HIGH EFFICIENCY SOLAR CELL RESEARCH FOR SPACE APPLICATIONS

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ABSTRACT

NASA involvement in photovoltaic energy conversion research, development, and applications spans over two decades of continuous progress. Led by the Lewis Research Center's Photovoltaic Branch, Agency programs in solar cell research and development have produced a sound technology base for a broad range of space applications. Although space power requirements are mission dependent, there are fundamental objectives which guide the NASA photovoltaic program. They are to improve efficiency, increase life, reduce mass, and reduce the cost of photovoltaic energy converters and arrays. Consequently, the programs in place at Lewis Research Center range from fundamental research on advanced concepts to technology advances for improving the space-worthiness of solar arrays. This paper will describe several key activities in the Lewis program.

INTRODUCTION

The cell research activities at Lewis divide roughly into the following categories: advanced devices, gallium arsenide and other III-V compound solar cells, and high efficiency silicon cells. Work in all of these categories will be described. Particular attention will be given to a new strategy for efficient solar energy conversion which seeks to overcome the fundamental limitations inherent with all semiconductor photovoltaic converters. The approach exploits a well-known mechanism for absorption of light in thin metallic films of common metals, such as aluminum or silver: the coupling of light to surface plasmons. Surface plasmons can have suitable ranges for energy transport, (up to centimeters in the IR), and can absorb from the ultraviolet to the infrared. Energy conversion then occurs by transfering the surface plasmon energy to an array of inelastic tunnel diodes, where a current of tunneling electrons can be created. Key technical barriers have been identified and will be discussed, along with recent results aimed at eliminating them.

The magnitude of NASA's photovoltaic space power activities can be seen in Figure 1. With the exception of the Skylab launch in 1973, most NASA missions have been at the 2 or 3 kilowatt level or below. Future NASA missions may be an entirely different story, however. The desire for more sophisticated, longer-lived missions will push power requirements up an order of magnitude and more. A low-earth orbiting manned space station, for example, might require up to 125 kilowatts of power in the station itself. This would, in turn, require a solar array output capacity in excess of 300 kilowatts, and would represent over two and one-half times the power generating capacity that NASA has launched in the past 20 years. Such an array will be the dominant physical feature of the Space Station, and will place a premium on reducing the area, weight, and cost of large space arrays.

Future power requirements for geosynchronous applications are also expected to rise in the coming decades, although few such missions will be soley NASA's. The primary uses of GEO spacecraft will be for commercial and military communications networks. In these applications in particular, a premium is placed on higher efficiency, lighter weight, and longer life. Cost is important, but is not as important a driver as it is for large LEO arrays. A key figure of merit for GEO arrays is the ratio of power out to total array mass in W/kg. NASA's most recent GEO satellite, TDRSS, had an approximate beginning-of-life specific power of 35 W/kg, with a BOL power of about 3 kilowatts. Future communications satellite power requirements are expected to be from 3 to 5 times that level. Moreover, volume and weight constraints of current and proposed GEO launch vehicles make it desirable to increase both efficiency and specific power significantly beyond present levels. End-of-life specific powers approaching 250 W/kg may well be required to meet such constraints. The payoff will be measured directly in terms of increases in the active payload of the satellite.

The foregoing discussion is by no means exhaustive of all future space photovoltaic applications. It is intended only to put into context the rationale behind the current major thrusts of NASA's solar cell research and development program.

HIGH EFFICIENCY SILICON SOLAR CELL RESEARCH

Figure 2 summarizes the situation with regard to space solar cells since approximately 1960. Essentially, all space cells flown at that time were made from 10 ohm-cm starting material, and had AMO efficiencies on the order of 10 percent. Work in the early 1970's resulted in the COMSAT violet cell (Reference 1) with an efficiency approaching 15 percent, but it quickly became clear that higher efficiencies could not be achieved without improving the open-circuit voltage, and that could not be done without lowering the resistivity of the starting material. Current densities in the high efficiency 10 ohm-cm cells approached 50 ma/cm^2, and could not reasonably be expected to go much higher in that material. In the mid 1970's, therefore, Lewis Research Center initiated a concerted effort to develop an 18 percent AMO cell, which had been estimated by Brandhorst (Reference 2) to be the maximum practical efficiency for silicon. The effort concentrated on raising the open-circuit voltage to the 700 millivolt range. The initial work resulted in open circuit voltages of nearly 650 mV, but efficiencies were lower than desired because of the lower current-generating capabilities of the low resistivity cells.

