THE PAST, PRESENT AND FUTURE OF SPACE PHOTOVOLTAICS

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ABSTRACT

This paper discusses the migration of crystalline space solar cell technology from silicon, to gallium arsenide then to the multiple junction devices in use today. Thin film technologies have migrated from the Cu_2S/CdS and similar cells to the amorphous silicon multijunction devices to copper indium diselenide devices. Array technologies have moved from flat plate arrays with shingled cells to concentrator arrays of several designs – some of which have reinvented 40-year old approaches. Crystalline cell efficiency in space has risen from about 10% to 30%, whereas thin film cell efficiency has risen from about 5% to 12%. Array specific power has gone from about 20 W/kg to over 300 W/kg (in design). Arrays have flown away from the sun to about 3 AU and are on their way to Mercury. Opportunities for future cell research will be included with the promise of devices with efficiencies over 40%.

INTRODUCTION

Space photovoltaic arrays have been flying since 1957 – just three years after the effect was discovered in silicon! The initial flight on the grapefruit-sized Vanguard satellite used silicon cells as the power source. Interestingly, the other option that received serious consideration was single crystal CdS with a Cu_2S active layer. These cells were 1x1 cm in size. However, because of the use of silicon in the electronics industry, the silicon solar cell grabbed the lead in space. The only space missions that did not use a photovoltaic power system were those that either went away from the Sun, beyond Mars that needed radioisotope sources or that were powered by a nuclear reactor.

THE SPACE ENVIRONMENT AND MISSION TYPES

Space Environment

There are three general earth orbital conditions: Low Earth Orbit (LEO), Geosynchronous Earth Orbit (GEO) and mid-Earth Orbit (MEO). The first two are the orbits where most satellites fly. LEO is fairly benign – limited space radiation but atomic oxygen and micrometeoroids. These orbits are used for earth observation and space stations. On the other hand GEO has no atomic oxygen but electron and proton space radiation (plus solar flares). Another issue that affects GEO satellites is space charging that can lead to serious arcing and loss of the power system. This orbit is used primarily for global weather and communications satellites. Figure 1 shows a schematic representation of the Earth-Sun radiation environment and the magnetic field of the Earth that leads to the Van Allen radiation belts. MEO orbits have very high radiation doses so have not been heavily used – Global Positioning System and other observational spacecraft will use these orbits. Of course, lunar orbits and those at the Earth-Sun and Earth Moon libration points are now being explored.

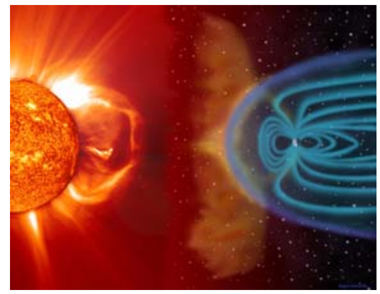

Figure 1: Earth-Sun Environment

For missions that go toward the Sun to Venus or Mercury, temperature in the primary issue, although solar flares are also a consideration. Examples of these missions are the MESSENGER spacecraft heading to Mercury and several Venus-orbiting missions to map the surface with radar. At Mercury, the solar intensity is about 9400 W/m^2, and solar array temperatures can reach over 200 ºC unless special designs are used. No solar arrays can be used on the surface of Venus due to its high temperature and opaque atmosphere.

Solar arrays can easily be used at Mars, as evidenced by the Mars Exploration Rovers "Spirit" and "Opportunity" that continue to operate well with horizontal solar arrays. At Jupiter solar arrays meet with substantial challenges. The distance from the Sun (5.2 A.U.) and the intense radiation belts that are several orders of magnitude worse than those around the Earth serve to limit the use of solar arrays there. But with the modern lightweight, radiation-tolerant array designs, solar-powered missions there are possible. Beyond Jupiter, the solar intensity falls too low to make solar arrays practical options for satellite power supplies.

