New Architecture for Space Solar Power Systems: Fabrication of Silicon Solar Cells Using In-Situ Resources

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Lunar Power Requirements

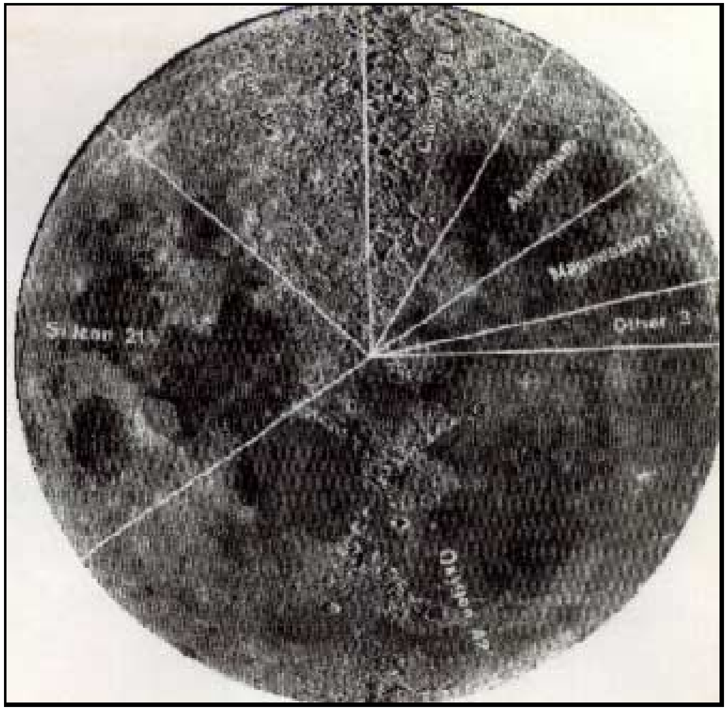
- Initial : 100kW to 1 MW
- Non-Nuclear/ Non-Mechanical
- Solar Cells
    - Current technology: 300 W to 500 W/kg
    - From 300 to 3000kg to transport lightweight cells
    - High costs

$\Rightarrow$ ***Manufacture Solar Cells Directly on the Moon by Utilizing In Situ Resources***

