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Development of Thin Film Solar Cells for Space Applications at NASA Glenn Research Center

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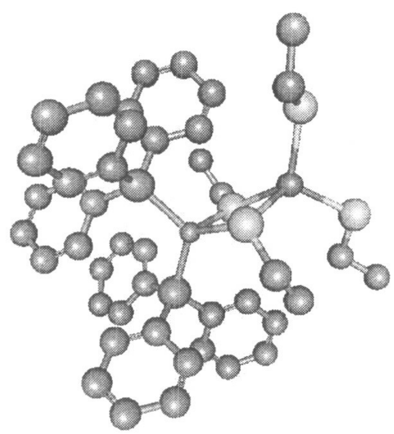

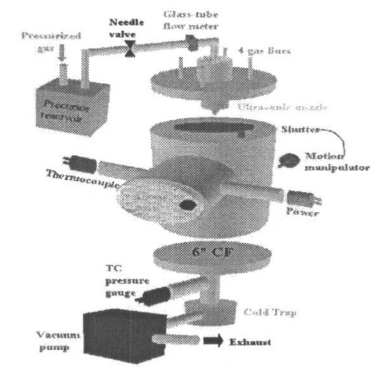

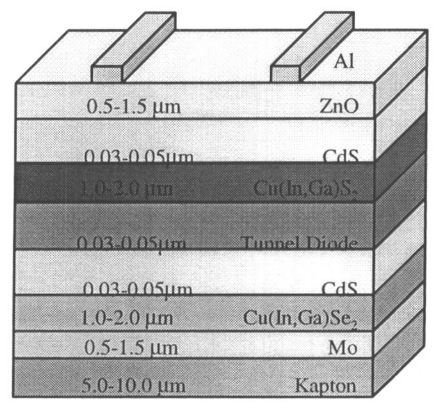

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ABSTRACT

NASA GRC Thin Film Solar Cell program is developing solar cell technologies for space applications which address two critical metrics: higher specific power (power per unit mass) and lower launch stowed volume. To be considered for space applications, an array using thin film solar cells must offer significantly higher specific power while reducing stowed volume compared to the present technologies being flown on space missions, namely crystalline solar cells.

The NASA GRC program is developing single-source precursors and the requisite deposition hardware to grow high-efficiency, thin-film solar cells on polymer substrates at low deposition temperatures. Using low deposition temperatures enables the thin film solar cells to be grown on a variety of polymer substrates, many of which would not survive the high temperature processing currently used to fabricate thin film solar cells. The talk will present the latest results of this research program.

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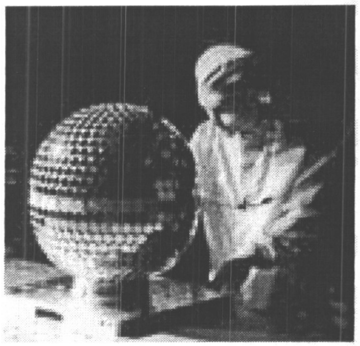
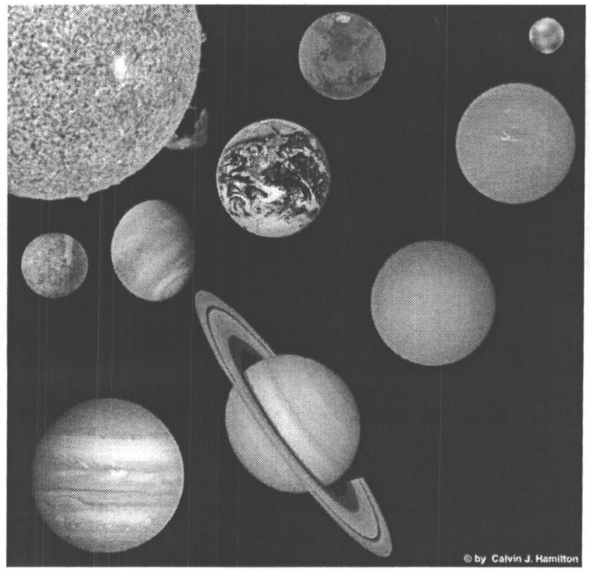
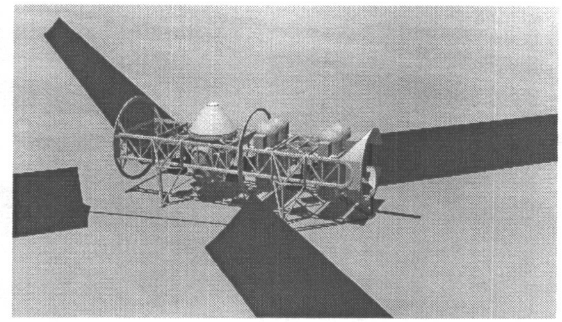
Missions for Thin Film Technology