CRYSTALLINE SOLAR CELL OPTIONS

There are four general classes of space solar cells at the present time: silicon cells, multijunction crystalline cells, thin film cells and emerging cells such as quantum dot cells. Use of silicon cells in space has nearly phased out. A plot prepared by the National Renewable Energy Laboratory shown in figure 2 provides a 30 year look at the progress of cell type and efficiency for terrestrial cells. Note that space efficiency (AM0 conditions) is about 15% lower than these values.

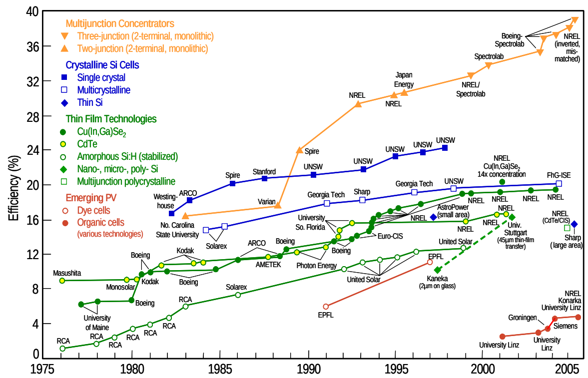

Figure 2: Trends in solar cell efficiency (AM1.5 values)

Silicon solar cells

The solar cell is deceptively simple. Many companies have been fooled by that apparent simplicity, albeit simple, it is not easy to make with high efficiency. The early p/n silicon cells were about 7% efficient. The efficiency climbed from that level to over 17% in the next 20 years – a rate of 0.5% in efficiency per year. Furthermore, because of the results of high altitude nuclear weapons tests, the p/n cell was quickly replaced by the n/p design for increased radiation tolerance. Major experimental and theoretical advances led to understanding of the back surface field, multi-layer antireflection coatings, surface texturing, wrap-through contacts, mid-gap and heavy doping effects, radiation tolerance, dopant types, wide temperature performance and metallurgy. There is not enough room here to be more specific, but reference to the 2nd to the 15th IEEE Photovoltaic Specialists Conference proceedings will provide exceptional detail on these advances. Research on this cell for terrestrial uses has pushed its efficiency beyond 20%. This cell laid the foundation for further theoretical understanding and new designs; it is no longer a significant option. Although a few satellites still prefer these cells, manufacture of them in the US has virtually stopped.

GaAs-based III-V Solar Cells

A major breakthrough occurred in 1982 with development of an 18% efficient (AM0) 2x2 cm GaAs cell made by liquid phase epitaxy. This major efficiency increase led to several programs that successfully produced the cells by vapor phase epitaxy. The costly GaAs substrate was soon replaced by Ge which remains in use today. The use of vapor phase epitaxy has directly led to the development of the multijunction cells of today. Today's triple junction solar cells have reached efficiencies of 30% and 33% efficiency is likely to be achieved by 2008 as shown in figure 3.

These levels of performance are stunning, but the path to efficiency as high as 40% is projected in the next decade. Approaches used are examining four to six-junction cells and various metallurgical approaches. One exciting new

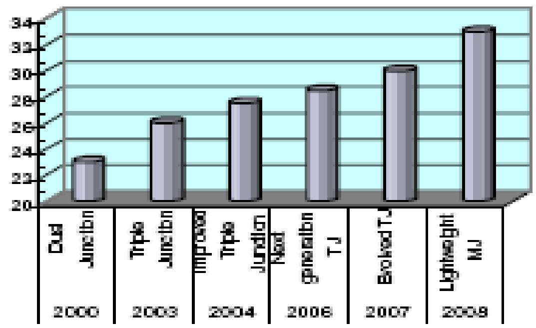

Figure 3: Multi-junction solar cell efficiency trends (%)

opportunity is emerging in production of 10µm thick triple junction cells. A critical issue for these cells is the means of interconnection. Thin cells require thin interconnects or some other approach. If many issues in production and array fabrication are solved, these cells can lead to planar arrays with specific power in excess of 1kW/kg.

