$

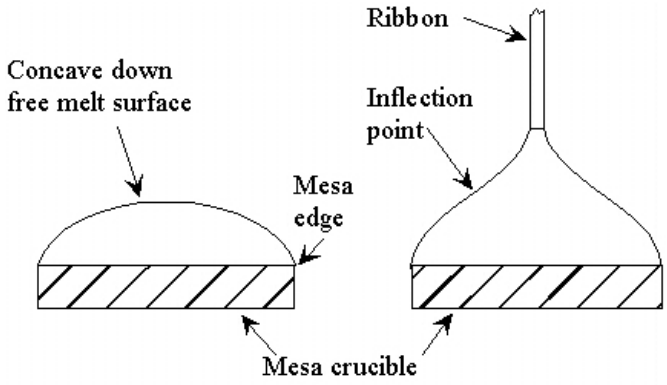
Restoring Index for typical Mesa ~ .40

Restoring Index for infinite melt ~ .10

New String Ribbon Technology; Mesa Crucible

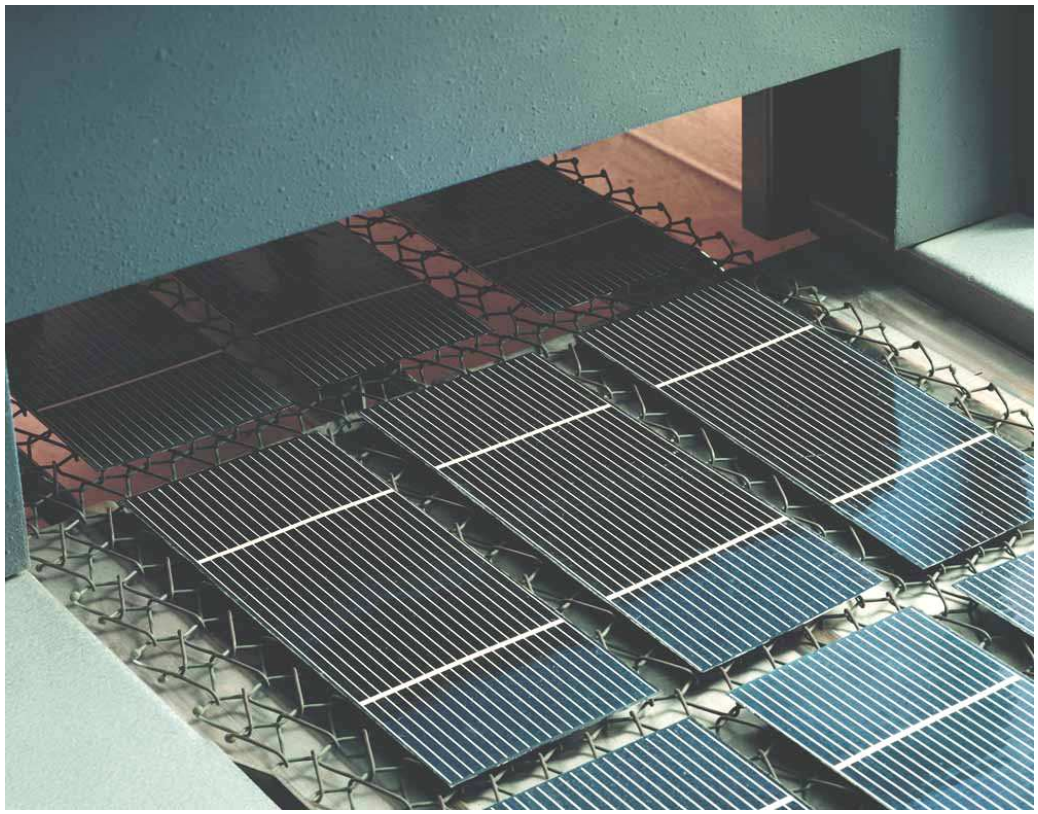