Production of Solar Cells on the Surface of the Moon from Lunar Regolith

Past Interest in Lunar Resource Utilization: Extraction of Oxygen

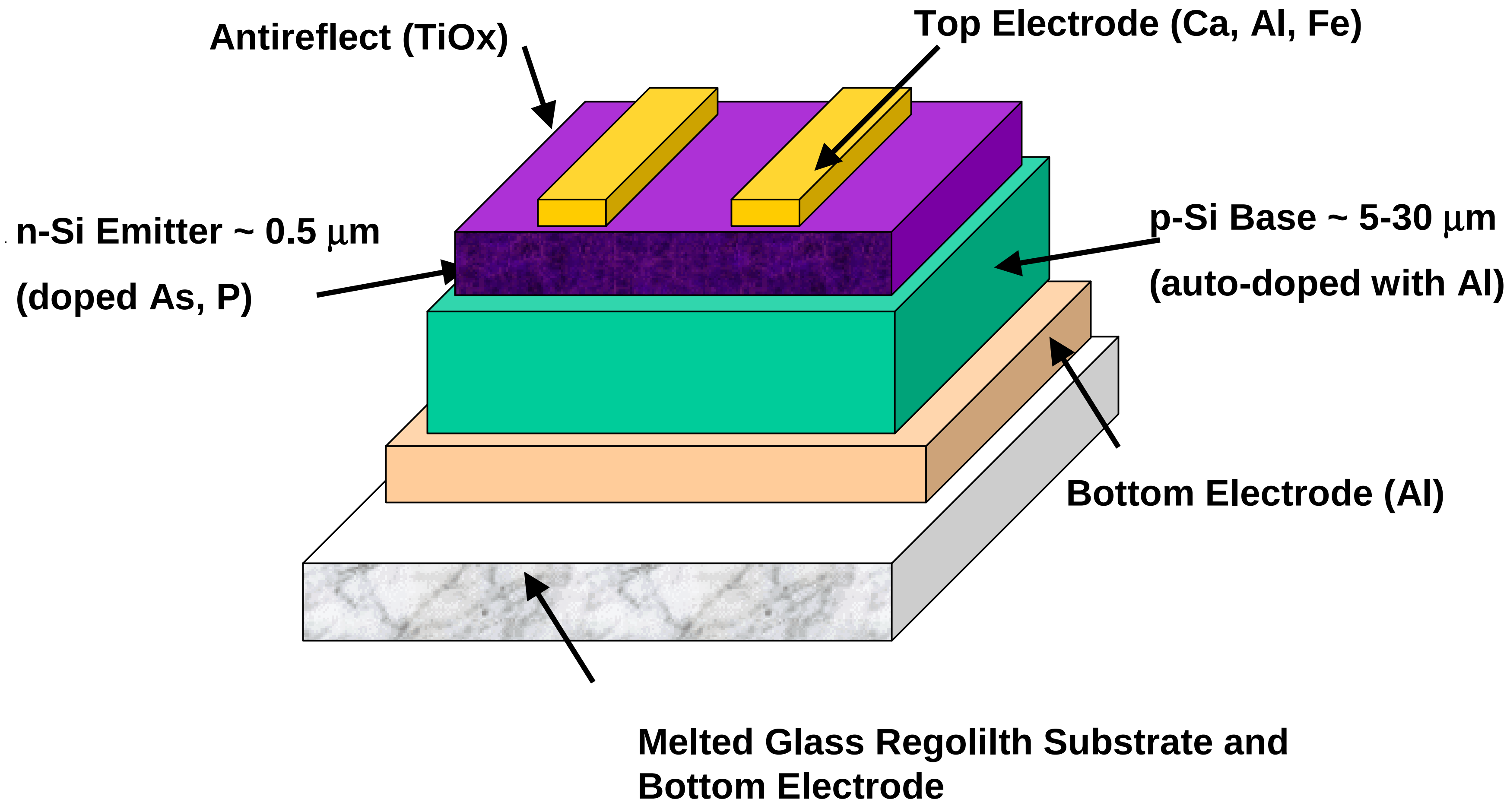
(waste by product Si, Al, Ca, Ti, Fe etc..)



- **Elements Required for Si-based Solar Cells are Present on the Moon**
  - **Silicon**
  - **Iron**
  - **Titanium Oxide**
  - **Calcium**
  - **Aluminum**

. Moon's Surface is an Ultra-High Vacuum
  - **~ 10^{-10} Torr (day)**
  - **Use vacuum evaporation to make thin film solar cells**