Several techniques have been advanced for raising the voltage in low resistivity cells. Among them is the multi-step diffusion process developed at Lewis Research Center, which produced a Voc approaching 650 mV (Reference 3). The process was later used by COMSAT to produce a 14.5 percent AMO cell (Reference 4). This achievement was quickly followed by the development of cell designs at the University of New South Wales, under a NASA grant, which achieved 16 percent AMO, and Voc's approaching 680 mV. These cells, developed by Martin Green and co-workers (References 5, 6), have been subjected to an intensive analysis at Lewis Research Center in an attempt to elucidate the mechanism(s) responsible for their improved performance. That work, reported by Weizer (Reference 7) at the last Photovoltaic Specialists Conference, has produced some surprising results. In brief, it was shown that:

1. It is not the perfection of the emitter, but a previously unrecognized improvement in the base that is responsible for the high Voc's obtained in the MINMIS cell.

2. The high voltage in the MINP cell is the result of the same improvement in the base as in the MINMIS cell, coupled with a reduction in the emitter Io.

3. The enhanced base characteristics of both cell designs are the result of a reduced minority carrier mobility in the starting silicon material used for these cells.

Based on these results, it now appears that voltages approaching 800 mV are achievable in 0.1 ohm-cm silicon cells with full utilization of the MINP surface passivation techniques. AMO efficiencies approaching 20 percent may yet be possible in silicon. Work toward that goal will be continued in the Lewis Research Center program.

III-V CELL RESEARCH

Emphasis in the NASA solar cell research program has shifted from silicon during the past few years to the wide variety of semiconducting compounds formed from elements in columns three and five in the periodic table. The program ranges from basic materials science to pre-pilot cell design optimization studies. The activities fall roughly into three categories: (1) GaAs concentrator cells; (2) thin film cells; and (3) multi-junction cells. Resistance to the damage caused by charged particle radiation in the natural space environment is a major consideration in the III-V cell area, and along with efficiency, forms an important part of the justification for it.

NASA's interest in III-V concentrator cells arises in part because of their potential for lowering the cost of very large solar arrays, such as are anticipated for a future Space Station. Figure 3 summarizes the results of a study of multi-hundred kilowatt array designs (Reference 8). The plot of combined cell and component costs versus concentration ratio shows the existance of a broad minimum between approximately 20x and 200x. Figure 4 illustrates a concentrator design currently under development at TRW, under contract to Marshall Space Flight Center. Specifications for this miniature cassegrainian system call for a 4 mm diameter cell capable of 20 percent at 125x and 85°C. Lewis Research Center has two contracts in place, one with Varian and one with Hughes Research, to design and produce such cells. With 19 percent already demonstrated, there appear to be no apparent technical "show-stoppers" which will prevent realization of the program goal of 22 percent at operating conditions. This application dramatically illustrates the higher efficiency and higher temperature capabilities of GaAs compared to silicon. GaAs concentrator cells will have over twice the efficiency of silicon at the operating temperatures projected for this array design. The physical dimensions of the cell are illustrated in Figure 5. The diameter of the illuminated area is 4 mm, while the length of one edge is 5 mm. The approximately 60 to 1 reduction in processed semiconductor area compared to a planar of equal output is the primary reason for the projected lower cost of this array design. An additional assumption, of course, is that the cost per unit area of the concentrator optics will be significantly lower than the equivalent area of processed semiconductor material. The anticipated cell output at operating conditions is approximately 0.4 watts. Based on informal estimates, the projected cost of such cells could be on the order of 30 to 50 $/watt.

Cost is not the only reason for interest in concentrator arrays for space application. A second very important reason, again depending on mission requirements, is the inherent shielding provided by the concentrator element against the natural radiation environment encountered in many orbits. Although not important for LEO applications, the design may make possible the use of photovoltaic power generators in some of the mid-altitude orbits that have previously been dismissed because of their high density radiation environment. Beyond that, if high efficiency can be coupled with lightweight concentrator optics, such arrays could eventually be flown in GEO.