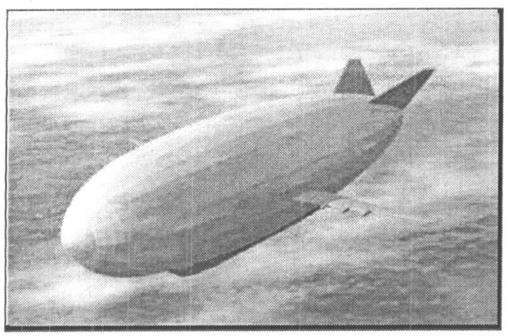


(Nano-)Satellite Power

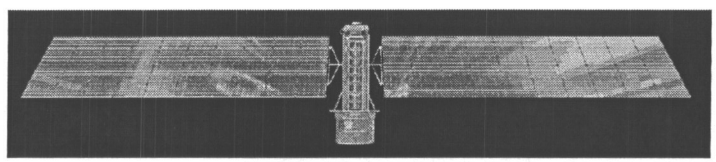




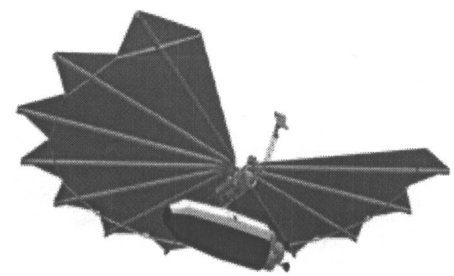
Planetary Surface Power



Ultra-Large Airships



Space Solar Power



Solar Electric Propulsion

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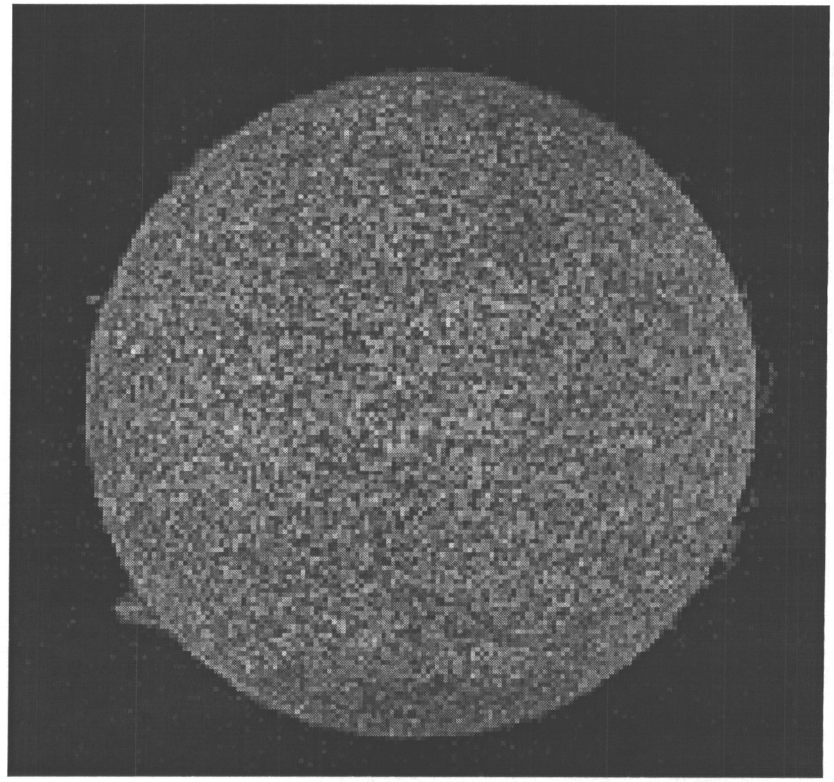
Why CIS & CISe Thin Films?

Radiation tolerant

CIS, CISe solar cells are among the most radiation tolerant cells.

High efficiency

The record CISe solar cell has an efficiency of 18.8%.



Objectives: Key TF Array Issues

- **Thin-film cell efficiencies increase and/or substrate mass decreases**
  - Need economical large-scale production of large-area (>10-cm^2) thin-film cells with stable efficiencies ~ 10% to 15% (1-Sun AM0) on low-mass substrates (1-mil metallic, 5-mil composite, 2-mil polymer):

    LTCVD offers opportunity to employ polymer substrates

- **Thin-film solar arrays are designed and space qualified**
  - Need packaging, deployment systems and support structures **tailored** to thin-films:

    Work in partnership with Array TPA to produce new structural and support technologies

- **Thermal issues identified as major impediment to good EOL efficiency**
  - TF array benefits should not be mitigated by spacecraft-level operations issues associated with larger area, low-mass devices:

    Develop new device structures (Back/front), new (clear) substrates (CP-1), and high emmisivity coatings (conducting oxide films - e.g. WO_3 or MoO_3)

Thin Film Technology Road Map

NASA GRC Space Power Technology Road Map

Technology Focus Area	2002 – 2005 Establish a Presence	2006 – 2010 Expand Our Horizons	2011 – 2023 Develop the Frontiers
Thin-Film Solar Cells Provide advanced thin-film technologies for challenging environments and applications. Innovative chemical concepts and processing will enable use of polymer substrates. This technology is enabling for very large inflatable arrays and numerous aerospace exploration missions such as: direct-drive electric propulsion, high-altitude airships, and space solar power.	• **Demonstrate** AM0 cell efficiency >8% on lightweight substrates using single-source precursor, low-temperature deposition process on polymers. • **Integrate** thin-film technology and lightweight array design. • **Investigate** high-emissivity coatings for high-voltage array operation.	• **Demonstrate** dual-junction thin-film cells on lightweight substrates. • **Develop** monolithic interconnection technologies for thin-film cells. • **Demonstrate** dual-junction cell with AM0 cell efficiency >20%.	• **Develop** multi-junction thin-film cells on lightweight structures with efficiencies >20%. • **Demonstrate** array operation at high-voltages (>1000V) with high-emissivities.