THIN FILM SOLAR CELL OPTIONS

CdS/Cu_2S Cells

There has been a strong fascination with thin film solar cells since the beginning of the 1960s. The allure of the thin film cell has been the potential high specific power and for "roll-to-roll" manufacturing (cost reduction). The limitation of the thin film cell has been its low efficiency. As a point of reference, figure4 shows a CdS/Cu_2S solar cell produced in 1979. It is still functioning today. In 1979, this Kapton-covered cell had an efficiency of ~5%. Had it been covered with a transparent cover, it would have achieved about 7%. A 23.5 ft^2 array with bi-stem deployment was also demonstrated in the mid-1970s. These cells were space cycle tested in vacuum and thermal expansion mismatch issues were apparent. In addition, process control and cell uniformity in production proved problematical. All these challenges have been seen in present thin film efforts. This cell was also resistant to electron and proton radiation and the damage could be annealed (just as in other thin film cells).

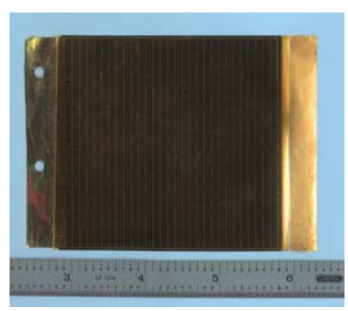

Figure 4: Cu_2S/CdS thin film cell

Amorphous Silicon Cells

The amorphous silicon cell has received substantial attention over the past 30 years. From a single junction device to a triple junction Si/SiGe/SiGe cell, the efficiency has not risen above 10% in large area cells. Roll-to-roll production is producing megawatts of arrays for terrestrial use, with volumes continually increasing. In addition, space array designs up to 130 kW have been developed, but none have flown. The low efficiency is proving hard to overcome. Also, the device shows the Staebler-Wronski effect which causes a loss in power of about 15-20% upon illumination. Attempts to solve this by allowing the cell to become microcrystalline have not succeeded. Thus its future use in space may be questionable.

Copper (Indium/Gallium) Diselenide Cells

The most promising thin film cell is the copper indium-gallium di-selenide (CIGS) cell. This cell shows stability under illumination and has a space efficiency of 10-12%. It is resistant to radiation damage and the damage can be annealed. However, the low efficiency still becomes a limiting factor. Production of cells has not had the uniformity needed for space use and issues of pin holes and short circuits remain problematical. In addition, matching thin film cells into an array will require cell matching which will require further manufacturing control. Because most space arrays operate at ~70 VDC, issues of reliable series connection of these cells becomes paramount. Arc discharges may also be an issue. Temperature cycling of these cells has uncovered thermal mismatch issues and the need for a protective coating has been shown to be essential. Because of the substantial fluence of low energy protons in the earths' radiation belts, it appears that at least 25 µm of a transparent protective layer will be required to prevent annihilation of the cells. This will erode the cell specific power.

Emerging Devices

A wide range of new thin cell options are being developed. These include nano-composite and quantum well cells, quantum dot cells, dye cells and organic cells. Quantum dot cells provide the hope of achieving full use of the solar spectrum with efficiencies exceeding 50%. Quantum dots of many appropriate materials are available and the means of interconnecting the dots and achieving power seem to be under control. However, efficiencies remain low. One novel approach is shown in figure 5 wherein quantum dots are attached to single wall nano-tubes. This attachment provides a host that is conductive and allows multiple size dots to be attached. Thus it may offer a new way to boost efficiency. The other types of cells have similar issues: the organic and dye-based cells are susceptible to bleaching and most likely won't survive the rigors of the space environment. The other types mentioned deserve attention as well.

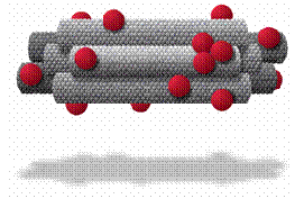

Figure 5: QD-SWNT complex

In summary, there are many thin film cell options under investigation. However, all have limitations with respect to uniformity, elevated voltage operation and survival in the space environment. Furthermore, emergence of thin, high efficiency crystalline multijunction cells may be eroding the perceived advantages of thin film cells.