Research on thin film solar cells is directed toward improving their performance, not only in terms of their efficiency, but also in terms of their radiation resistance. An important thrust for the NASA space power program is the development of technology for the next generation of GEO communications spacecraft. At present, about 23 percent of the satellite mass launched to orbit must be dedicated to the power system, which is approximately the same fraction that is available for the payload itself. The benefits derivable from reducing the power system mass are directly translatable into revenue for commercial satellites, and into increased capability for non-commercial satellites. One approach under investigation at the present time for producing ultralightweight solar cells is the CLEFT process developed at the Lincoln Laboratory by John Fan and co-workers (References 9, 10, 11, 12). Progress in this area is well-known, and a detailed discussion need not be included here. The NASA goal is to demonstrate a 4 micron thick GaAs cell with at least 20 percent AMO efficiency, which suffers no more than a 10 percent loss of power after 10 years of exposure to the GEO radiation environment. The goal is ambitious, but achieving it could result in significant reductions in the mass of the solar array for GEO systems. The cell development work at Lincoln Laboratory is supported at Lewis Research Center by in-house cell evaluation measurements and radiation damage studies. The best cell specific power demonstrated to-date is 5400 watts/kg, achieved with a 5.5 micron thick cell with gridded back contacts with an AMO efficiency slightly greater than 14 percent. A cross-section of the cell is shown in Figure 6. The illuminated area is 0.51 cm^2. There are many technological challenges to overcome before the CLEFT cell can be considered a viable candidate for use in space. Chief among them are the following: development of a UV-resistant adhesive to use in the film transfer process; improving the open-circuit voltage and fill-factor; establishing the radiation tolerance of the cell; and perhaps the most formidible among them, developing a suitable interconnect technology for joining 5 micron thick cells together in an array.

As is well-known, the efficiency of a typical single junction solar cell is limited fundamentally by the location of its bandgap within the solar spectrum, in this case the air mass zero (AMO) spectrum. Early calculations of multi-bandgap cell efficiencies at AMO (Reference 13) indicated that a total conversion efficiency of approximately 30 percent could be achieved in a three-cell stack under 100x illumination. The cell structure initially selected by NASA is shown in the first column of the table below, and was driven by the assumed requirement that the structure had to be lattice-matched throughout. The second column shows the current distribution of bandgaps for the structure, and is a result of the successful demonstration of composition grading between the various active layers of the cell. The latter technique allows for greater flexibility in the choice of bandgaps to achieve short-circuit current matching from each constituent cell in the stack. The lower bandgaps should produce a slightly higher efficiency than those of column one, and should make fabrication of the tunnel junction between the bottom and middle cells somewhat easier. (The high doping densities required for a tunnel junction interconnect are easier to achieve in a lower bandgap material.) The interconnect between the middle and top cells can be some sort of metal interconnect, such as the Varian-developed MIC (Reference 14).

TABLE 1

Multi-Junction Cell Bandgaps

Cell	L-M	C-G
Lower	1.15	1.15
Middle	1.55	1.43
Upper	2.05	1.95

An interesting simplification of the above structure is to use just two junctions, and to mechanically stack them. As has been pointed out by Fan (Reference 15), such a structure can be either a two, three, or four terminal device, without introducing much complexity into its fabrication. The monolithic stack, on the other hand, is most easily made into a two terminal device. There is some loss of efficiency in the AMO spectrum for a two junction cell, but there may also be a trade-off in the radiation hardness of the two structures which favors a two-junction, four terminal device. If the end-of-life performance of a series-connected multi-junction cell is to be maintained at reasonable levels, it becomes necessary to develop constituent cells which degrade by in a matched fashion in a radiation environment. Although possible in principle, it presents a formidable challenge to realize in practice. A four terminal device avoids the requirement for current-matching altogethers and does not, therefore, suffer any additional degradation beyond that of each of the constituent cells.

ADVANCED CONCEPT SOLAR CELLS

The calculated efficiency of an ideal cascade solar cell reaches a maximum when more than six bandgaps have been included in the stack, and can approach 60 percent in the AMO spectrum (Reference 16). Taking the real system losses into account, however, shows that the maximum has been passed after three bandgaps have been included (Reference 17). As mentioned above, the practical maximum AMO efficiency of a three cell stack is expected to be 30 percent, even under 100x illumination. The question that naturally arises is whether that efficiency limit, which appears to be inherent with semiconductor p-n junctions, can be transcended by some means. The problem is that the ordinary p-n junction solar cell in effect converts the incoming broadband solar radiation into a flow of monoenergetic electrons (and holes), the energy of which is determined by the semiconductor bandgap. While the coupling mechanism, i.e. the creation of electron-hole pairs, is broadband in nature, the excess kinetic energy imparted to the electron-hole pairs by photons with energies greater than the bandgap is essentially not transportable. It is lost in collisions with lattice phonons in a matter of picoseconds, resulting in very short ranges for the excited carriers. An initial requirement, then, for any major increase in efficiency, is to identify a mechanism for broadband absorption of the solar spectrum which creates a corresponding spectrum of electronic excitations in the absorber with ranges long enough that energy can be extracted from them. Thin films of common metals such as silver, aluminum, and gold can support a quantized, oscillatory excitation of their two-dimensional quasi-free electron gas known as a surface plasmon. The surface plasmons are produced by exterior electric fields incident on the boundary between the metal film and a dielectric medium. For large wave vectors the plasma waves behave like real surface waves: their electromagnetic field is concentrated around the boundary within a distance of approximately 10 angstroms. For small wave vectors the fields extend far into space, and resemble more and more those of a photon propagating along the boundary. The surface plasma wave behaves very much like a guided electromagnetic wave in a dielectric waveguide, except that the waveguide in this case is a metal film, and therefore very lossy. The latter fact limits the range of the surface plasmons at the high energy end of the spectrum to distances on the order of 70 to 100 microns. Propagation lengths for surface plasmons in the infrared, however, can approach several centimeters (Reference 18). A large body of literature exists which describes the properties of surface plasmons, and discusses several experiments in which they can either be observed or utilized. (See e.g., the monograph by Raether, Reference 19). The coupling between surface plasmons and photons can be very strong under the proper conditions, and is well understood theoretically. It can be shown that only the p-polarized component of the incident radiation can be coupled to a smooth film for example, and in such a way that the width of the acceptance angle is very small. In addition, the acceptance angle itself varies with wavelength. Such properties have all been verified experimentally.