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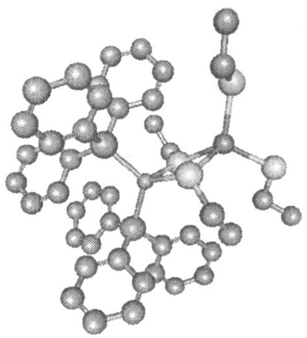
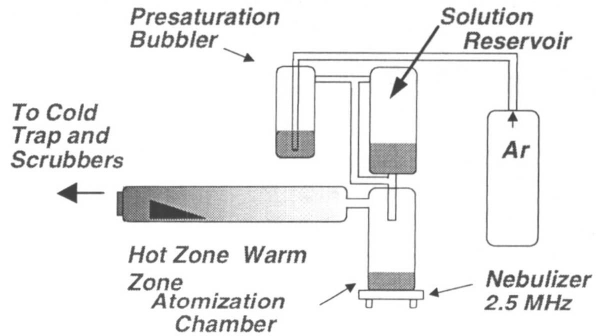
Overview of Technical Approach

- Low-temperature processing with Single-Source Precursors

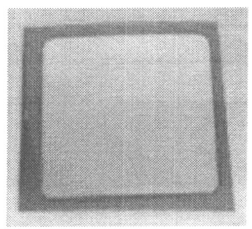


Single-source precursor

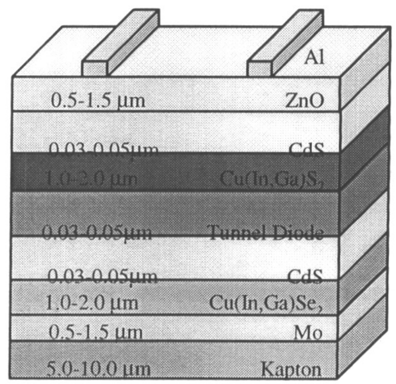


Horizontal Chemical Spray Pyrolysis or CVD Reactor

- Advanced materials (substrates) and novel devices (multi-junction)



Mo on polymer substrate



Multi-junction thin film device

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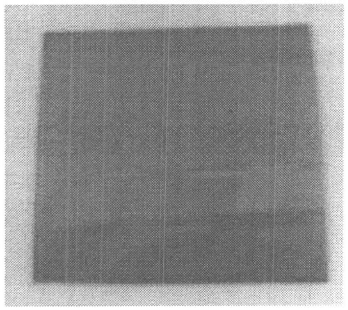
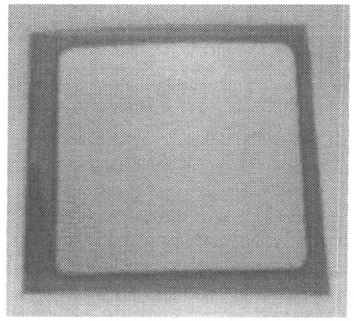
Polymer Substrates Require Low Processing Temperatures

Kapton™



A thin-film space qualified flexible polymer substrate

1 μm molybdenum deposited by rf sputtering



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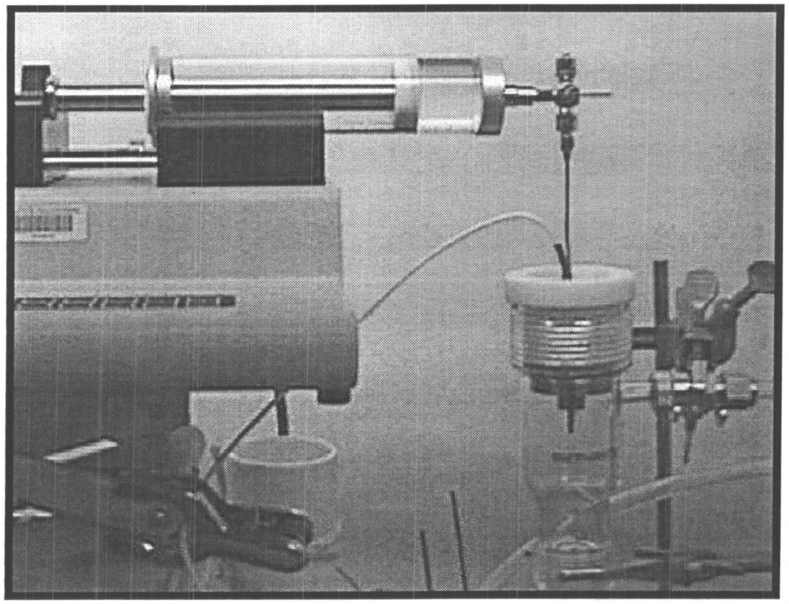
$CuInS_2$ Thin Film Deposited with Liquid Single-Source Precursor

- Method: Spray pyrolysis under Ar-flow (vertical cold-wall reactor), Commercial ultrasonic spray nozzle (freq: 120 kHz)
- Substrate temperature: 400 °C
- Precursor: Liquid phase single-source, $[\{P(n\text{-}Bu)_3\}_2Cu(SEt)_2In(SEt)_2]$ (Decomposition temperature: ~ 260 °C)



- No need to control the height of the liquid column (reliable droplet size distribution)
- No deposits at the wall and better transport of sprays (better yield)
- Easy to model aerosol dynamics to explore the process parameters