SPACE SOLAR ARRAY DEVELOPMENTS

Although high emphasis is placed on the solar cell and its potential for improvement, the solar array is the final proof of success. Arrays must withstand many different space environments, must do it reliably at acceptable cost. The next sections describe those particular issues.

Solar Array Trade Studies

In order to assess productive directions in array design, trade studies are essential. However, they are invariably limited to the knowledge on hand at the time of the study. Figure 6 shows just such a study conducted in 1993 by ATK Space. As can be seen for a GEO-orbiting satellite,

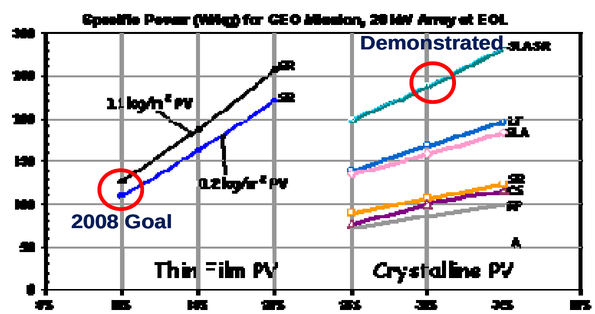

Figure 6: Array trade study results for GEO orbit

crystalline arrays have a substantial advantage over a thin film array in terms of specific power (W/kg). However, in a high-radiation orbit like MEO, the difference narrows. A thin film cell Ultraflex array at a 2008 goal may yield about 100 W/kg, the Stretched Lens Array/SquareRigger array (SLASR) will yield 140 W/kg. Increased annealing of the thin film cells will add to their performance. Furthermore, as innovative array designs tailored for thin film cells are developed, this difference will certainly be reduced.

Space array design has moved forward vigorously in the last decade. Designs have been evolving and two of the lightest weight arrays will be discussed next. These are chosen because weight savings is always important and will be major drivers in the future.

Stretched Lens Array on SquareRigger Platform

This concentrator array design has been the product of continuous improvement over the past decade. The earliest version flew successfully on NASA's Deep Space 1 mission. This mission was launched in 1998 and visited the asteroid Braille in 1999 and the comet Borrelly in 2001. The basic design of that array was a linear Fresnel concentrator lens (8x concentration level) that had a glass cover over it for protection. This was also the first flight of multijunction solar cells for NASA. The design worked as planned and cell temperatures and performance over the 38 month mission was within 2% of predicted.

Since then, the glass covering over the arches has been eliminated. The silicone lenses are now coated with a thin UV-protective coating. Because of the 8x concentration level, the size of the III-V multijunction solar cells is much smaller. Cells in this array are only 12 mm wide and 35 mm long. Thus much less solar cell material is used, reducing array cost and improving cell yield. Figure 7 shows the latest development in this array. This wing is 2.5 by 5 m in size and, if fully populated with lenses and cells, would produce 3.75 kW of power. It has a specific mass more than 300 W/kg with present day high efficiency cells and can increase to 500 W/kg with the new thin triple junction cells.

Figure 7: 2.5 by 5 m SLASR wing

In addition, this array has some other major benefits in contrast to a planar array. First, in a high radiation orbit, thick cover glasses are needed to reduce power loss. For this array, its mass will increase with cover glass thickness at only 1/8th that of a planar array due to the concentration level difference. Thus the array is lighter and has increased protection for longer life. Figure 8 shows such a comparison for a high radiation MEO orbit (6,000 x 12,000 km at a 28.5º inclination). The planar array is the lightest possible and is on the SquareRigger platform. Both start at the same specific area (300 W/m^2) but the SLASR has nearly a 4:1 advantage after 10 years on orbit. The specific mass of the planar array is 2.57 kg/m^2 compared to the SLASR at 2.15 kg/m^2.