Conceptually, the direct conversion of solar energy to electricity requires the following processes: photon absorption, which either creates "free" charges (electron-hole pairs, photoelectrons, etc.) or imparts kinetic energy to a charge carrier (the surface plasmon, e.g.); and charge separation. The latter occurs by creating a potential barrier for some of the charge carriers while others are allowed to pass (the p-n junction for electron-hole pairs, e.g., and a tunnel diode for energetic electrons). If photon absorption does not occur in the region where the charges are separated, then energy transport must occur from the absorption region to the barrier region. Charge collection and flow in an external circuit complete the picture. Since the surface plasmon is a quantized, collective oscillation of a two dimensional electron gas, the momentum imparted to the surface plasmon by the incoming photon must be transferred to a mobile, free electron below the surface before any charge separation can occur. The latter requires, therefore, some sort of interaction mechanism between the surface plasmon and a free electron.

It is clear from the preceeding discussions that any attempt to create a solar energy conversion device based on surface plasmon absorption of the solar spectrum must address for key technical barriers: (1) broadband coupling of sunlight to surface plasmons at a single acceptance angle; (2) low-loss energy transfer from the absorption to the barrier region; (3) coupling between the surface plasmons and mobile charge carriers in the region of the potential barrier; and (4) efficient charge transfer from the low to the high energy side of the potential barrier. A possible approach for dealing with the fourth problem involves inelastic electron tunneling through a thin film metal-insulator-metal structure. If the film thicknesses have been properly chosen, such a structure supports a coupled mode between surface plasmons in both metal films. This coupled mode, or junction plasmon, is able to propagate along the length of the structure, and by virtue of the strong electric field it creates in the oxide, can provide an inelastic tunneling channel for an electron impinging on the barrier at that instant. Preliminary calculations conducted at Lewis Research Center indicate such a mechanism, while possible in principle, is beset with difficulties. Not the least among them are the need to limit the reverse tunneling current to acceptably low levels, and the very limited range of the junction plasmon in general (typically a few tenths of a micron). A suitably chosen semiconductor thin film can be incorporated on the low energy side of the junction in such a way that its bandgap eliminates the final states for the reverse tunneling process, but the impact of doing so on the ability of the structure to support a junction plasmon is unknown at present. In order for the process to go at all, it is first necessary to transfer energy from the surface to the junction plasmons. Here the problem is that the junction plasmon has a much lower velocity than a surface plasmon of the same frequency, so some sort of momentum-matching transfer mechanism is required. Figure 7 shows schematically one possibility. Calculations show that a grating can promote energy transfer between monoenergetic surface and junction plasmons with better than 90 percent efficiency (Reference 20). The feasibility of doing the same with a broad spectrum of plasmons has yet to be firmly established. The proposed approach in effect uses a junction plasmon as an intermediary between the surface plasmons and tunneling electrons. What is still required, however, is experimental verification of the approaches that have been outlined here.

