
A. Ignatiev and A. Freundlich
Space Vacuum Epitaxy Center
University of Houston

M. Duke
LPI/Colorado School of Mines

S. Rosenberg
In-Space Production, Ltd.

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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

⇒ 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
  - $\sim 10^{-10}$ Torr (day)
  - Use vacuum evaporation to make thin film solar cells
Lunar Silicon Solar Cell

- **Melted Glass Regolith Substrate and Bottom Electrode**
- **p-Si Base ~ 5-30 µm** (auto-doped with Al)
- **n-Si Emitter ~ 0.5 µm** (doped As, P)
- **Top Electrode (Ca, Al, Fe)**
- **Bottom Electrode (Al)**
- **Antireflect (TiOx)**

**Melted Glass Regolith Substrate and Bottom Electrode**
<table>
<thead>
<tr>
<th>Terrestrial Material</th>
<th>Purpose</th>
<th>Lunar Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/Silicon</td>
<td><em>Substrate</em></td>
<td>Lunar Melted Glass</td>
</tr>
<tr>
<td>Silicon</td>
<td><em>Solar Cell Absorber</em></td>
<td>Silicon</td>
</tr>
<tr>
<td>Aluminum</td>
<td><em>Back Contact</em></td>
<td>Aluminum</td>
</tr>
<tr>
<td>Silver</td>
<td><em>Front Contact</em></td>
<td>Aluminum or Calcium</td>
</tr>
<tr>
<td>TiO2</td>
<td><em>Anti-Reflection Coating</em></td>
<td>TiO₂, Phosglass, or Geikeilites (TiMgO mineral)</td>
</tr>
<tr>
<td>Boron</td>
<td><em>P-Type Dopant</em></td>
<td>Aluminum</td>
</tr>
<tr>
<td>Phosphorous</td>
<td><em>N-Type Dopant</em></td>
<td>Phosphorous</td>
</tr>
<tr>
<td>Copper</td>
<td><em>Cell Interconnects</em></td>
<td>Aluminum or Calcium</td>
</tr>
</tbody>
</table>
## Typical compositions of lunar mare regolith, anorthite, ilmenite and pyroxene (weight %)

|                   | Apollo 15 Regolith | Ilmenite (FeTiO$_3$) | Anorthite (CaAl$_2$Si$_2$O$_8$) | Low-Calci
|-------------------|--------------------|-----------------------|-------------------------------|------------
| SiO$_2$           | 46.7               | 0.1                   | 44.2                          | 52.4       |
| TiO$_2$           | 1.7                | 52.2                  |                               | 0.4        |
| Al$_2$O$_3$       | 13.2               |                       |                               | 1.89       |
| Cr$_2$O$_3$       | 0.4                | 0.5                   |                               | 1.0        |
| FeO               | 16.3               | 44.4                  | 0.2                           | 16.9       |
| MnO               | 0.2                |                       |                               |            |
| MgO               | 10.9               | 1.4                   |                               | 23.9       |
| CaO               | 10.4               | 0.2                   | 19.7                          | 2.6        |
| Na$_2$O           | 0.4                |                       | 0.2                           |            |
| K$_2$O            | 0.2                |                       |                               |            |
| P$_2$O$_5$        | 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*
- Solar powered

  Solar Electric Motion

  Solar Thermal Evaporation

- Continuous lay-out of cells on lunar surface

- Remotely controlled
- 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

<table>
<thead>
<tr>
<th>Task</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
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</thead>
<tbody>
<tr>
<td>Site selection</td>
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<tr>
<td>Extraction Process Defn.</td>
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<tr>
<td>Cell Fab Process Defn.</td>
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<tr>
<td>Modeling Cost/ Benefit</td>
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<tr>
<td>Other Application (Mars)</td>
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<tr>
<td>Phase II Definition</td>
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<tr>
<td>Final Report</td>
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</table>
Direct Fabrication on the Surface in Equatorial Regions
- Front side of Moon
  - Lunar Base
  - He³ 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°, 85°S. 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.
e.g. Carbothermal Reduction of Anorthite