Lunar Silicon Solar Cell



Lunar *vs* Terrestrial Solar cell Materials

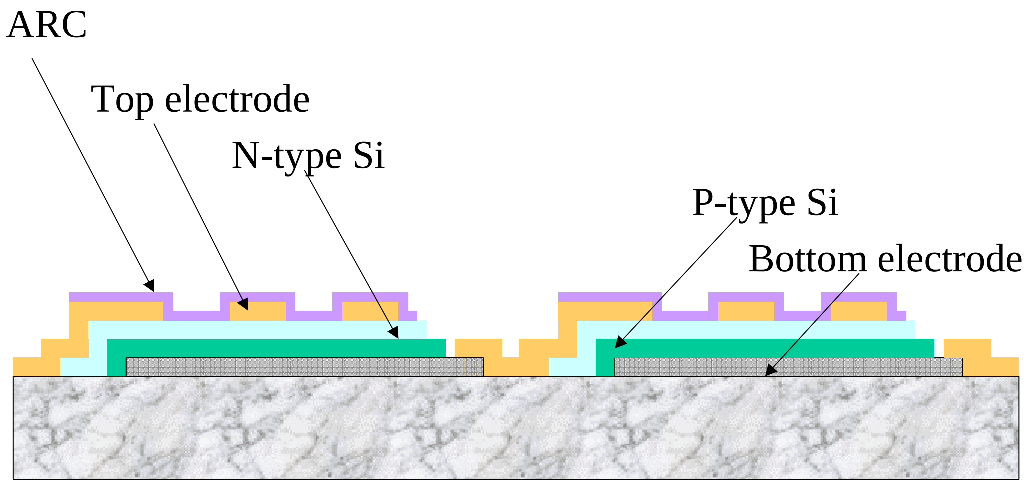
Terrestrial Material	*Purpose*	Lunar Material
Glass/Silicon	*Substrate*	Lunar Melted Glass
Silicon	*Solar Cell Absorber*	Silicon
Aluminum	*Back Contact*	Aluminum
Silver	*Front Contact*	Aluminum or Calcium
TiO2	*Anti-Reflection Coating*	TiO_2, Phosglass, or Geikeilites (TiMgO mineral)
Boron	*P-Type Dopant*	Aluminum
Phosphorous	*N-Type Dopant*	Phosphorous
Copper	*Cell Interconnects*	Aluminum or Calcium

Typical compositions of lunar mare regolith, anorthite, ilmenite and pyroxene (weight %)

	Apollo 15 Regolith	Ilmenite ($FeTiO_3$)	Anorthite ($CaAl_2Si_2O_8$)	Low-Calcium pyroxene $(Ca,Mg,Fe)SiO_3$
SiO_2	46.7	0.1	44.2	52.4
TiO_2	1.7	52.2		0.4
Al_2O_3	13.2		35.8	1.89
Cr_2O_3	0.4	0.5		1.0
FeO	16.3	44.4	0.2	16.9
MnO	0.2	0.2		
MgO	10.9	1.4		23.9
CaO	10.4	0.2	19.7	2.6
Na_2O	0.4		0.2	
K_2O	0.2			
P_2O_5	0.2			
S	0.1			
Total	100.7	99.0	100.0	99.14