Mechanisms which affect surface plasmon coupling and range (barriers 1 and 2) are relatively well-known and understood. Recent results for the latter obtained in the NASA program are summarized in Figure 8 (Reference 21), which contains a plot of surface plasmon range as a function of wavelength with film thickness as a parameter. The structure for which the propagation distances have been calculated is shown in the inset. An important result is that the calculated damping matches experimental results on dirty films, and seems to indicate that ohmic losses have been overestimated in previous calculations. A series of experiments aimed at exploring surface plasmon propagation in such structures has been started. The initial work will investigate the so-called end-fire coupling technique for injecting surface plasmons into the structure shown in Figure 8. The technique is well-known in integrated optics. Instead of matching the incident field to a surface plasmon wave vector along the direction of propagation, the field distributions are matched across the end face of the sample. That is, the incident field is focussed onto the end face of the structure with a field distribution which matches as closely as possible that of a surface plasmon. In addition to investigating the generation of long-range surface plasmons, the same experiments will investigate the coupling efficiency of the technique. The results of a first order perturbation theory calculation are shown in Figure 9 (Reference 22). The salient point is that an optimized incident field distribution yields a greater than 80 percent coupling efficiency for a silver film for wavelengths from 0 4 microns to more than 1.2 microns, and as the figure shows, the efficiency is relatively independent of the incident spot size. This approach has several important features. For example, all of the modes originate at the same point, and therefore the propagation distance can be used to discriminate wavelength regions for absorption. In addition, the beam shaping and focussing can be done by external, miniature optics. Both of these have impact not only on the experimental efforts just described, but also on the actual configuration of such a device should it become a reality. Is is conceivable, for example, that such a device could be used in the miniature cassegrainian concentrator system described earlier in this paper.

A second approach for investigating the coupling of sunlight to surface plasmons is shown schematically in Figure 10. In this approach, the film on which surface plasmon generation is desired is evaporated onto a glass prism, and is covered with a dielectric layer onto which a metal-island film is then evaporated. The effect of the island film is to broaden the acceptance angle from a few tenths of a degree to as much a five degrees at half-maximum in the absorption (Reference 23). The measurements also show that as much as 90 percent of the p-polarized component of the top quarter of the solar spectrum can be absorbed by a silver island-film, with similar results for the mid-quarter with a gold island film. The results can be explained in terms of an incident radiation field interacting with dipole located near a conducting thin film, with suitable modifications which take the macroscopic size of the metal-island into account. By combining measurements of the surface plasmon dispersion curve for a silver film and measurements of the dipole frequency shifts (isolated dipole vs. a dipole ne a conducting film) with theory, the coupling efficiency between the radiat ield and surface plasmons can be estimated. (The dipole absorbs energy fr the normally-incident, unpolarized light beam and loses it by one of three processes: reradiation; surface plasmon generation in the thin film; and ohmic heating.) The earlier reflectivity data indicated that as much as 97 percent of the indicent radiation was absorbed by a silver island film. However, the detailed calculations indicate that a maximum of about 40 percent of the total incoming energy is transfered to surface plasmons in the underlying silver film (Reference 24). Moreover, the maximum is a function of both the wavelength of the incident light, and of the spacer-layer thickness. An important feature of this approach, however, is that both the s and p polarizations can couple to the structure. Additional work is required to assess the importance of the shape of the metal-islands on the absorption, and to determine the optimum structure for maximum efficiency.

As the preceeding discussion demonstrates, there are several key barriers that must be addressed just to determine the feasibility of a surface plasmon solar converter. Although we have made strides in our basic understanding of many of them, the final outcome is far from clear. Work will continue on the key questions that have thus far been identified. If and when any technical "show-stoppers" are identified, the progran will be brought to an end. Until such time, however, the effort presumes success.

CONCLUSION

The NASA space photovoltaic research and technology program has its roots in the days of the first real solar cell. In the three decades since then (1954-1984), the Agency's program has not only developed technology for the current generation of photovoltaic power systems in space, it continues to lay foundations for the future. A key element in the success of the NASA program is its overriding philosophy that the most important driver is high efficiency. Without exception, program objectives are to achieve high cell efficiency first, and to address balance-of-system considerations second. The success of this approach is attested to by the many applications of space photovoltaics, from NASA to military to commercial missions. Once the path to high efficiency has been demonstrated, additional developments follow which reduce it to practice in a cost-effective manner. In many instances those developments are encouraged with government funding. In many other instances such developments have occurred at the initiative of the commercial sector. The net result has been steady progress for nearly three decades.