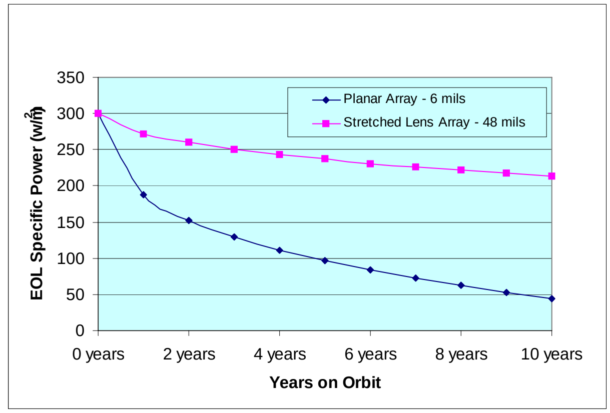

Figure 7: Specific area comparison of Stretched Lens Array with a planar array in a high radiation MEO orbit

A second advantage of the SLASR over a planar array comes directly from the concentrator design. The cells can be completely encapsulated by the cover glass/adhesive combination. The edges of the cells are completely sealed off from space plasma and charging effects. This enables very high voltage operation. Tests have been conducted at a bias of 1000 V in the presence of simulated space plasma and under micrometeoroid bombardment with no arcing of the module. This advance opens the door to new electric propulsion options.

Ultraflex 174 array

The Ultraflex 174 planar array was originally developed as a deployable array on the Mars lander 2001 mission that did not fly. A picture of the Ultraflex 174 that is scheduled to fly on NASA's ST-8 demonstration satellite is shown in figure 8. It has a lightweight mesh backing which holds the solar cells and it deploys fan-wise. For ST-8, the array is 2.2 m in diameter and the design is scalable to a 7 kW size. Its specific power is 174 W/kg with multijunction cells. A major benefit is that it has high packing density. For the moment this is the lightest planar array in development and will be used on the upcoming Mars lander in 2008. In a high radiation orbit it still will need additional back shielding for protection.

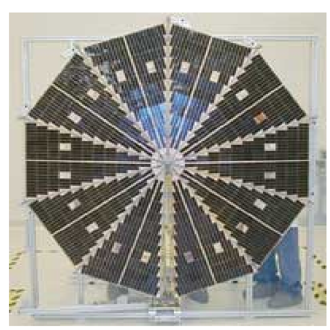

Figure 8: Ultraflex 174 array

EMERGING MISSIONS THAT IMPACT ARRAYS

From the preceding discussion, planar and concentrator arrays can use crystalline or thin film cells and each type has particular advantages and disadvantages. Array development goals that were proposed in the late 1970s included 300 W/kg, 300 W/m^2, and 300 V arrays. To date, the first two goals have been achieved. The last goal will need to be achieved to permit high power solar arrays of the future. High voltages are needed to keep the mass of wiring low to avoid major mass increases. The International Space Station is using array voltages of 140 V with wrap-around contact silicon solar cells. Missions include earth orbit (MEO), lunar and Mars surface arrays, solar electric propulsion, high power spacecraft, and stations or depots. Although all these missions have particular solar array issues, we will look at only two of these future missions and their effects array choices.

Solar Electric Propulsion Missions

With the recent flight of ESA's Smart 1 which flew a spiral-up solar electric propulsion mission to the moon, attention is returning to the benefits of solar electric propulsion for many other mission classes. These include flights to the Moon and Mars as well as orbital adjustments near earth. Smart 1 used a 1.35 kW Hall thruster and a planar array and spiraled up through the radiation belts around earth. It then spiraled down into lunar polar orbit where it has been surveying the lunar surface. It has run out of propellant and will impact the moon in August 2006.