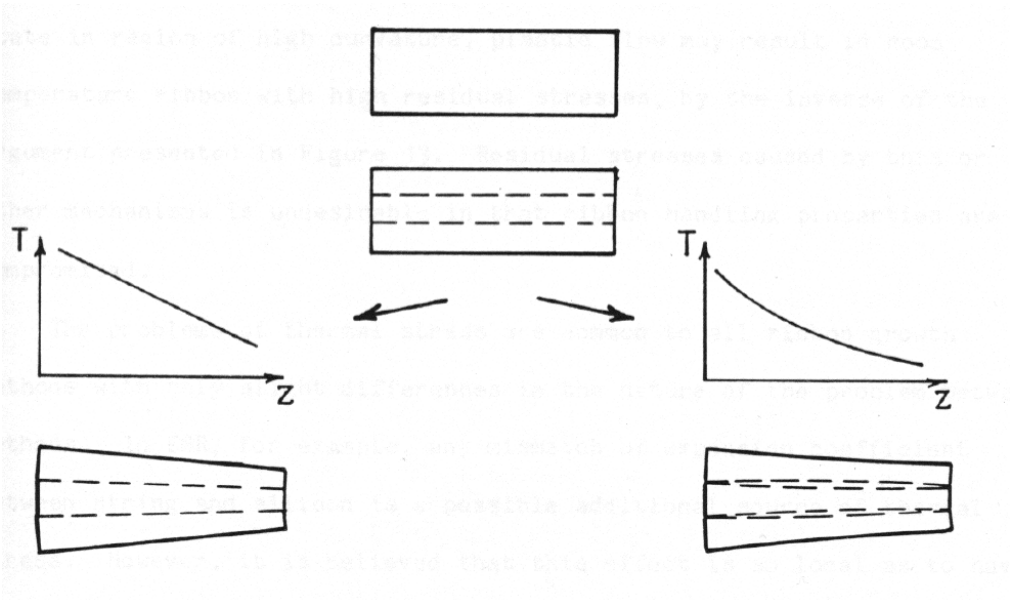
No grinding, no slicing, no etching

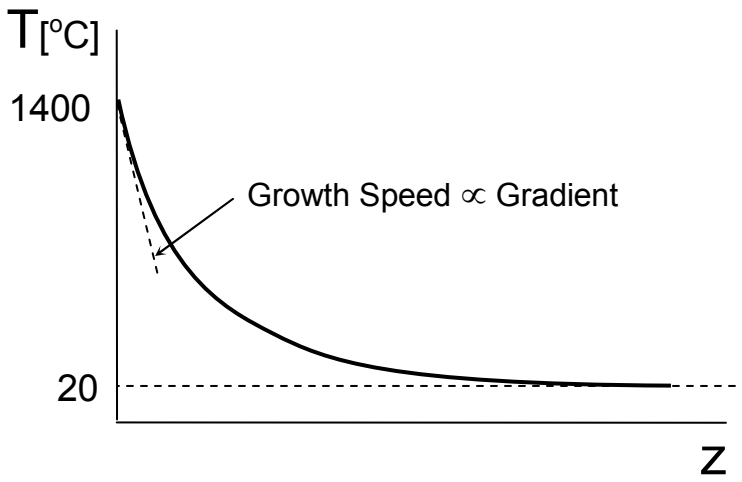
- Ribbon is laser cut into wafers
- Wafers go DIRECTLY onto belt furnace for p-n junction diffusion

