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FLEXIBLE COPPER-INDIUM-DISELENIDE FILMS AND DEVICES FOR SPACE APPLICATIONS*

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With the ever-increasing demands on space power systems, it is imperative that low-cost, lightweight, reliable photovoltaics be developed. One avenue of pursuit for future space power applications is the use of low-cost, lightweight flexible PV cells and arrays [1]. Most work in this area assumes the use of flexible amorphous silicon (a-Si), despite its inherent instability and low efficiencies. However, polycrystalline thin-film PV such as copper-indium-diselenide (CIS) are inherently more stable and exhibit better performance than a-Si. Furthermore, preliminary data indicate that CIS also offers exciting properties with respect to space applications. However, CIS has only heretofore only produced on rigid substrates. The purpose of this investigation was first to explore the implications of flexible CIS upon present and future space power platforms. Results from this investigation indicate that space-qualified CIS can dramatically reduce the cost of PV, and in most cases, can be substituted for silicon (Si) based on end-of-life (EOL) estimations. Furthermore, where cost is a prime consideration, CIS can become cost effective than gallium-arsenide (GaAs) in some applications. Second, investigations into thin-film deposition on flexible substrates were made, and data from these tests indicate that fabrication of flexible CIS devices is feasible. Finally, data will also be presented on preliminary TCO/CdS/$CuInSe_2$/Mo devices.

INTRODUCTION

Emphasis from DoD on large space-power platforms and from NASA regarding the Space Exploration Initiative (SEI) identify the need for advanced photovoltaics for future space-power programs. In particular, prospects for future exploration on the lunar and Martian surface clearly illustrate the need for inexpensive, lightweight power systems. Prospects for a nuclear power solution have fallen into disfavor politically based on safety issues during launch, and increasing weight requirements for shielding. Other power alternatives exist, but photovoltaics (PV) have a definite advantage in that it requires no additional safety considerations and PV have proven reliable in many years of space flight. Concerns regarding this technology are (1) stability in space environment often results in significant reduction of initial power ratings and (2) cost of these facilities is often accelerated by the amount of hand-layup, manual interconnection, and the associated quality control.

While design improvement can attempt to minimize the effects of space environment, inherent material issues remain. A baseline for end-of-life (EOL) for PV after 7 years in geosynchronous orbit (GEO) is a 25-40% reduction in maximum power from a silicon-based array, and 15% for a gallium-arsenide. Based on these numbers, array

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size must be designed not on the basis of beginning-of-life (BOL) efficiencies, but on projected EOL for a particular mission. At this rate, the glamour of multi-junction, high (BOL) efficiency devices is often subdued by the reality of EOL projections of a particular array.

Further concern regarding PV is the weight associated with the PV blanket and the subsequent support structure needed to hold the array. Often, GaAs is used for applications with requirements for high efficiency due to a need for minimum array area and weight. Conventional GaAs, however is both expensive and heavy, although array weight is typically more crucial than blanket weight in these instances. Advanced GaAs on germanium and thin GaAs improve on its weight, but the fragile nature and small size of all GaAs, particularly thin GaAs, could lead to increased cost during fabrication.

One recognized solution to this dilemma is the use of thin-film PV, primarily amorphous silicon (a-Si). Thin-film devices such as these fabricated over large areas (minimizing installation labor) possess high power-to-weight ratios despite moderate beginning-of-life BOL efficiencies. However, a-Si possesses inherent instabilities in ultra-violet light which results in rather dramatic power reduction by EOL [2]. New cell designs utilizing a-Si can improve their performance in space, but the inherent instability in a-Si devices remains [3].

Polycrystalline thin-film PV such as CIS offer the promise of an alternative to Si for most applications, and possible substitution for GaAs where space environment and cost, not array size, is a primary concern. CIS has the highest tolerance of any PV material for radiation (Fig. 1), and has proven itself far more stable than single-junction a-Si (Fig. 2) [2,4]. These devices, which nominally do not exceed 5-8 μm thickness (excluding substrate), have been reported with efficiencies as high as 14% with promise soon to exceed the 15% efficiency goal set by SERI/DOE [5]. Although most of the work on these materials have been towards terrestrial applications, excellent work at Boeing [6] indicate that these materials can indeed excel in a space environment.