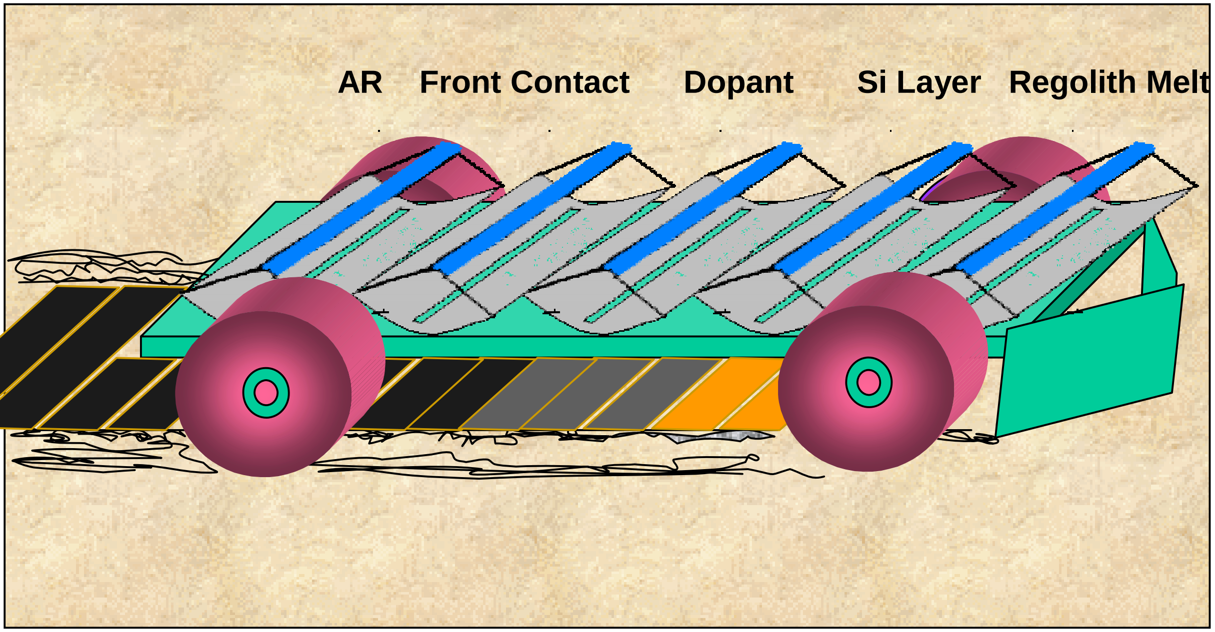
Fabrication of Silicon Solar Cells

- Use lunar materials (Si, Fe, TiO_2, etc.)
- Lunar 'glass' substrate - melt regolith by solar heat
- Deposit polycrystalline silicon solar cells by solar evaporation
- Interconnect solar cells serially for ~50-100V
- Do cell fabrication robotically



Lunar Solar Cell Monolithic Interconnection

Mechanized Solar Cell Growth Facility - Rover



- Solar powered

  Solar Electric Motion

  Solar Thermal Evaporation

- Continuous lay-out of cells on lunar surface
- Remotely controlled

Mechanized Regolith Processing Rover/Crawler

- Regolith scoop
- Solar thermal/ electric heat
- Regolith processing flow
- Closed-cycle processing
- Recycle volatiles
- Feed solar cell production rover(s)

Phase I objectives

1-Selection of typical locations for solar cell production on the Moon

2-.Definition of available raw materials on the Moon and definition of processes for extraction of solar cell materials

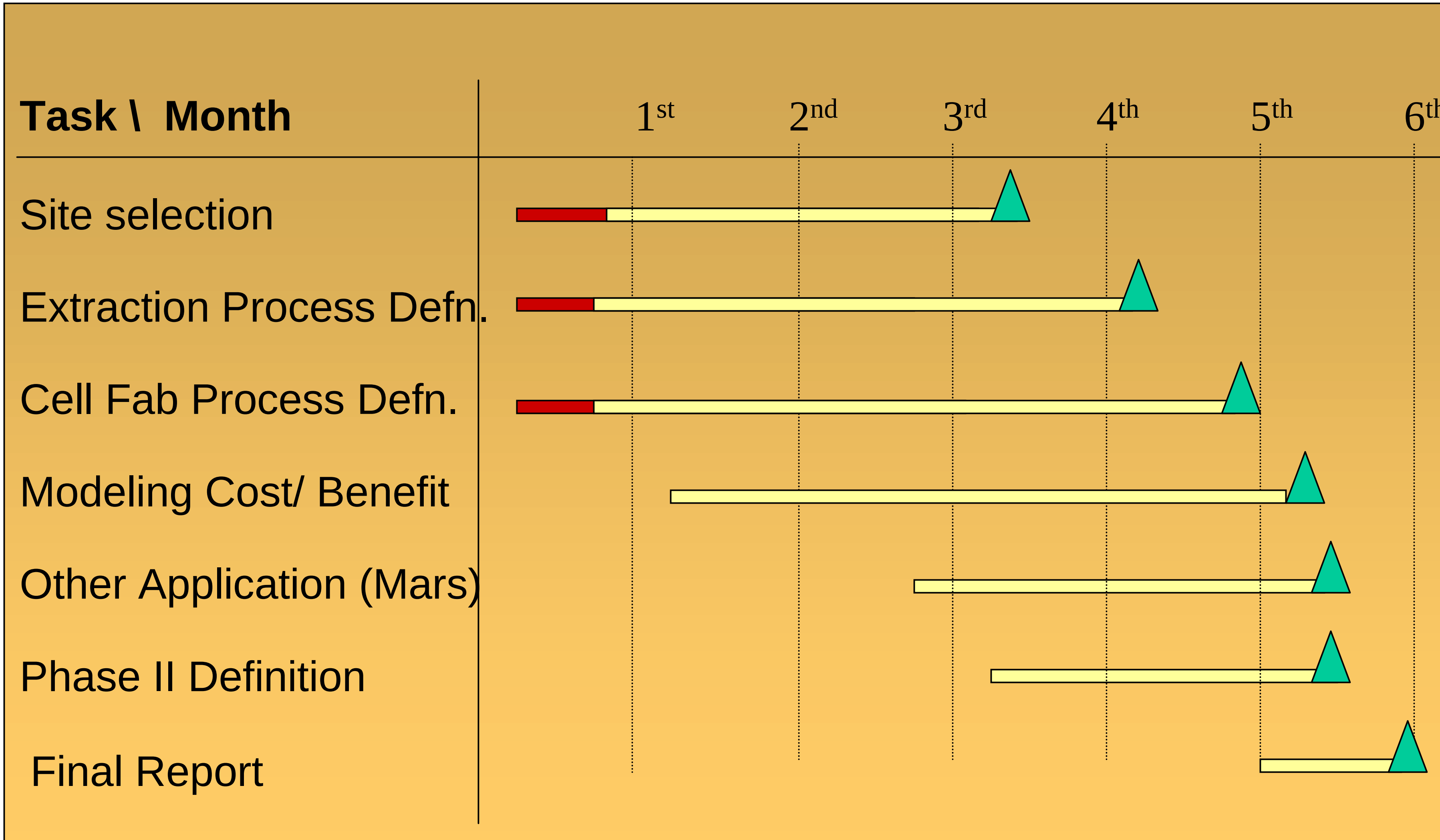
3-Definition of production process for solar cell arrays on the surface of the Moon