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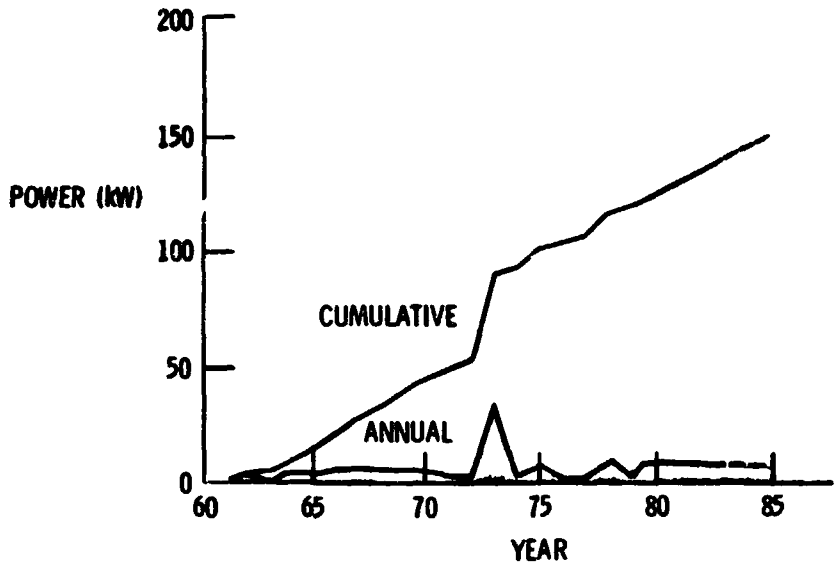

Figure 1. Total Space Power Launched for NASA Missions.

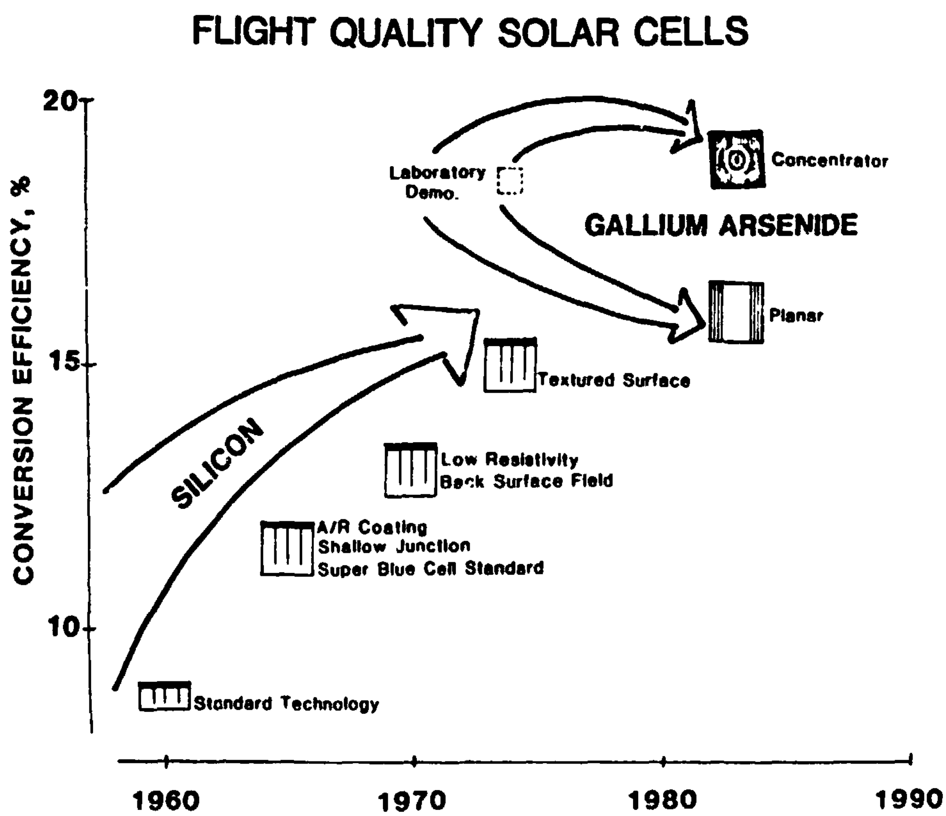

Figure 2. Space Quality Solar Cell Technology.