Step 1. \[ 4 \text{CH}_4 \rightarrow 4 \text{C} + 8 \text{H}_2 \]  

1400°C

Step 2. \[ \text{CaAl}_2\text{Si}_2\text{O}_8 + 4 \text{C} \rightarrow \text{CaO} + \text{Al}_2\text{O}_3 + 2 \text{Si} + 4 \text{CO} \]  

1650°C  

(anorthite)  
m.p. 1521°C

Step 3. \[ 4 \text{CO} + 12 \text{H}_2 \rightarrow 4 \text{CH}_4 + 4 \text{H}_2\text{O} \]  

250°C

Step 4. \[ 4 \text{H}_2\text{O} + \text{electrolysis} \rightarrow 4 \text{H}_2 + 2 \text{O}_2 \]  

75°C

⇒ Closed cyclic process yielding both OXYGEN and SILICON:

\[ \text{CaAl}_2\text{Si}_2\text{O}_8 \rightarrow \text{CaO} + \text{Al}_2\text{O}_3 + 2 \text{Si} + 2 \text{O}_2 \]
Ilmenite Reduction (Hydrogen or Carbon)

- \( \text{FeTiO}_3 \ + \ H_2 \quad \rightarrow \quad \text{Fe} \ + \ \text{TiO}_2 \ + \ H_2O \)

- \( \text{FeTiO}_3 \ + \ C \quad \rightarrow \quad \text{Fe} \ + \ \text{TiO}_2 \ + \ \text{CO} \)

- \( 3\text{FeTiO}_3 \ + \ \text{CH}_4 \quad \rightarrow \quad 3\text{Fe} \ + \ 3\text{TiO}_2 \ + \ 2H_2O \ + \ \text{CO} \)

⇒ Yields iron for interconnect and TiO\(_2\) for antireflect
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**

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

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

[Graph showing vapor pressure in Torr vs. temperature in degrees Centigrade for various elements.]
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 suggest Si Solar cell efficiency ~6-9%
- ~ 10-100 µm/hr evaporation rate (30-300 m² 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
• 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 m² 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

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness Range</th>
<th>Type</th>
<th>Source Materials</th>
<th>Indigenous Minerals</th>
<th>Fabrication Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top electrode</td>
<td>0.1-1 micron</td>
<td>Metallic Ca, Ca/Fe, or Al</td>
<td>Lunar Ca, CaAl, Fe</td>
<td>Yes: Anorthite, Ilmenite</td>
<td>Vacuum thermal evaporation</td>
</tr>
<tr>
<td>Antireflection Coating</td>
<td>0.1-0.2 micron</td>
<td>TiO$_2$ or SiO$_x$ or AlO$_x$</td>
<td>Regolith</td>
<td>Yes :from Ilmenite (FeTiO$_3$) Anorthite (CaAl$_2$Si$_2$O$_8$)</td>
<td>Vacuum Thermal Evaporation</td>
</tr>
<tr>
<td>N-type Si</td>
<td>0.1-0.3 micron</td>
<td>Si doped with As, P, or S (doping about 100-200PPM)</td>
<td>Lunar Si N-dopant</td>
<td>Yes: (Anorthite) PO$_x$ and S are present in low quantities in minerals</td>
<td>Co-evaporation of Si and dopant</td>
</tr>
<tr>
<td>P-type Si</td>
<td>1-10 micron</td>
<td>Si doped with Al (20-50 PPM)</td>
<td>Lunar Si</td>
<td>Anorthite</td>
<td>Vacuum thermal evaporation</td>
</tr>
<tr>
<td>Bottom Electrode</td>
<td>1 -2 micron</td>
<td>Al, Ca/Fe</td>
<td>Lunar Al</td>
<td>Anorthite</td>
<td>Vacuum thermal evaporation</td>
</tr>
<tr>
<td>Substrate</td>
<td>2-5 mm</td>
<td>Glass mineral</td>
<td>Lunar soil</td>
<td>Yes</td>
<td>Solar thermal melting</td>
</tr>
</tbody>
</table>
• Silicon p/n junction (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$_2$