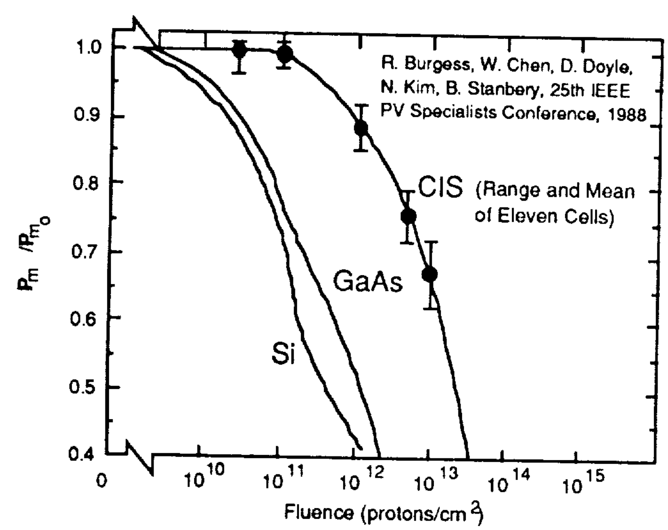

Figure 1 - Effects of 1 MeV Proton Exposure as a Function of Fluence in Terms of Percent of Original Power Output.

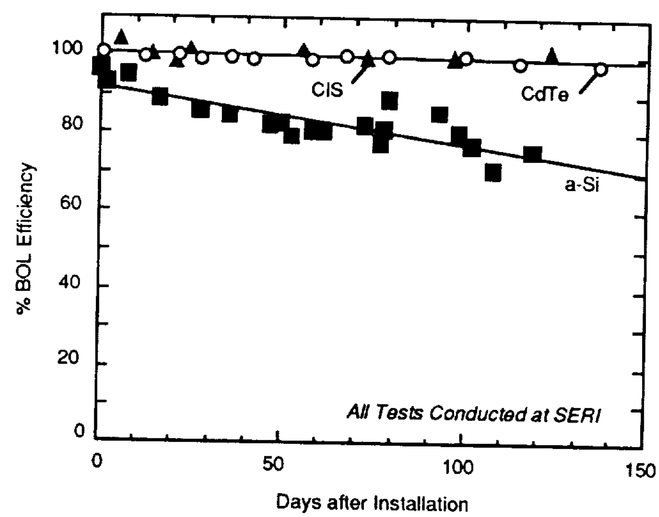

Figure 2 - Stability of Thin-Film PV Technologies as a Function of Time of AM 1.5 Insolation in Terms of % BOL Efficiency.

As a result, Martin Marietta has initiated an effort to investigate CIS for space applications. Reported here are the results of investigations into potential cost and weight savings from CIS on future large space-power platforms. Secondly, initial investigations into deposition of CIS and CdS/CIS stacks on flexible substrates will be reported. Finally, the first flexible CIS cells will be shown and preliminary performance values will be given.

COST ANALYSIS FOR SPACE POWER APPLICATIONS

Most certainly one of the most difficult aspects of PV system design with a new technology is the true cost of array fabrication for space applications. When discussing CIS for terrestrial applications, the cost to produce devices is often clouded by extremely large volume projections that do not coincide with demands in the space power community and lack of stringent reporting and quality control. In this light, special care was taken to evaluate the cost of these materials based on realistic material cost. Emphasis also focused on incorporating the most enticing features of CIS, namely large-area deposition and monolithic integration, into the cost estimate. Chosen for a baseline is a future 10 kW space-based array (with both DoD and NASA significance) presently identified as using silicon.

Table 1 illustrates the calculations used to calculate space-qualified CIS for this investigation. Because of the high labor cost required for space-qualified PV, the size of the individual cells is important to cost reduction. Thus, technologies such as polycrystalline thin-film PV has two major advantages: first, the size of the device can be easily scaled to sizes larger than that found in Si and GaAs technology, and second, low-cost monolithic integration techniques compatible with thin-film deposition technology can produce low-cost modules. These advantages are clearly shown in Table 1 as monolithic integration of modules on only a 30.5 x 30.5 cm scale (1 ft^2) will have tremendous cost savings on space-qualified PV arrays. Furthermore, if a large volume market exists for space in the near future, material costs as low as $10-12 per square foot could be realized [7].