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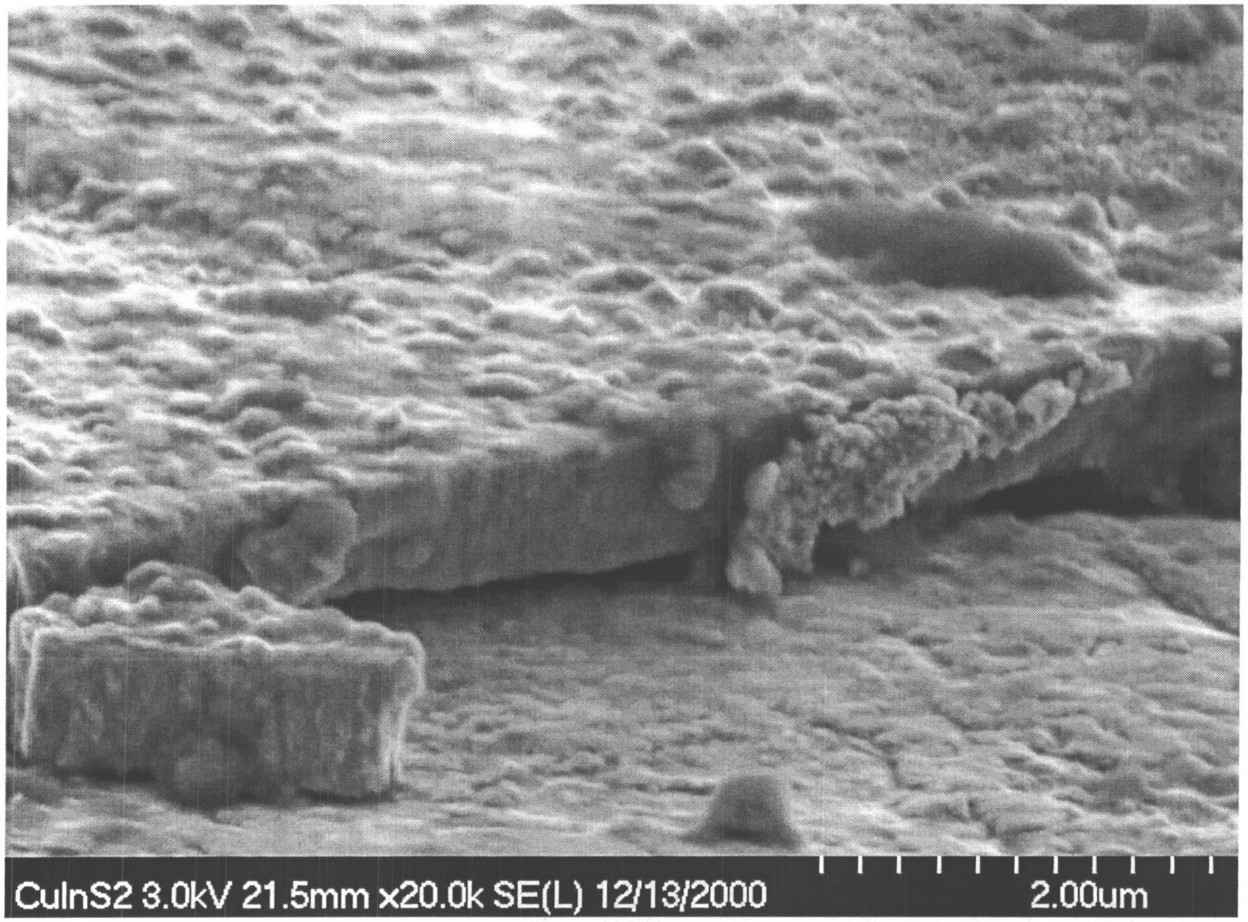
SEM of Surface of $CuInS_2$ Thin Film on Mo



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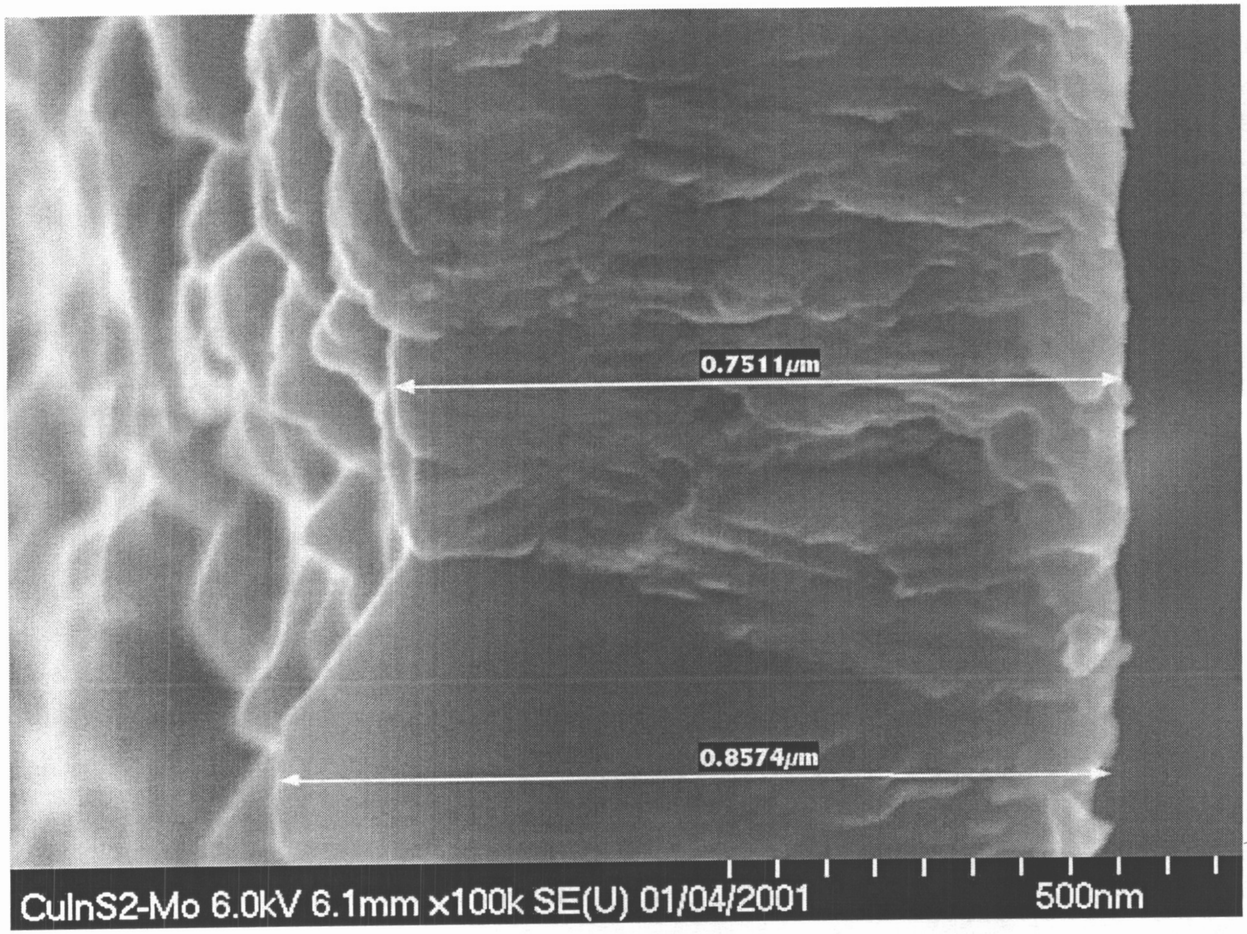
SEM of Edge View of $CuInS_2$ Thin Film on Mo