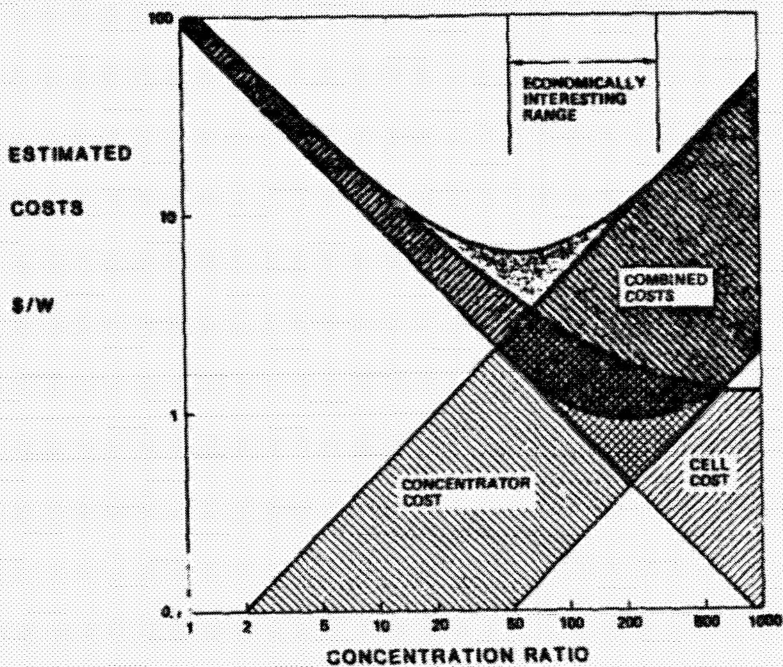

Figure 3. Array Component Costs Versus Concentration Ratio.

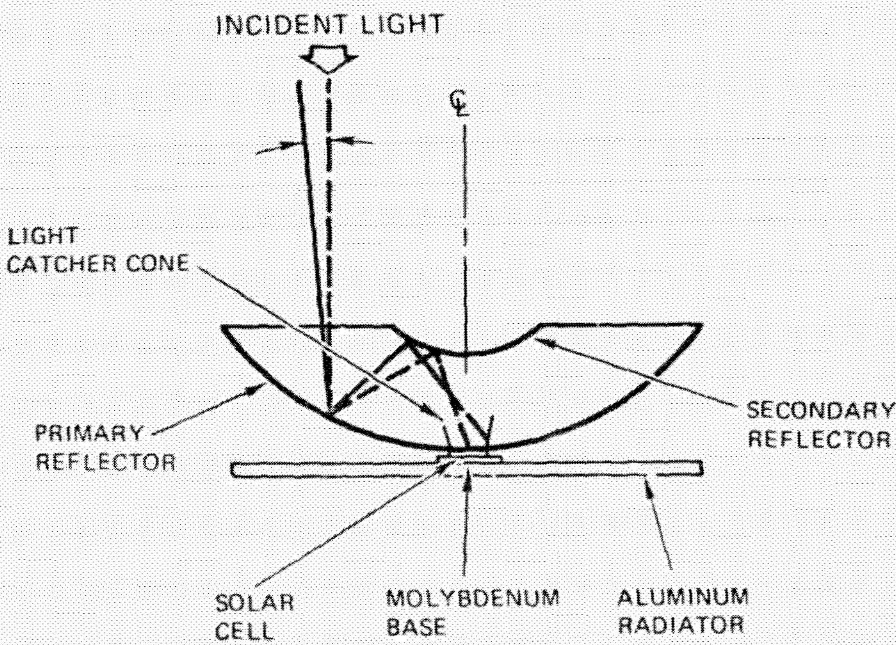

Figure 4. Miniature Cassegrainian Concentrator Concept.

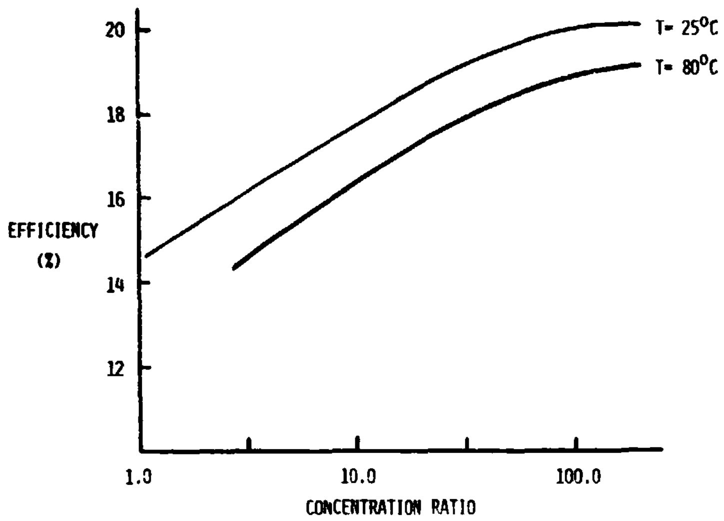

Figure 5. Miniature Concentrator Cell Efficiency vs. Concentration Ratio (AMO).

