FROM DEEP SPACE TO EARTH: PHOTOVOLTAIC CONCENTRATORS IMPACT THE FUTURE OF TERRESTIAL SOLAR ENERGY PRODUCTION

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ION BEAM OPTICS INC.

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Experience Summary

- **Optical Coating Laboratory Inc. (OCLI)**: 1973 to 1989
  Process Engineering; First end-Hall ion source in production
- **PSI Max Optics, Inc.** 1989 to 1990
  Developed DWDM coating system—OCA / Corning Prototype
- **Boeing High Technology Center**: 1990 to 1993
  World Record Space Solar Cell; IAD Development
- **Avimo Singapore Ltd.** 1993 to 1997
  Filter Cathodic Arc; IAD; Night Vision; Center of Excellence
- **ZC&R Coatings for Optics Inc.** 1997 to 2000
  High Out Put IAD; IFCAD; Space Station Window Program
- **Rockwell Science Center** 2000 to 2003
  Laser Eye Protection; Mars Reconnaissance Orbiter
Presentation Summary

- Basic Description of Thin-Film Coating Technology
- Ion-Assisted-Deposition (IAD)
- Space Applications of IAD Technology
  - Windows for International Space Station
  - Next Generation Space Solar Power System
  - Terrestrial Solar PV Concentrator Development
- Filtered Cathodic Arc (FCA) Technology
- Lightweight Space-Based Deposition Technology
- SSU Galbreath Reserve Wildlands Observatory Project
- Concluding Remarks
Large Coating Chamber
Basics of Thin-Film Coating Technology

- **Vacuum**: Chamber with Hard Vacuum ~ $10^{-6}$ Atm (Torr)
- **Substrates**: Glass; Metal; Ceramic; Plastic; etc.
- **Evaporation Materials**: Metals; Metal Oxides; Semiconductors; Metal Fluorides; Mixtures, Compounds; etc.
- **Optical Interference**: Complex Designs based on thin layers of high and low refractive index materials
  - Anti-Reflection (ophthalmic)
  - Laser Mirrors: and laser eye protection coatings
  - Band Passes (Telecom): extremely narrow and robust
- **Measure film thickness**: in Nanometers and Angstroms
- **Coatings used in many applications**: commercial, space and military
Filament Cathode Ion Source for Ion-Assisted-Deposition (IAD)
Hollow Cathode Source for Ion-Assisted-Deposition (IAD)
Ion Beam in Ion-Assisted-Deposition (IAD) Chamber
Thornton Film Growth Model (1974)
TiO₃ Film Deposited at 300°C using PVD
TiO₂ Film Deposited at 50º C. using IAD
### TiO$_2$ Refractive Index using IAD vs. PVD

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>n IAD</th>
<th>n PVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>2.85</td>
<td>2.60</td>
</tr>
<tr>
<td>400</td>
<td>2.76</td>
<td>2.42</td>
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<tr>
<td>500</td>
<td>2.55</td>
<td>2.30</td>
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<tr>
<td>600</td>
<td>2.47</td>
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<tr>
<td>700</td>
<td>2.42</td>
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<tr>
<td>800</td>
<td>2.41</td>
<td>2.21</td>
</tr>
<tr>
<td>1000</td>
<td>2.40</td>
<td>2.20</td>
</tr>
</tbody>
</table>
TiO$_2$ Refractive Index using IAD vs. PVD

**IAD TiO2 (Ambient) vs PVD TiO2 (300 deg. C.)**

- **IAD**
- **PVD**

% Transmittance vs Wavelength (nm)
SiO₂ Film Deposited at 50° C. using IAD
Al₂O₃ Film Deposited at 50° C. using IAD
Si$_3$N$_4$ Film Deposited at 50$^\circ$ C. using IAD
Laser Protection Filter @ 1064 nm using IAD
Laser Protection Filter