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EDS Spectrum for CIS_2

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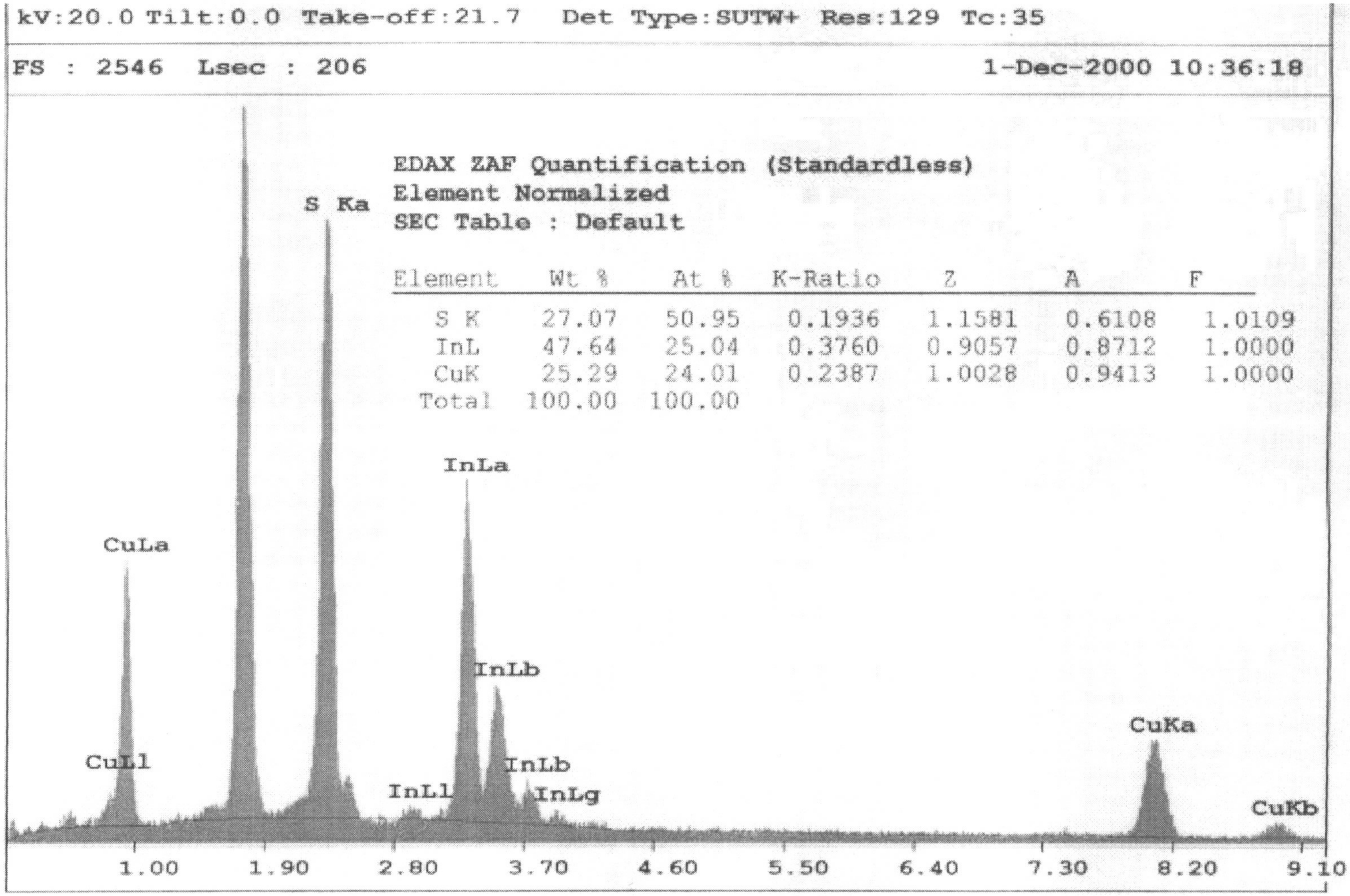

Element	Wt %	At %	K-Ratio	Z	A	F
S K	27.07	50.95	0.1936	1.1581	0.6108	1.0109
InL	47.64	25.04	0.3760	0.9057	0.8712	1.0000
CuK	25.29	24.01	0.2387	1.0028	0.9413	1.0000
Total	100.00	100.00				