4-Performance modeling for assessing cost/benefit ratio for the power system concept

5-Evaluate extension of the concept beyond the Moon (e.g. Mars)

6-Identification of key Tasks for Phase II of the program

Phase I tasks/objectives



Lunar Site selection

Direct Fabrication on the Surface in Equatorial Regions

- **Front side of Moon**
  - **Lunar Base**
  - **He^3 mining**
  - **Tourism**
- **Back Side**
  - **Radio astronomy**

South Pole - Circumferentially Covered Mountain Peak

- **Continual sunlight**
  - **Earth view (power beaming)**
  - **Possible water mining**

Site Selection: ***Mineral composition and surface topography will impose a Solar cell design /Solar Cell Layout***

Solar Cells on the Surface of the Moon from Lunar Regolith

This image was prepared by J-L Margot, Cornell University, from Earth-based radar measurements of the Moon. The illuminated mountain at the bottom of the picture is located at 0^o, 85^oS. This is artificially illuminated, but approximates the illumination at noon on the Moon. The dark side never views the Earth and much of it is in permanent shadow. The scale of the picture is 50x70km. The illuminated peak is about 150 km from the South Pole and is ~6km above the plains to the north.

Solar Cell Material Extraction Process (1)

SVEC

e.g. Carbothermal Reduction of Anorthite

Step 1. $$4\ CH_4 \xrightarrow{1400^oC} 4\ C + 8\ H_2$$

Step 2. $$CaAl_2Si_2O_8 + 4\ C \xrightarrow{1650^oC} CaO + Al_2O_3 + 2\ Si + 4\ CO$$

(anorthite)
m.p. 1521°C

Step 3. $$4\ CO + 12\ H_2 \xrightarrow[250^oC]{Ni\ Catalyst} 4\ CH_4 + 4\ H_2O$$

Step 4. $$4\ H_2O + \text{electrolysis} \xrightarrow{75^oC} 4\ H_2 + 2\ O_2$$

⇒ **Closed cyclic process yielding both OXYGEN and SILICON:**

$$CaAl_2Si_2O_8 \longrightarrow CaO + Al_2O_3 + 2\ Si + 2\ O_2$$

Solar Cell Material Extraction Process (2)