- Ta$_2$O$_5$ / SiO$_2$ Material Combination
- Substrate: Commercial Grade BK7
- Optical Density @ 1064 nm = 4.5 to 5.0
- Average Damage Threshold Measure at LLNL
- 10.7 J/cm$^2$ @ 1064 nm / 3-ns pulses
- Best Technique: Hf metal $\rightarrow$ IAD(O$_2$) $\rightarrow$ HfO$_2$
Wedge Filter Band Pass: Hyper-Spectral Filter for Mars Reconnaissance Orbiter: Launched August 2005

- **Linear Variable Filters** - Center Wavelength Changes Smoothly With Position Along Filter
- **Patterned Stripe Filters** - Distinct Filter Sections With Custom Transmission Bands
- **Wide Spectral Range** From Visible to Far Infrared
  - Visible: 0.45 - 0.9 μm
  - Near Infrared: 0.9 - 1.9 μm
  - Mid Wave Infrared: 1.9 - 5.5 μm
  - Long Wave Infrared: 8 - 14 μm
- **Bandpass (FWHM)** 1.0 - 1.5% of Center Wavelength
- **Variety of Substrate Materials**
- **Custom Blocking Filters** Available to Extend Performance
- **One of six coating designs on the hyper-spectral filter for the Mars Reconnaissance Orbiter**
Early Artist Rendition of International Space Station (1990)
International Space Station 2007
International Space Station Windows

Space Station Window Anti-Reflection Coating

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>% Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>450</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>550</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>650</td>
<td>0</td>
</tr>
<tr>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>750</td>
<td>0</td>
</tr>
</tbody>
</table>

AR Coating: Reflectance remains low across the spectrum.
Uncoated Glass: Reflectance increases significantly at longer wavelengths.
International Space Station Windows

**DESIGN: Side 1**

- 16.5nmH 28.2nmL 126.0nmH 61.4nmL 13.0nmITO
- ITO for Thermal Control
- Sheet Resistance = 400 ± 50 Ω / Sq

**DESIGN: Side 2**

- Anti-Spall AR Applied to Lexan
- Largest size: 29 inches diameter
Space Station Windows: Large Area IAD (ZC&R)
Space Station Windows: Large Area IAD (ZC&R)
Space Station: Observation Cupola
Space Power: Concentrator Solar Arrays (1990 to 2004)
Solar Spectrum: Comparing Solar Cell Absorption
Boeing: World Record Solar Concentrator Cell (1993)
Boeing: Solar Concentrator Cell Assembly
Early Coating Stress Failure on Silicone Lens
Boeing: PASP Module Flown in 1994
(Orbit: 363 x 2,550 km, 70 degree Inclination)

PASP+ Flight Test Results for Selected Array Types

- ENTECH Mini-Dome Lens Over Boeing GaAs/GaSb Dual Junction Cell
- Planar Gallium Arsenide Cell
- Planar Crystalline Silicon Cell
- Planar Amorphous Silicon Cell

Mini-Dome Lens Array had the highest performance and the lowest degradation of all 12 PASP+ Arrays.

Silicone Mini-Dome Lenses used thin vapor-deposited protective coating which worked well – current loss was only 3% due to cell, coverglass, and lens degradation combined.
Ray Trace: DC93-500 Silicone Fresnel Lens (Entech)

Ray Traces Run for (GaInP) Top Junction; similar to Middle Junction (GaAs) and Bottom Junction (Ge)

± 2 Degree Pointing Accuracy for Solar Tracking
Deep Space One (DS1) - 720 ENTECH Lenses

*Popular Science*
*Cover Story*
*July 1998*

*DS1 Successfully Launched 10/24/98*
Thin Film Technology Chamber: Silicone Lens Coating (2004)
Chamber: Masked Lens During Deposition
Spectral Performance: Silicone (DC93-500) Sample

Entech UV Blocker Run # 10 (3-8-10)

% Transmittance

Wavelength (nm)
NASA Marshall VUV Exposure Testing of UVR-Coated Silicone Sample

Details in Critical Spectral Region

Initial and Final Curves over Full Spectrum
Outdoor Test May 28, 2004: EMCORE Cell Under UVR-Coated (By Ion Beam Optics) ENTECH Stretched Lens