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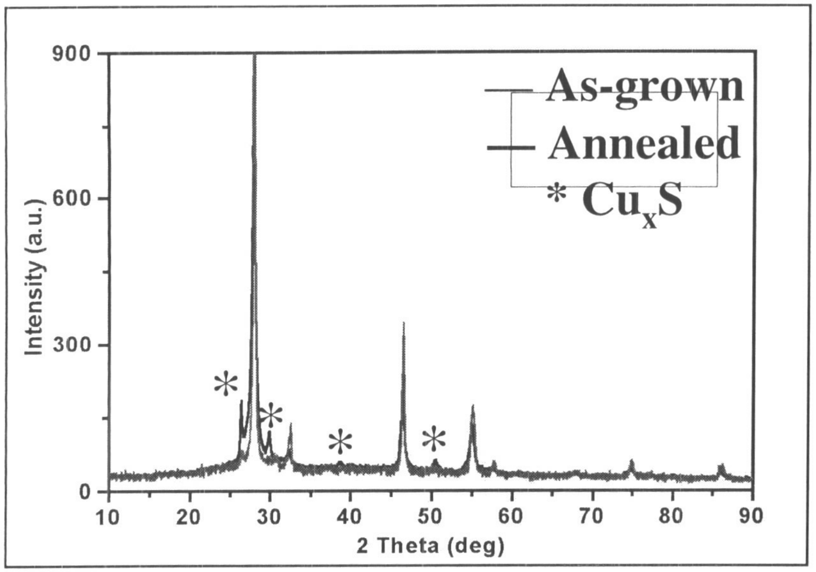
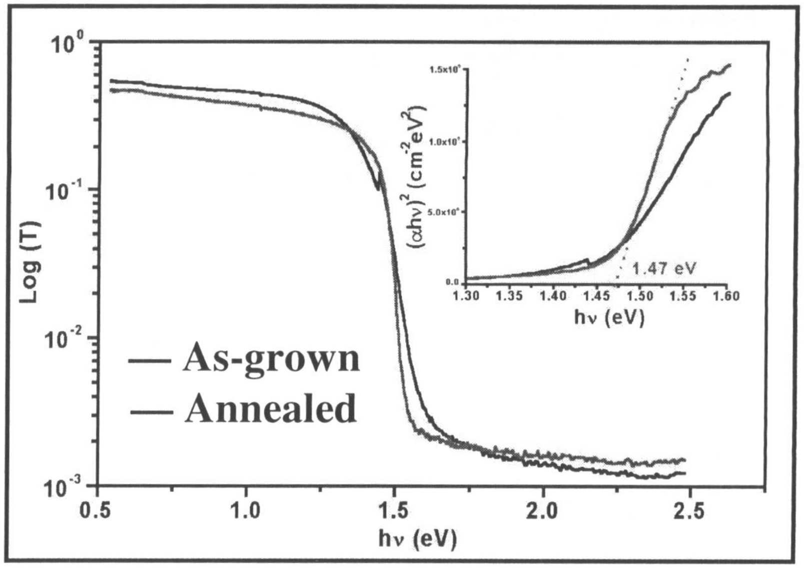
$CuInS_2$ Thin Film Deposited with Liquid Single-Source Precursor

X-ray diffraction and optical analysis





- Chalcopyrite-$CuInS_2$ confirmed with XRD and EDS.
- Volatile secondary phase can be easily removed by annealing.

- Band gap : ~ 1.47 eV after post-thermal treatment.
- Improved band-edge absorption after annealing.

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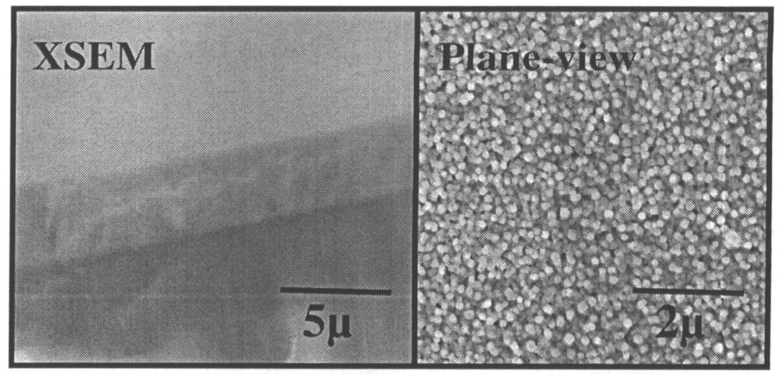
$CuInS_2$ Thin Film Deposited with Liquid Single-Source Precursor

Tencor profiler (Roughness)
RMS deviation: ~ 200 nm
(well agreed with grain size)

4 point probe measurement (Resistivity)
3~20 Ω-cm (before annealing)
1~5 Ω-cm (after annealing)

- Better yield: Growth rate > 3Å/s
- Grain size : ~ 200 nm



m m

Best conductivity among films grown with same family of single-source precursors synthesized at GRC

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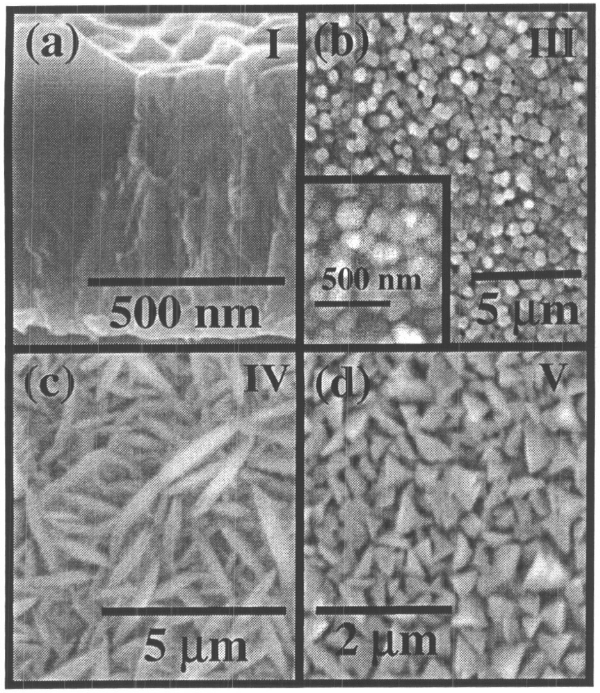
Texture and Composition of $CuInS_2$ Films by AACVD Using Single-Source Precursors