Significant advances have also been made in electric propulsion hardware. Ion engine life has exceeded 30,000 hours and Hall thrusters with power levels above 150 kW have been tested. With these advances in mind, Aerojet and ENTECH, Inc. have studied the impact of a solar electric propulsion mission that would deliver 22 MT of cargo to the lunar surface. The notional spacecraft, shown in figure 9 produces 600 kW of power and will deliver that cargo to the

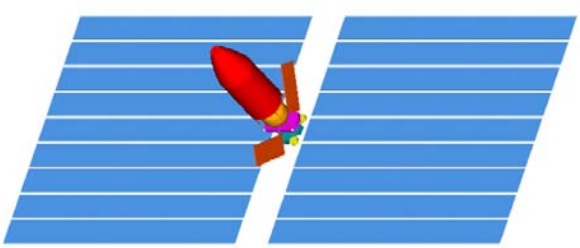

Figure 9: Notional 600 kW SEP spacecraft (courtesy Aerojet)

moon once per year for 5 years. It is reusable and has a trip time to the Moon of less than one year. This requires ten round trips through the radiation belts.

The array is the SLASR discussed earlier and has an area of approximately 2,000 m^2. This size is less than four times larger than those on the International Space Station. An important feature of this array is that it also uses "direct drive" from the solar array to the Hall thrusters. Direct drive eliminates significant power processing electronics mass and permits the array to have low mass wiring. The array voltage will be between 300 and 600 V.

With those features in hand, the study shows that a cost saving for the NASA Exploration Architecture will be at least $4 billion and can be as high as $11 billion. These savings include the cost of building the new vehicles. If cost saving is an issue, cargo transport to the Moon and Mars is certainly an attractive option.

In order to achieve the full potential of higher voltage solar arrays, fundamental design changes must be made to the arrays. One of the hidden problems that can affect long life arrays is corona breakdown. A potential design of such an array cross section is shown in figure 10. As can be seen, dual layers of corona tolerant Kapton is used in the blanket.

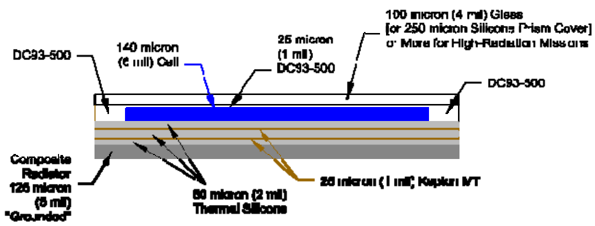

Figure 10: Cross section of a long-life high voltage array

In addition, the cells are completely encapsulated to prevent arcing due to charge accumulation or solar storms. Cover glass thickness can be changed depending on the radiation environment. This design is suitable for a concentrator array as well as a planar array.

MEO Orbit Missions

As noted before, flight to these orbits requires a major step forward in radiation protection. Missions like the Global Positioning System and other Earth observation missions benefit from these orbits. Depending on mission, either packing density or mass to achieve the requisite end-of-life power are the critical design factors.

For increased packaging density, the Ultraflex-type design appears to be suitable. However, the mesh backing will not provide enough shielding and the cover glass thickness must be increased. On the other hand, the SLASR will be lighter in weight, but will not have as good a packing density. Figure 11 gives a comparison of a planar and SLASR array in the 6,000 to 12,000 km orbit noted above. Shielding thickness (front and rear sides) has been optimized for this orbit. The array specific power of the SLASR is about 3x greater at one year and 4x greater at 10 years in this very difficult orbit. However, this comparison does not include any spacecraft specific requirement such as packing density.

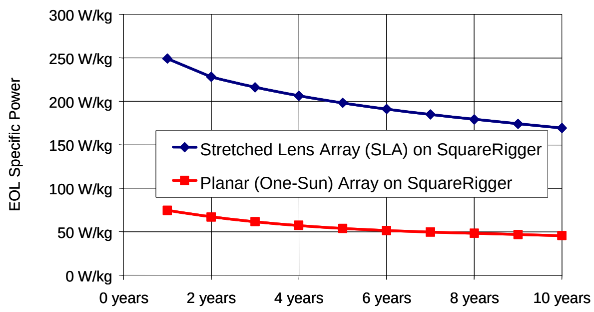

Figure 11: Planar array comparison with SLA on SquareRigger platform in a 6,000 x 12,000 km, 28.5º inclination orbit

Future Array Issues

One of the major considerations for solar arrays of the future will be their cost. A general rule of thumb is that the solar array today costs about $1 million per kilowatt. It is interesting to note that solar array sizes have not progressed much above 20 kW for commercial GEO satellites. Figure 12 shows a typical 16 kW communication satellite platform.