- The Coated Lens Performs Extremely Well in the Stretched Condition
- Also, 200 Thermal Cycles from -170°C to +70°C (at ABLE) Caused No Degradation in Transmittance of Coated Silicone Sample
- Also, 1,067 Equivalent Sun Hours of VUV Exposure (at MSFC) Caused No Degradation in Transmittance of Coated Silicone Sample
ENTECH’s Space Fresnel Lens Photovoltaic Concentrator Evolution


Launched in 1998: SCARLET Array on Deep Space 1 Performed Flawlessly for 38-Month Mission on First Spacecraft Powered by Triple-Junction Cells

Developed in 1999-2000: Flexible-Blanket Version of Stretched Lens Array (SLA)

Developed in 2001-2002: Rigid Panel Version of SLA

Developed in 2003-2006: SLA on SquareRigger with Unprecedented Performance Metrics


Lens Stowed Against Radiator

Stretched Lens Array
SLASR Stowed For Acoustic Testing

Lens and Cell Blanket is Stowed in Cavity Between Frame
See Deployment Video at www.slasr.com
SLASR Powered Blanket Deployment at ATK Space
First SLASR Full-Scale Bay Prototype

- Full-Scale SLASR Bay is approximately 2.5 m x 5.0 m
- Bay is only partially populated with real stretched lenses and live photovoltaic cell circuits, with rest of bay populated with simulated lenses and cells
- Bay was built under NASA SBIR Phase II contract with ABLE Engineering (now ATK Space) as Prime and ENTECH as Key Subcontractor (providing lenses, photovoltaic receivers, and basic patents on SLA technology)
- Prototype Bay has undergone a series of successful tests and evaluations at ATK Space, including launch vibration, deployment, and solar simulator testing
Near-Term Applications of Stretched Lens Array (SLA) Technology in the Earth-Moon Neighborhood

**Lunar Surface Power**
(Solar SLA for Endless-Sunlight Polar Ridges, Laser SLA for Endless-Darkness Polar Craters, and Dual-Use Solar/Laser SLA for Other Regions)

**Power on Earth Orbit**
(CEV’s, Stations, Depots, DOD Rad-Hard Missions)

**Power for Solar Electric Propulsion**
(ISS Drag Compensation, Reusable Tugs)

**Power on Lunar Orbit**
(CEV’s, Stations, Depots)

**Power for Cislunar Operations**
(CEV’s, Stations, Depots)

**Near-Space Missions**
(High-Altitude Airships, Unmanned Aerial Vehicles)

**Ground Solar Power**
(The Spinoffs Are Coming!)

Why Is SLA Best for these Near-Term Missions?
- Areal Power Density = 300-400 W/m² for Full Solar Array
- Specific Power = 300-500 W/kg for 100 kW Solar Array
- Stowed Power = 80-120 kW/m³ for 100 kW Solar Array
- Scalable Array Capacity = 100’s of W’s to 100’s of kW’s
- Super-Insulated Small Cell Circuit = High-Voltage Operation
- Super-Shielded Small Cell Circuit = Radiation Hardness
- 85% Cell Area Savings = 66%-75% Lower Array Cost per Watt
- Modular, Scalable, & Mass-Produtcache at MW’s per Year
Color-Mixing Silicone Lenses (8.5 cm Wide) Over Prism-Covered Spectrolab Triple-Junction Cells (1.0 cm Wide) Provide 30% ± 1.5% Net Lens/Cell Operational Efficiency Under Outdoor Terrestrial Sunlight

These Cells Are Optimized for Space Sunlight and Provide Outstanding Space Performance: 27.2% Net Lens/Cell Efficiency (AM0, 25C) Based on NASA Lear Jet Flight
Each Concentrator Module Uses a 3 m² Color-Mixing Lens to Focus Sunlight at 26X Concentration onto a Boeing/Spectrolab Triple-Junction Cell Receiver