Table 1 — Breakdown Estimates for PV Blanket Fabrication Cost

	Single Crystal Silicon	Polycrystalline Thin-Film CIS	Polycrystalline Thin-Film CIS Module§
Cell Stack Total ($)*	70.0	61.0	19.5
Cell Cost ($/$ft^2$) (@99 Cells/$ft^2$, 85% PF)	6930	6039	1930.5
Laydown Cost ($/$ft^2$)	2779	2779	28.0†
Total Cost ($/$ft^2$)	9709	8818	1958.5
Total Labor ($/$ft^2$)	6739	6739	562.0
Total Material ($/$ft^2$)	2970	2079	1396.5

* Includes Cell Cost, Interconnects, Testing, Assembly, Cover Glass, and Reporting
§ Monolithically Integrated
† Labor Reduced by Large Device Size

END-OF-LIFE PERFORMANCE ANALYSIS

The most important criteria when designing a PV power system is the performance of such a device in a space environment. In many cases, cost savings are sacrificed in the process of meeting mission requirements. As was discussed earlier, EOL comparisons of these materials for a chosen mission are the only true basis of comparison. Factors used in this analysis include temperature performance, radiation degradation, packing factors, assembly losses and solar variance (Table 2). For this estimate, 50 μm (2 mil) silicon and 300 μm (≈12 mil) cells were selected as conventional technology. Because CdTe and CIS technologies require thin-film deposition onto a substrate, the specific power of these devices is critically dependent upon the choice of substrate. For CIS, a 6.25 μm (1/4 mil) flexible metal foil was chosen as a substrate (flexible cell design) and 50 μm (2 mil) glass was chosen as a superstrate. While cost projections were made on cells with cover glass, weight estimates for all technologies assume no cover glass. Values for thermal performance were established for Si and GaAs, CIS performance was predicted by typical 2 mV/°C variance from 28°C with a nominal 490 mV output. Efficiency factors for CIS and CdTe were estimated at 11% (AM0) for reasonable near-term efficiencies. Packing factors for Si and GaAs are based on hand layup while CIS and CdTe assumes monolithic integration. Packing factor for CIS and CdTe is assumed to be higher than conventional technology due to monolithic integration.

Table 2 - Basis of Performance Estimates for Conventional and CIS Space Power

Material	Solar Radiance W/m²	Areal Density kg/m²	Blanket Cost k$/m²	Thermal Deg (%/°C)	Radiation Damage (%)	Assembly Loss (%)	Packing Factor (%)	Solar Variance (%)
Si	1352.53	0.37	104.48	0.5000%	25.00%	98.00%	85.00%	98.60%
GaAs	1352.53	1.51	192.60	0.1300%	15.00%	98.00%	85.00%	98.60%
CIS	1352.53	0.08	20.98	0.3900%	2.00%	98.00%	95.00%	98.60%
CdTe	1352.53	0.12	20.98	0.2400%	2.00%	98.00%	95.00%	98.60%

Table 3 — BOL Estimates for Arrays

Material	BOL Cell Efficiency (%)	BOL Array Efficiency (%)	BOL Cell Power W/m²	BOL Array Power W/m²	BOL Cell Density (W/kg)	BOL Array Density (W/kg)
Si	14.50%	11.91%	196.12	161.08	535.60	439.91
GaAs	18.00%	14.78%	243.46	199.96	161.02	132.25
CIS	11.00%	10.10%	148.78	136.57	1770.42	1625.19
CdTe	11.20%	10.28%	151.48	139.06	1263.77	1160.10

Array Performance at 28°C

EOL array performance projections are shown in Table 3. Strictly on BOL power and efficiency estimates for arrays, CIS cannot compete with GaAs and direct competition with Si is only significant in terms of power-to-weight ratio. Based on these data, one critique of future use of polycrystalline thin-film devices is that their lower efficiency would increase array size, thereby contributing to difficult station-keeping and drag in low earth orb its (LEO). Furthermore, larger array size would contribute to weight gain on the spacecraft. Once again, the required array area must be based on EOL projections alone. On the basis of data presented in Tables 2 and 3, the following results were determined for BOL performance of arrays manufactured with these technologies (Table 4).

Table 4 — EOL Estimates for Arrays Indicating Stability of CIS and CdTe

Material	EOL Cell Efficiency (%)	EOL Array Efficiency (%)	EOL Cell Power W/m²	EOL Array Power W/m²	EOL Cell Density (W/kg)	EOL Array Density (W/kg)
Si	10.88%	8.93%	147.09	120.81	401.70	329.93
GaAs	15.30%	12.57%	206.94	169.97	136.86	112.41
CIS	10.78%	9.90%	145.80	133.84	1735.01	1592.68
CdTe	10.98%	10.08%	148.45	136.28	1238.49	1136.90

Data in Table 4 reflect the degradation in performance due to radiation damage after a 7 year mission at GEO. CIS and CdTe exhibit similar to superior performance compared to silicon-based cells in terms of EOL array efficiency and power output. Arrays with CIS have nearly a factor of five higher power-to-weight ratio than silicon, and over 14 times lighter than a comparable GaAs system. Clearly, CIS and CdTe could be substituted for silicon in these cases with a corresponding reduction of weight due to smaller arrays and a lighter PV blanket.