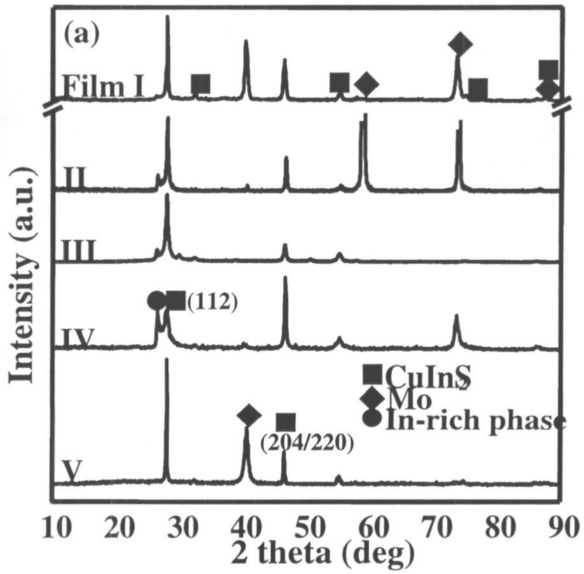
A - (A (s) @ 400°C; 760 torr)

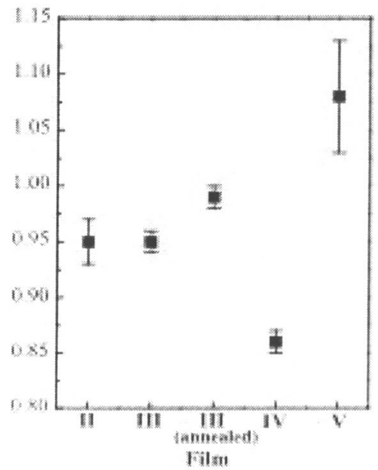
B - (B (l) @ 400°C; 760 torr)

C, D - (C (l) @ 400°C; 10 torr)

Dense, faceted grains: A & D

(Increased flow rate C to D)





- **(112)-Oriented films**
  - Without secondary phase
  - **Slightly Cu-rich**
- **(204/220)-Oriented films**
  - **In-rich**
  - Always included secondary phase
- Cu/In ratio increased by **removing the secondary phase**
  - Post-growth annealing at 600 °C
- Single-phase chalcopyrite $CuInS_2$ films with a **dense columnar grain structure** were obtained
  - Depositing (112)-oriented films
  - Grain size was small (≤ 0.5 µm)
    - Due to the absence of a quasi-liquid Cu binary phase
- **Further development necessary to grow films with higher [Cu] to obtain bigger grains suitable for solar cells**

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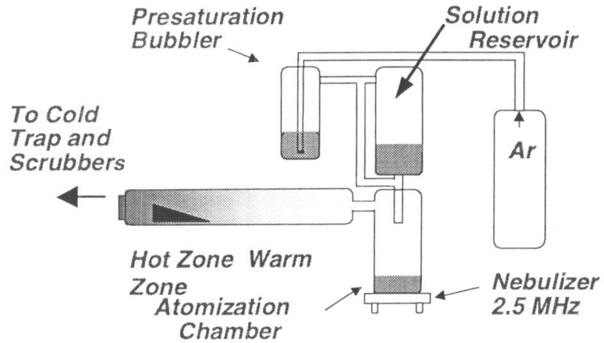
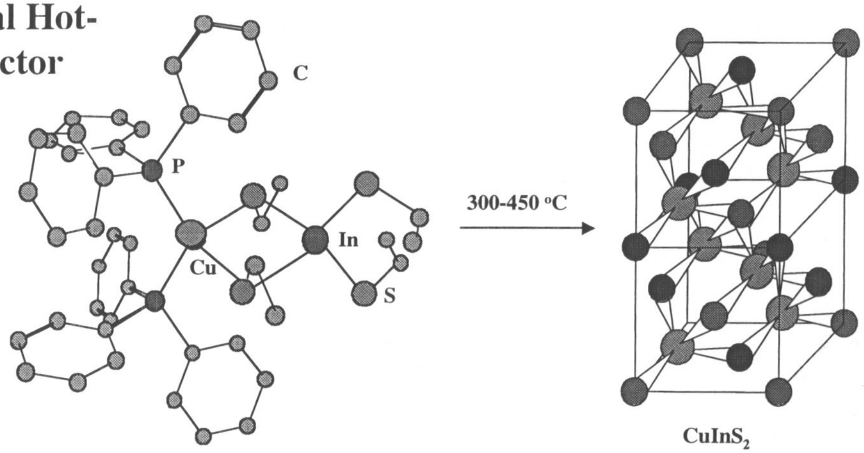
Low-Temperature Spray CVD Process for $CuInS_2$ Uses Single-Source Precursors



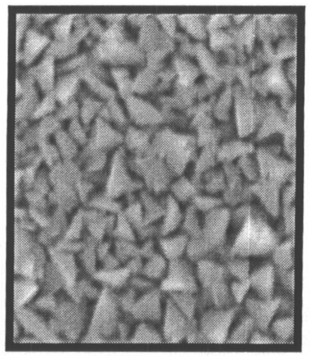
Schematic of Horizontal Hot-Wall Spray CVD reactor