Measured IV Curves for Both Modules – Note that Each Module Produced Over 600 W of Power

(This Array Is Now at ENTECH in Keller, Texas)

Boeing Developed the Photovoltaic Receivers for this Test (July to Dec 2003) of the First-Ever Terrestrial Multi-Junction-Cell Array Over 1 kW
ENTECH’s Ground Solar Power Background:
Robust Systems Compared to other Technologies

One 800 W *SunLine*  

Four 25 kW *SolarRows*: power for 33 homes

- Large-Area (3 m²) Module Uses 84-cm-Wide Acrylic Lens Focusing Onto 4-cm-Wide Silicon Cells (Modified One-Sun) Mounted to Extruded Aluminum Heat Sink
- Same Module Used in 2-Module *SunLine®* Array or 72-Module *SolarRow®* Array
- SolarRow Array at PVUSA-Davis Performed Very Well for Many Years
Spectacular Convergence of ENTECH’s Space and Ground Solar Power Technologies

• When We Take Our Patented Space Concentrators Outdoors and Test Them Under Ground Sunlight, They Are Twice as Efficient (30% Versus 15%) as Solar Products on the Market Today

• For Ground Applications, The Same Basic Lens and Cell Technology Can Be Adapted to Be Cost-Effective on the Ground, Opening the Way to Reducing Dependence on Foreign Oil and Other Polluting Fossil Fuels

Note: Entech is in acquisition negotiations which may accelerate the commercialization of this technology
Ion-Assisted Filter Cathodic Arc Deposition (IFCAD)
The cathodic vacuum arc is a high current discharge between two metallic electrodes:

- cathode material is transferred to plasma at the spots (current density on the order of $10^6$ to $10^8$ A cm$^{-2}$)

- Spots move rapidly across the cathode surface

- Spot motion is random in the absence of a magnetic field but can be steered with a magnetic

- Plasma can be cleaned from “macroparticles” when guided through a curved duct (particle filter).
Freestanding S-filter: Carbon
Ion-Assisted-Deposition

• The plasma beam is scanned at the exit of the duct by an electromagnet.

• Ions can be accelerated by a substrate bias, permitting well adhered coatings

• Deposition rate ~ 5 nm/s per in² for carbon

• The addition of an End-Hall Ion Source to the Arc Process positively modifies the thin-film properties, increasing adhesion and converting the evaporation material to an oxide, nitride, etc.

• Ambient Temperature Depositions
IFCAD: Carbon Ion Beam Entering Chamber
IFCAD: Carbon Source Attached to Chamber
IFCAD: Metal Arc Source with IAD Source
IFCAD: Chamber with Door Open—Drum View
## Amorphous-DLC Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Nat. Diamond</th>
<th>CVD DLC</th>
<th>DLC (a:CH)</th>
<th>FCA (t:aC)</th>
</tr>
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<tbody>
<tr>
<td>Hardness GPa</td>
<td>100</td>
<td>80 - 100</td>
<td>10 - 50</td>
<td>70 - 100</td>
</tr>
<tr>
<td>Density g/cm³</td>
<td>3.5</td>
<td>3.2 – 3.4</td>
<td>1.7 – 2.2</td>
<td>3.0 – 3.3</td>
</tr>
<tr>
<td>Friction Coeff.</td>
<td>0.1</td>
<td>0.1 (polished)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Film Roughness</td>
<td>N/A</td>
<td>3μm</td>
<td>Optically Smooth</td>
<td>Optically Smooth</td>
</tr>
<tr>
<td>Adhesion</td>
<td>N/A</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
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<tr>
<td>Process T °C</td>
<td>N/A</td>
<td>&gt;600</td>
<td>20 – 325</td>
<td>20 - 150</td>
</tr>
<tr>
<td>Structure</td>
<td>Crystalline Sp3</td>
<td>Crystalline Sp3</td>
<td>Amorphous mostly Sp2</td>
<td>Amorphous mostly Sp3</td>
</tr>
<tr>
<td>Reactive Gas</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Transform T °C</td>
<td>N/A</td>
<td>&gt;600</td>
<td>250 – 350</td>
<td>&gt;500</td>
</tr>
</tbody>
</table>
Other IFCAD Materials