Array Performance from -70 to +100°C

While data presented in Tables 3 and 4 were based on 28°C, it is imperative that estimates as a function of temperature be determined. Typically, high temperature applications (T>70°C) are usually dedicated to GaAs due to its temperature stability. Although performance from CIS and CdTe diminishes more with temperature than GaAs, EOL efficiency and areal power output of CIS and CdTe arrays can come close to the performance of GaAs due to their stability in a GEO environment (Fig. 3). Furthermore, at lower temperatures (martian bases, space probes) these thin-film technologies can outperform GaAs.

Power-to-weight ratio of these PV technologies as a function of operating temperature is shown in Figure 4. As was evident from Tables 2 and 3 earlier, flexible CIS clearly has a tremendous advantage in specific power, while CdTe on thin glass also has significant advantage over conventional technologies. At higher temperatures CIS and CdTe exhibit nearly the same specific power, which is a factor of five higher than Si and even greater than GaAs.

PV Blanket Cost with Respect to Operating Temperature — As was shown earlier in Table 1, cost is also a major advantage to polycrystalline thin-film PV. Based on EOL array performance, CIS and CdTe often exhibit an order of magnitude cost reduction over conventional space-power PV technologies, particularly at higher temperatures when compared to silicon (Fig. 5).

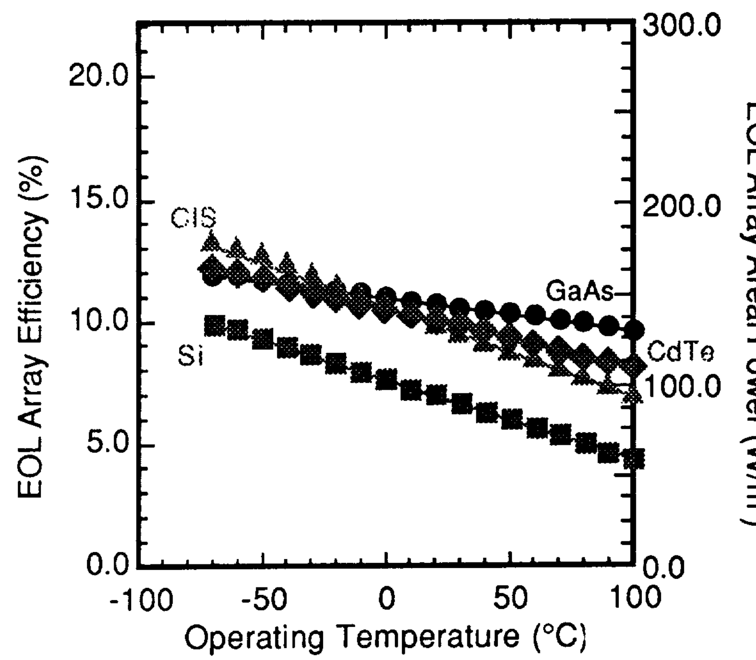

Figure 3 - EOL Array Efficiency and Areal Power for Conventional and Polycrystalline Thin-Film Technologies.

LIGHTWEIGHT, FLEXIBLE CIS DEVICES

By virtue of the thin-film nature of CIS, it should be possible to deposit the necessary layers onto a flexible substrate. This concept has two major advantages: first, the thin-film nature of these cells dictates the majority of the weight will reside in the chosen substrate, and second, techniques commonly used to deposit metallic films on kapton for space applications (e.g. reel-to-reel continuous deposition) lends itself to extremely large-area deposition. Selection of the substrate material must be made not only on the basis of weight, but also with regard to surviving the processing associated with CIS device fabrication. Monolithic integration will be required to minimize the potential for failure of manually-interconnected cells. Finally, a suitable flexible top coating must be investigated which will provide protection from atomic oxygen (AO) for low earth orbits and will serve as an anti-reflective (AR) coating.