Analytical Data for Series of Single-Source Precursors

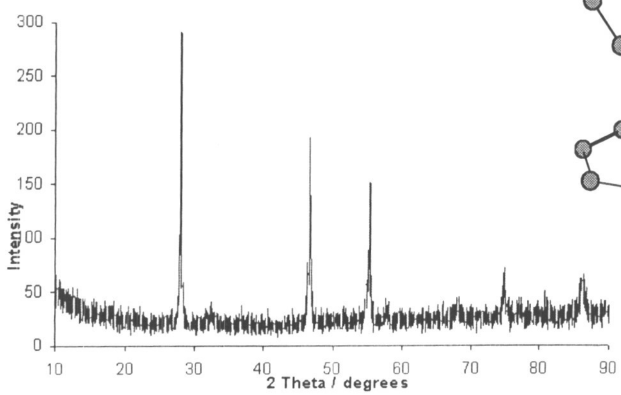
CIS/CISe Derivative	TGA		DSC	
	T°C@max % loss	% Residue	M.P. °C	Decomp. T°C
$[\{PPh_3\}_2Cu(SEt)_2In(SEt)_2]$	269	25	122	239, 266
$[\{AsPh_3\}_2Cu(SEt)_2In(SEt)_2]$	233	18	47	204, 276
$[\{SbPh_3\}_2Cu(SEt)_2In(SEt)_2]$	239	26	45	231, 271
$[\{P(n\text{-}Bu)_3\}_2Cu(SEt)_2In(SEt)_2]$	186	27	-	233, 269
$[\{PPh_3\}_2Cu(S(i\text{-}Pr))_2In(S(i\text{-}Pr))_2]$	254	29	163	260
$[\{PPh_3\}_2Cu(SPh)_2In(SPh)_2]$	325	22	117	170, 280
$[\{PPh_3\}_2Cu(SePh)_2In(SePh)_2]$	253	27	53	176, 219



Ball and Stick Schematic of Single-Source Precursor Synthesis of $CuInS_2$



SEM of Dense Faceted $CuInS_2$ CVD-Produced at 400°C (0.2 μm grains)



XRD Pattern of Single-Phase $CuInS_2$ Produced from Liquid Single-Source Precursor

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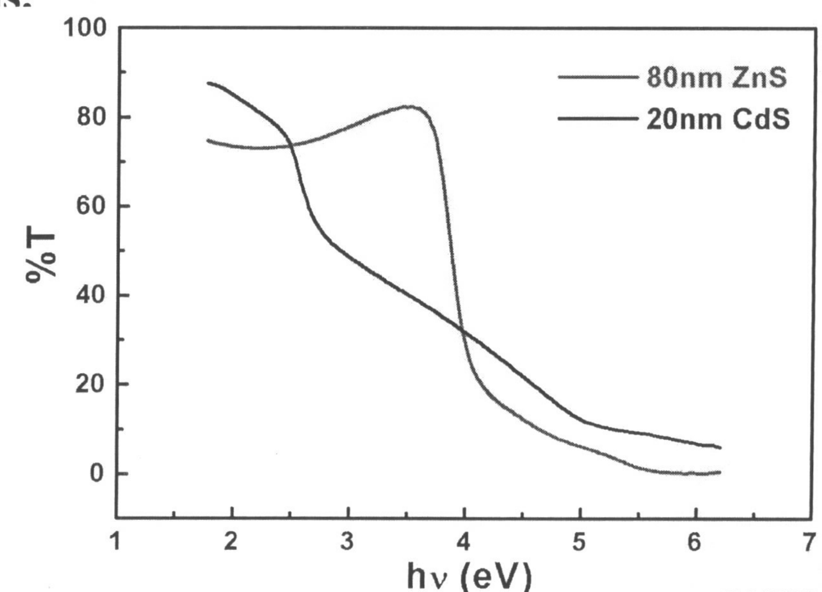
Interface Engineering

- Alternatives to CdS
  - **(Cd,Zn)S : Band gap (2.5 ~ 3.5 eV), ΔE_c (-0.45 to 0.5 eV).**
  - **Interface engineering: Cd or Zn solution treatment (n-type doping) followed by CdS deposition.**
- Advantages of chemical bath deposition over PVD
  - **Simple, easy, less damage, and conformal deposition.**
  - **Removal of the native oxide on the $CuInS_2$ surface re-establishing positively charged surface states for natural n-type inversion.**
  - **Doping effect from Cd ions.**

- CdS and ZnS thin films deposited using non-toxic complexing agents (tri-sodium citrate and ammonia)
  * hydrazine hydrate is commonly used.
- Barrier : single phase formation instead of solid solution.



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Tony Sutorik - MSU
Jen Hollingsworth - WUStL
Eva Lau - SUNYA (OAI)

Conclusions:
Thin Film Technology Issues

Thin-Film Arrays will be used in space WHEN…

- Thin-film *cell efficiencies increase* and/or *substrate mass decreases*
  - ✓Need economical large-scale production of large-area (>10-cm^2) thin-film cells with stable efficiencies > 10% to 15% (1-Sun AM0) on low-mass substrates (1-mil metallic, 5-mil composite, 2-mil polymer)
- Thin-film cell *space qualification* is completed
  - ✓Need to demonstrate tolerance to radiation, thermal cycling (delamination), mechanical strain (packaging and blanket tensioning) and (for amorphous silicon) light-induced instability
- Thin-film *solar arrays* are designed and *space qualified*
  - ✓Need packaging, deployment systems and support structures tailored to thin-films
- *Appropriate missions* are identified…
  - ✓…that would benefit from thin-film array attributes (high specific power, good package-ability, radiation tolerant, low cost – e.g. Solar Electric Propulsion missions)
  - ✓…whose benefits are not mitigated by spacecraft-level operations issues associated with larger area, low-mass arrays