- $\text{Al}_2\text{O}_3$: clear film of high hardness
- $\text{Ta}_2\text{O}_5$: optical coating material (2.1n)
- $\text{TiO}_2$: high index optical coating material (>2.6 n)
- $\text{AlN}$: purple decorative film
- $\text{TiN}$: hard reddish gold wear resistant film
- $\text{TiCN}$: dark gray and hard wearing
- $\text{CrN}$: dull gray with low coefficient of friction
- $\text{ZrN}$: brass colored film with good corrosion resistance
- $\text{ITO}$: transparent conductive thin-film
- $\text{C}_3\text{N}_3$: material exhibiting extreme hardness (potentially)
Future Outlook for Space-Based Deposition Technology

- Moon used as a Temporary Stop for Voyages to Mars
- Lightweight Deployable Structures for Space Power
- Space-Based Depositions for Large Area Telescopes
- Lunar Vacuum: $5.0 \times 10^{-13}$ Torr
- Low Earth Orbit: Not Suitable for Metal Film Depositions
- (LEO) Atomic Oxygen Fluence: $2.3 \times 10^{20}$ atoms/cm$^2$
- Filtered Cathodic Arc: Simple Process for High Quality Thin-Film Deposition
Light-Weight Pulsed CA Source

Use of low voltage and inductive energy storage

\[ \text{12-24 V input from solar panel bus system} \]

\[ \text{PULSED cathodic arc can readily be miniaturized, for example as “microthruster,” used to correct the orbit of satellites} \]
Coil current for producing the magnetic field is the arc current itself: no extra power supply is needed.

Reducing the Weight of the Deposition System

- Weight of arc source, filter, and power supply < 300 g (!)
- Vacuum is “free”
- Cathodic arc does not need any process gas

~ 500 kg → ~ 100 g
Solar Sail (L’Garde)
Inflatable Antenna Experiment (L’Garde)
Technology will be best used on the Lunar Surface
Advantages of Light-Weight Space-Based FCAD System

- Cathodic Arc Deposition can run in Ultra High Vacuum without any process gas
- Weight of system can be reduced by a very large factor by using a pulsed process
- Pulsed systems have been demonstrated
- Pulsed systems can have light weight pulsed filters
- Filters and arcs can be run in series using one power supply
- Pulsed power supplies can use an inductive storage principle, allowing use of low voltage and low weight
Future Work on Space-Based FCAD Technology

- No Free Lunch: the price of miniaturization is relatively slow deposition speed for large areas. This is OK!

- Robotic Control Design for In-Vacuum Large Area Terrestrial Depositions—time of deposition is not a critical. Vacuum is Free in Space.

- Design and Testing of miniaturized FCA source with continuous source material feed: Teaming with LBNL to develop this enabling technology for future space missions.

- NASA has announced plans to send man missions to the dark side of the moon: this technology could play a vital part in the future of space exploration.
Galbreath Wildlands Preserve Observatory Project

- Cutting-edge research and education in astronomy
- Demonstration project for sustainable development and maintenance for a high technology research facility
Galbreath Wildlands Preserve

- Southern Mendocino county
- Nearly 4000 acres
- Wild and isolated
- Some areas with sustainable logging since the 1940s
- Dark, dark, dark!
The Vision

• A 1-meter world-class research telescope
• Completely remotely operable using the internet
• On-site operators and observers NOT required
• Completely energy self sufficient
• An environmentally sustainable green facility
• Zero impact on the environment and ecosystems
• Support instruction in astronomy (plus science and math education in general) for K-12, undergraduate, and graduate students
The Telescope

This is an example of the type of telescope desired. This is a 1-meter class research telescope.
Concepts for Observatory Buildings
We will be sustainable!

http://yorty.sonoma.edu/~gordon/gwpo
Some Relevant Publications


Some Relevant Publications