Ilmentite Reduction (Hydrogen or Carbon)

- **$FeTiO_3$ + H_2 ----------> Fe + TiO_2 + H_2O**
- **$FeTiO_3$ + C ----------> Fe + TiO_2 + CO**
- **$3FeTiO_3$ + CH_4 ----------> 3Fe + $3TiO_2$ + $2H_2O$ + CO**

$\Rightarrow$ **Yields iron for interconnect and TiO_2 for antireflect**

Lunar Si Thin Film Evaporation

- Extracted Silicon is much poorer than electronics-grade (doubtful for solar cell fabrication)

Vacuum evaporation of lunar simulant-extracted silicon*

- Lab test
- 10^{-7} Torr
- E-beam evaporation

- **Find Vacuum Purification**

Silicon obtained by electrolysis and solidification from a hyperutectic Si- Al alloy (R. Keller)

Impurity Levels Measured in Starting Lunar-Si and Si Films Deposited on Al Foil

Impurities	Impurity levels in Si extracted from lunar regolith*	Impurity measured by SIMS on regolith films deposited on 1 mil-thick Al-foil
Aluminum (Al)	240 PPM	Non conclusive due to (substrate)
Calcium (Ca)	175 PPM	< 1 PPM
Lithium (Li)	31 PPM	< 1 PPM
Copper (Cu)	20 PPM	< 1 PPM
Iron (Fe)	18 PPM	< 1 PPM

(*) As measured by R. Keller from EMC Consultants.