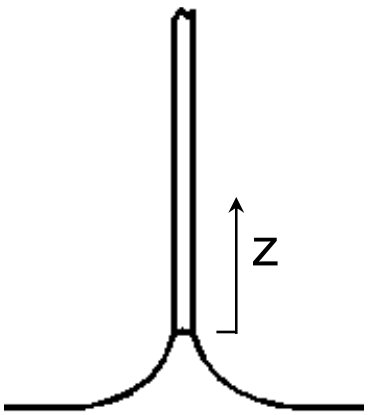


Finished cells emerging from firing of metallization

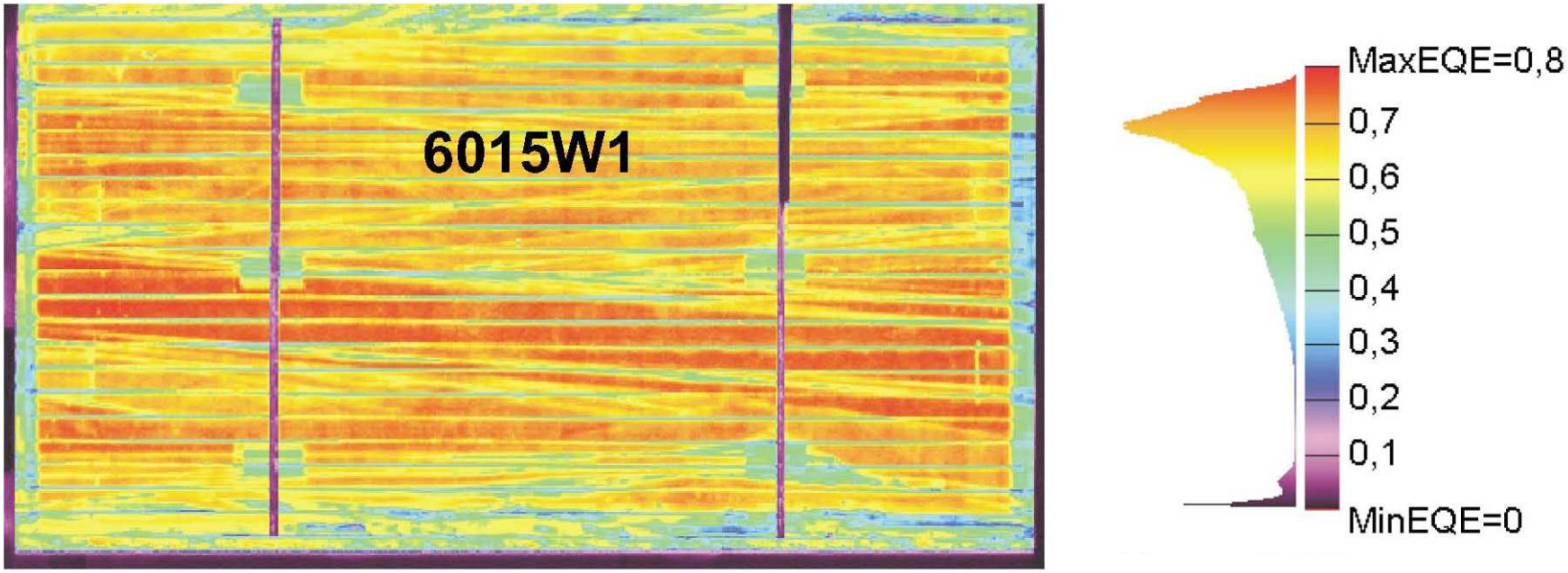
So, What's Wrong with String Ribbon ?







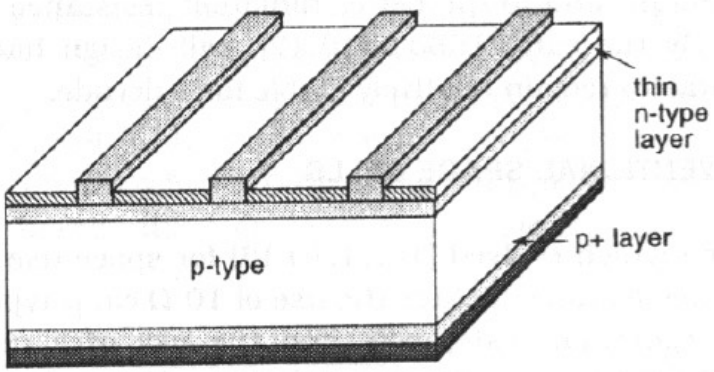
Stress + Grain Structure ⇒ Dislocations ⇒ Reduced diffusion lengths ⇒ Reduced near-IR Photoresponse



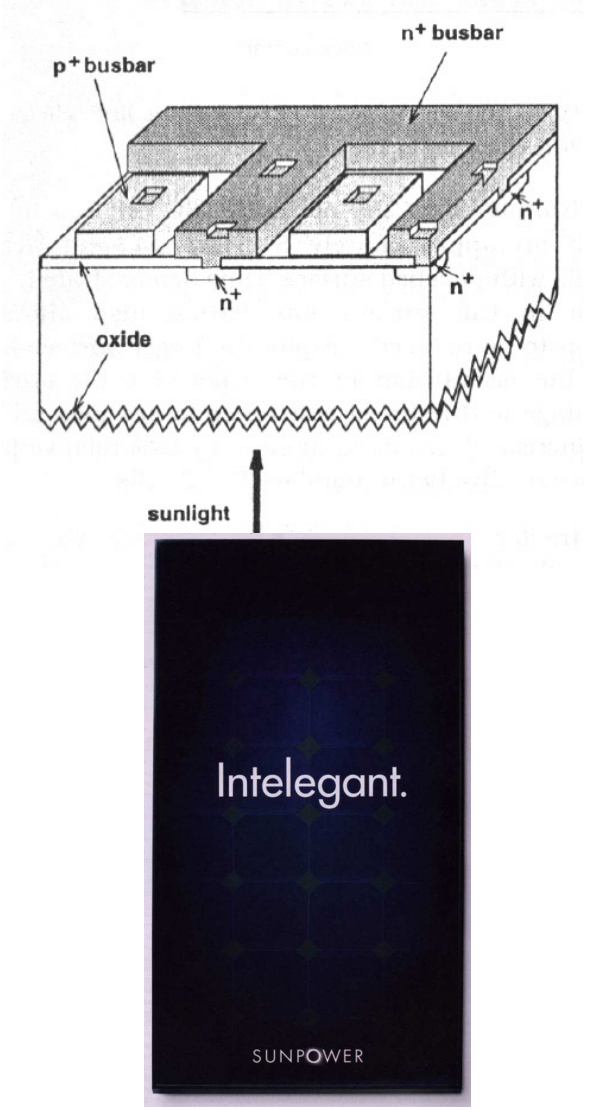
Different Cell Architectures co-exist in the Market