Little work has been accomplished in the area of flexible polycrystalline thin-film devices. The majority of the work conducted in this area is in amorphous silicon [8] despite concerns over stability with these devices. However, progress has been made with flexible a-Si over large areas by continuous deposition, thereby validating this concept for CIS as well.

Significant progress has been made by Martin Marietta and ISET in the area of flexible CIS films and devices with suitable adhesion. Experiments with absorber, window, and top contact layers and devices deposited onto thin flexible metallic foils (6.25 -25 μm thick) have proven successful. The $CuInSe_2$ was formed by evaporation using the ISET two-stage process [9, 10], while a CdS window layer was deposited by chemical immersion deposition. Figure 6 shows a glancing incidence diffractometry (GID) scan of a CIS film deposited onto a 25 μm Mo substrate, indicating that both $CuInSe_2$ and $CuIn_2Se_{3.5}$ are observed. Further investigations are in progress to determine if the existence of $CuIn_2Se_{3.5}$ is an

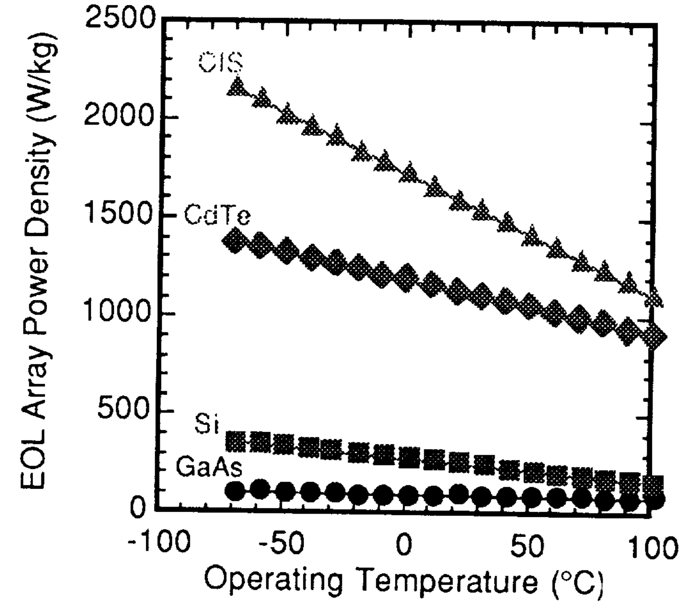

Figure 4 - EOL Array Power Density for Conventional and Polycrystalline Thin-Film Technologies.

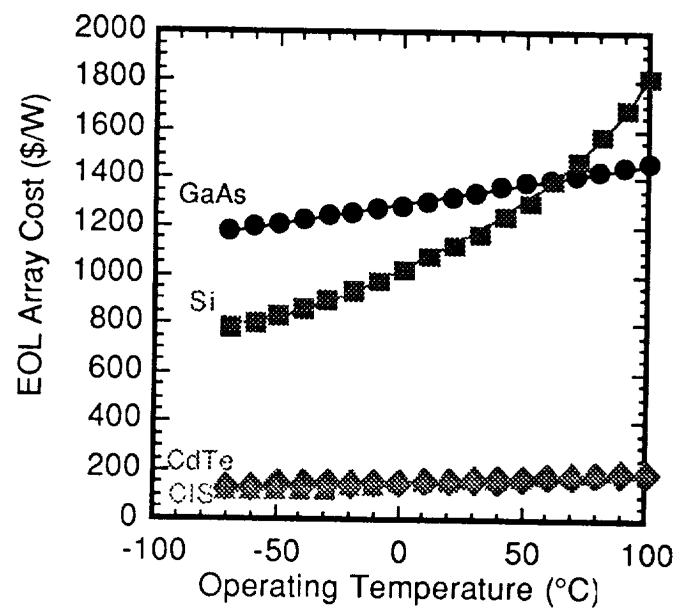

Figure 5 - EOL Array Cost for Conventional and Polycrystalline Thin-Film Technologies.