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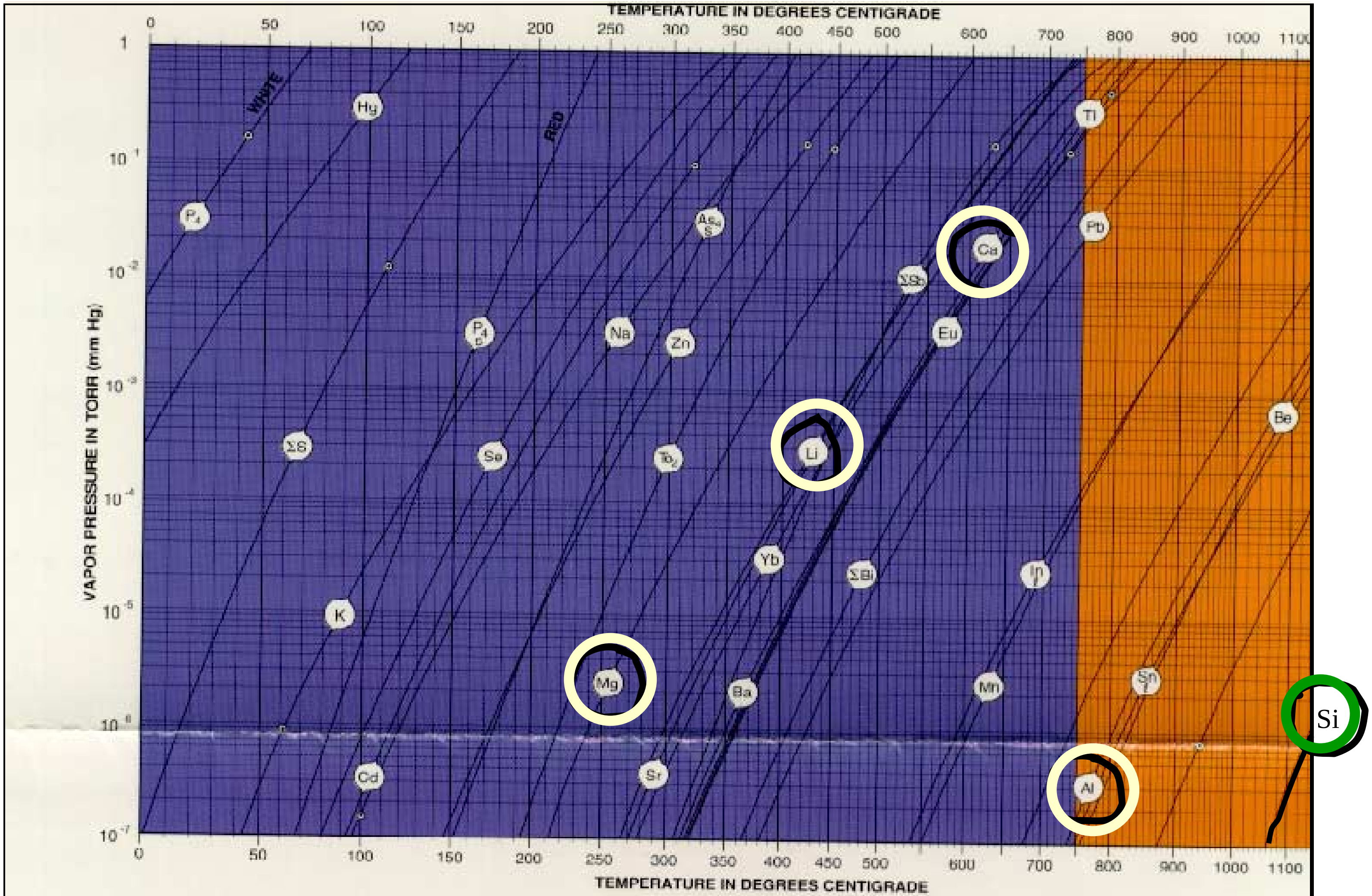
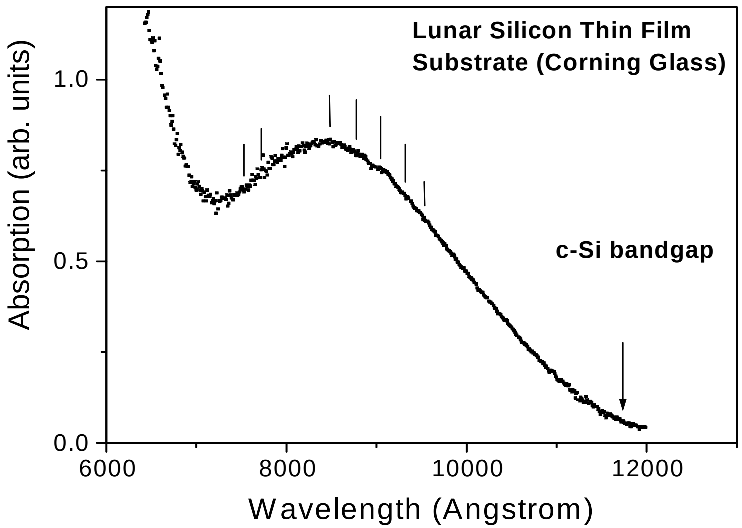
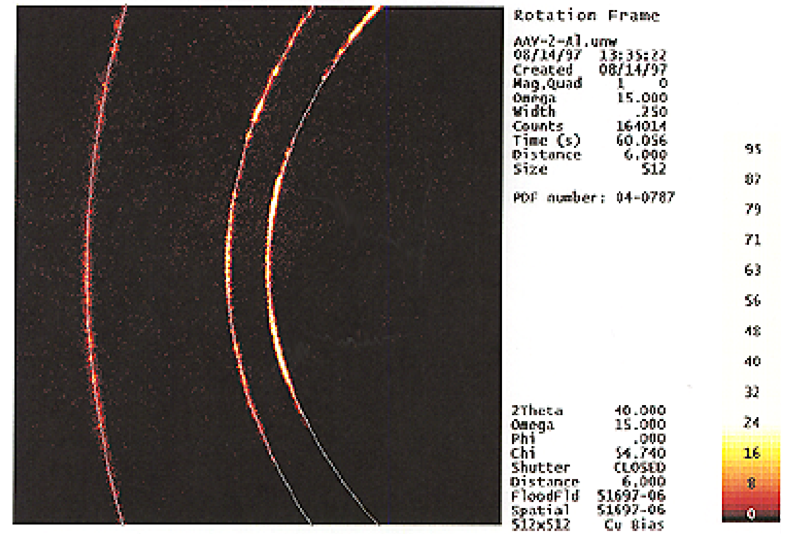
Volatile Impurities