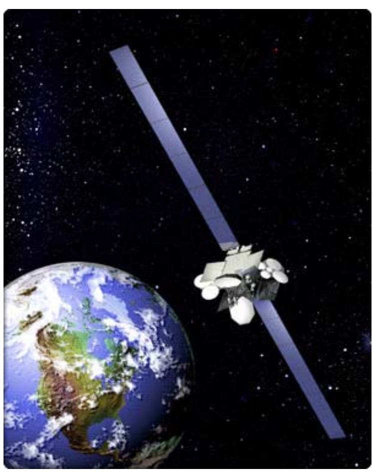

Figure 12: Boeing Space Systems 16 kW "702" platform (courtesy Boeing)

This array is a planar array that deploys from the sides of the spacecraft. It comes in several sizes up to 25 kW or so. It is similar to the arrays produced by other companies and so represents the state of the art. Given that the cost of the array can dominate the cost of the spacecraft, what steps can be taken to significantly reduce cost?

Cost reductions have to start with cell production. Thin film cells use roll-to-roll production. Crystalline cells, by their nature, cannot use this approach. Wafers are sliced from single crystal boules and processed into III-V multijunction cells with chemical vapor deposition in well-controlled reactors. Subsequently they are cut to size, cover glasses and interconnects applied and are integrated into cell strings. Array blankets are prepared and the cell strings attached to meet the desired voltage and power level.

All of these steps are amenable to automation and robotic assembly. Eliminating "touch" labor will be a major cost saving. Larger deposition reactors will improve throughput and yield. With improved slicing techniques, thinner slices will result making better use of the single crystal boule. Thin cells will also be a beneficiary of the thinner slices. If the process is automated, then all the tracking paper and other "travelers" can be eliminated for additional cost saving as well as better tracking of each product in the event that future array problems emerge.

Similar approaches can be used for arrays. Specific array designs lend themselves to lower cost by their design. The SLASR is one of these, because it uses 8x less solar cell material to achieve the same power output. Furthermore, the yield of smaller cells, and the number per processed wafer increase leading to reduced costs. Projections of the current SLASR projects costs are as low as $300 per watt, or a three-fold reduction over today's arrays. This array has not yet flown in space in this lightweight version, so the future will have to determine if these cost savings can be achieved. A higher degree of uniformity of size and design would amplify cost savings for all types of arrays and should be considered in the future. Testing and subsequent paperwork must also be controlled. However, a ten-fold reduction in cost seems possible.

SUMMARY AND CONCLUSIONS

Solar cell and array technologies have made spectacular advances over the past 50 years. Solar cell efficiency has climbed from 7% to above 30% AM0. Efficiency should continue to increase to over 40% in the next decade with more possible. Although crystalline cells have been the mainstay of space power systems, thin film cells are striving to find their place. Because of their lower efficiency, larger areas are required for the same power; "balance of systems" issues will drive the performance. It appears likely that AM0 cell efficiencies must reach 15% before they can achieve their spot in space. New cell studies including quantum dot devices also offer the hope for future efficiency increases.

Arrays of the future will be significantly lighter than today's arrays. Specific power levels from 300 to 500 W/kg are likely for concentrator arrays and up to 300 W/kg can be achieved for planar arrays with thin multijunction cells. The arrays of the future must cost substantially less than those of today. Cost reductions of ten-fold appear reasonable as goals. Future arrays will also have to be adaptable to high radiation orbits such as MEO and solar electric propulsion spiraling up missions to the Moon and beyond. It is likely that lightweight solar arrays will be used as far from the Sun as Jupiter and, as presently flying on MESSENGER, to within a few tenths of an AU from the Sun. Solar arrays on both the Moon and Mars surfaces will be common. Dust issues and design features will be adjusted as needed to meet these challenges.

All in all, the future of space solar arrays is bright and major opportunities for development await creative young researchers. Hop on board and help create the future!!