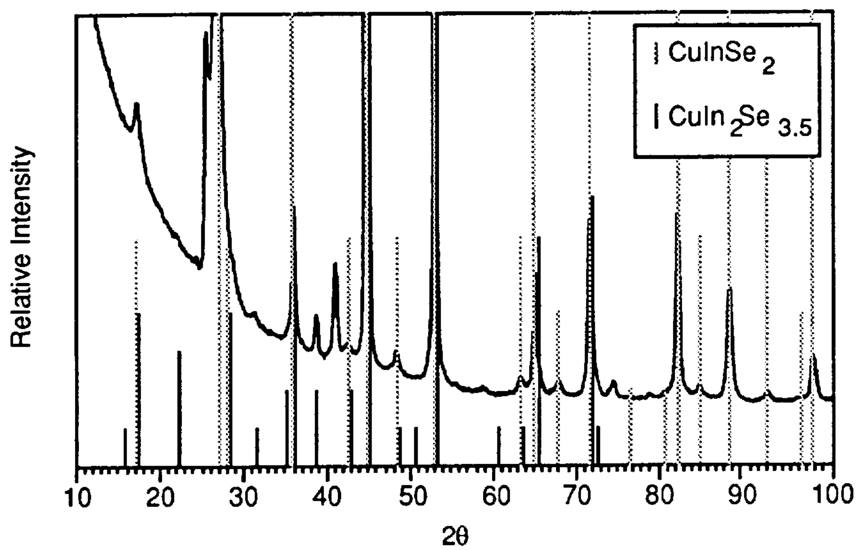

Figure 6 - Glancing Incidence Diffractometry (GID) of CIS Film on Molybdenum Substrate Indicating Presence of Two Phases.

artifact of the thin foil substrate or a component previously unseen with other X-ray diffraction technologies. Early coatings failed conventional tape pull tests, although sufficient adhesion existed with later films and devices to allow bending easily to a minimum radius of 0.75 cm. Furthermore, early films on thin substrates exhibited residual stresses which tended to curl specimens slightly upward. Subsequent improvement of deposition techniques has improved adhesion and reduce residual stresses.

Flexible cells were fabricated using this technology. Figure 7 is a schematic of the flexible CIS cell, indicating that a majority of the cross section is the substrate material. This indicates that significant work is still required to develop a lightweight substrate capable of handling temperatures and environments during fabrication while remaining pliable. A photograph of a flexible CIS cell is shown in Figure 8 which exhibited 6% efficiency (AM1.5).

SUMMARY

Future space-power applications will require PV technologies to be lighter, cheaper, and more stable. These requirements are paramount to the funding of aggressive projects involved with space exploration and large-scale space-power platforms. Three key advantages to polycrystalline thin-film PV for space applications are (1) potential for high power-to-weight ratios, (2) charged-particle environment stability, and (3) low-cost fabrication techniques. From a system design point-of-view, these technologies have great potential for low-cost, lightweight, stable PV for future space power applications. Given the climate within NASA and DoD, the timely development of these polycrystalline thin-film technologies is essential to the future of PV in space exploration.

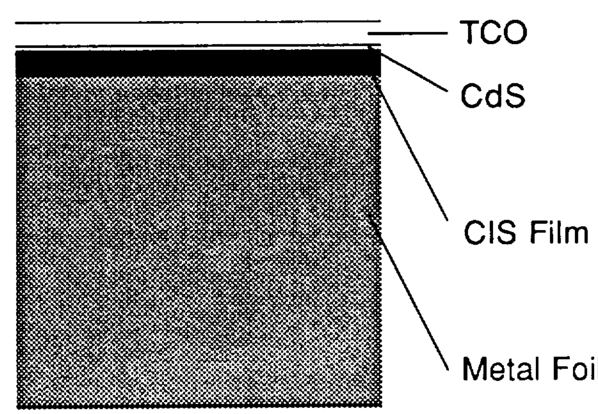

Figure 7 - Schematic of Flexible CIS Cell.

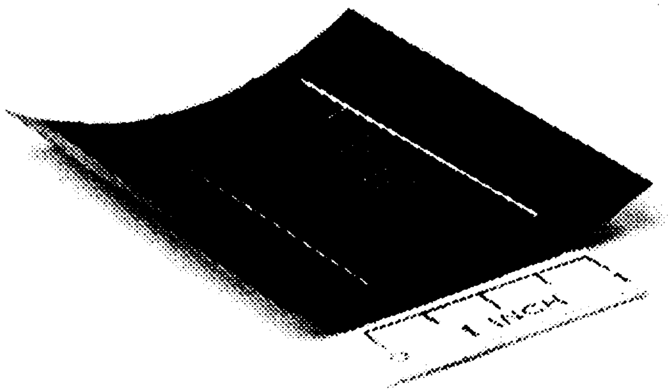

Figure 8 - Photograph of CIS Cell on Flexible Molybdenum Substrate.

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