Lunar Simulant Extracted Silicon Film

Optical/structural Properties





- **Bandgap ~ 1.1 eV**
- **Index of Refraction ~ 3.5**
- **Conductivity p-type (10^{18} cm^{-3})**

- **X-ray Diffraction**
  - **Films on Glass are nano-crystalline**

Preliminary film properties suggests Si Solar cell efficiency ~6- 9%

Projected Cell production rate /unit

- ~ 10-100 μm/hr evaporation rate (30- 300 m^2 in 1 lunar day)

- For 5-10% Efficiency Cells
  - ~ 5-50 kW/lunar day
  - ~ 50-500 kW/earth year

- Continuous Cell Replacement
  - Assume limited cell lifetime
    - . Radiation damage
    - . Particle damage

Summary

- Investigation of a new architecture for the development of solar cells using planetary (lunar) resources is proposed

- Ultra-high Vacuum on Lunar Surface Allows for Direct Thin Film Solar Cell Production
  - Less Mass to the Moon
  - Lunar Resources can be Utilized for Cell Production
  - Trade-off Cell Efficiency with Quantity
  - Multiple Facilities can be Utilized
  - Move to Industrial Scale Power Generation and Power Grid on the Moon

Production of Solar Cells on the Surface of the Moon from Lunar Regolith

- Solar Concentrator to Melted Regolith for ‘Glass’ Substrate
  - Low thermal conductivity
  - 1 m^2 collector should yield ~ 1 - 2 mm thickness of melted regolith ’glass’
  - Dope ilmenite w/Ca, Mg, Al for higher conductivity - bottom electrode?
  - Continuously form glass substrate/bottom electrode as robotic rover moves

Lunar Solar Cell Components

Layer	Thickness Range	Type	Source Materials	Indigenous Minerals	Fabrication Technique
Top electrode	0.1-1 micron	Metallic Ca, Ca/Fe, or Al	Lunar Ca, CaAl, Fe	Yes: Anorthite, Ilmenite	Vacuum thermal evaporation
Antireflection Coating	0.1-0.2 micron	TiO_2 or SiO_x or AlO_x	Regolith	Yes :from Ilmenite ($FeTiO_3$) Anorthite ($CaAl_2Si_2O_8$)	Vacuum Thermal Evaporation
N-type Si	0.1-0.3 micron	Si doped with As, P, or S (doping about 100-200PPM)	Lunar Si N-dopant	Yes: (Anorthite) PO_x and S are present in low quantities in minerals	Co-evaporation of Si and dopant
P- type Si	1-10 micron	Si doped with Al (20-50 PPM)	Lunar Si	Anorthite	Vacuum thermal evaporation
Bottom Electrode	1 -2 micron	Al, Ca/Fe	Lunar Al	Anorthite	Vacuum thermal evaporation
Substrate	2-5 mm	Glass mineral	Lunar soil	Yes	Solar thermal melting

- Silicon p/n juncton (solar evaporation)
  - ~10 to 40μm thick
  - p-doping with Al
  - n-doping with As or P (supplied terrestrially)
- Metallization
  - Bottom Electrode (Al)
  - Top Electrode (Ca /Al or Fe)
  - Evaporation through contact mask(grid pattern)
- Anti-reflection Coating
  - TiO_2 or SiO_2