Most Common Architecture

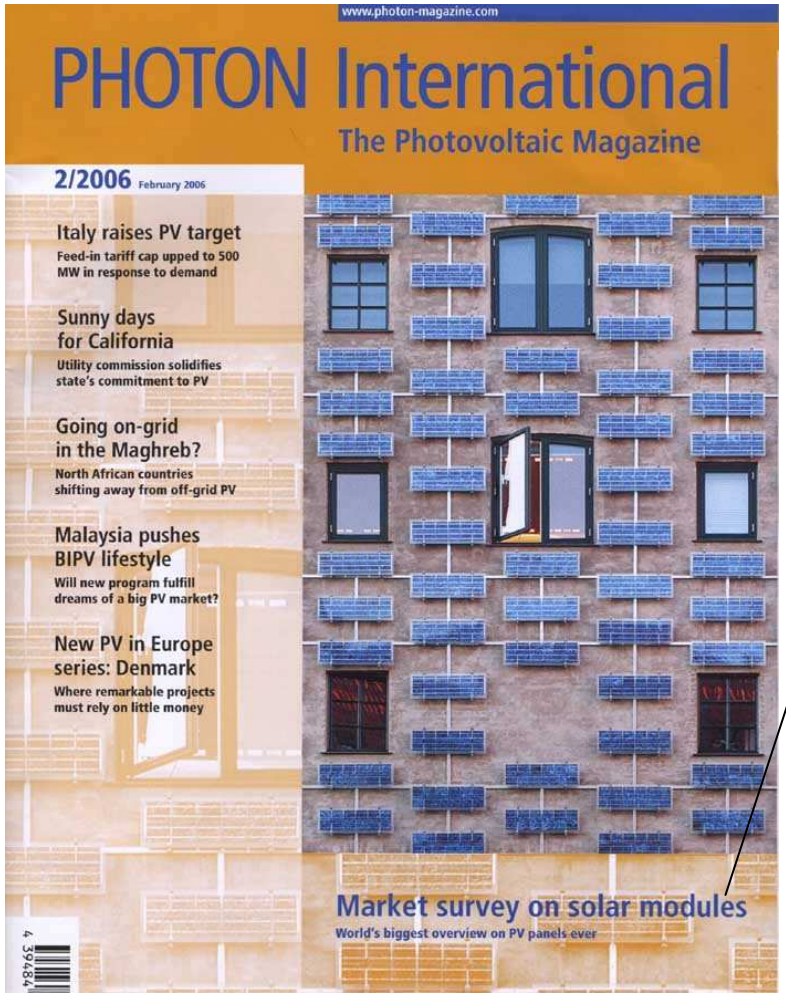
15% efficiency



Rear point contact cell
η~20%



Very Competitive!



- 110 vendors of PV Modules listed!!!
- Sharp 28% market share
- Kyocera 8%
- Evergreen 1%

Newest Entries

- Dye Sensitized Electrochemical Junction
  - "Graetzel" cell
- CIGS
  - Very high Efficiencies (19.1%)
  - Indium availability?
- Polymeric PV
- Photosynthetic PV

Environmental Issues

- Acids or Dry-etch?
- Recyling of modules?
- Change in albedo of planet?

Everything man-made that is now big was once small

2004 annual sales = 1.1 GW = .0011TW
2004 installed Base = 3 GW = .003TW

25% CAGR

2035 annual sales = 1100 GW = 1.1TW
2035 installed Base = 5500 GW = 5.5TW