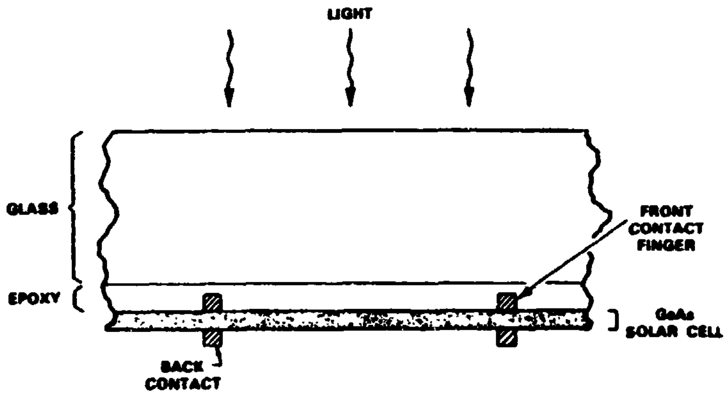

Figure 6. CLEFT Cell Cross Section.

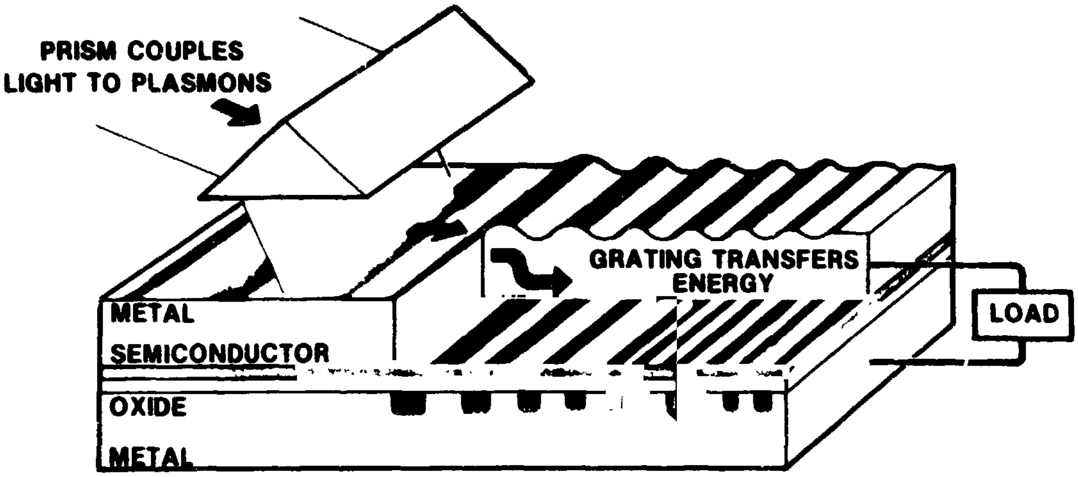

Figure 7. Surface to Junction Plasmon Grating Coupler Concept.

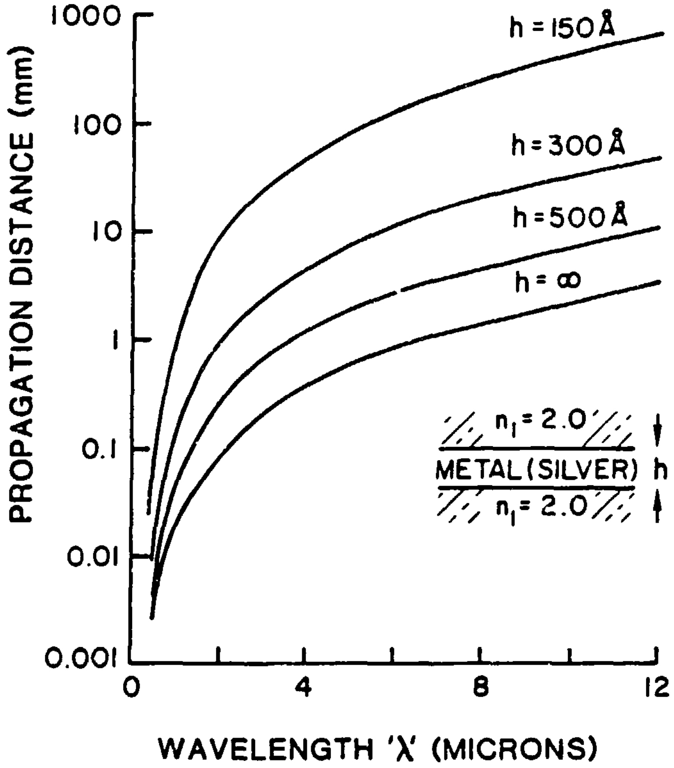

Figure 8. Surface Plasmon Range.

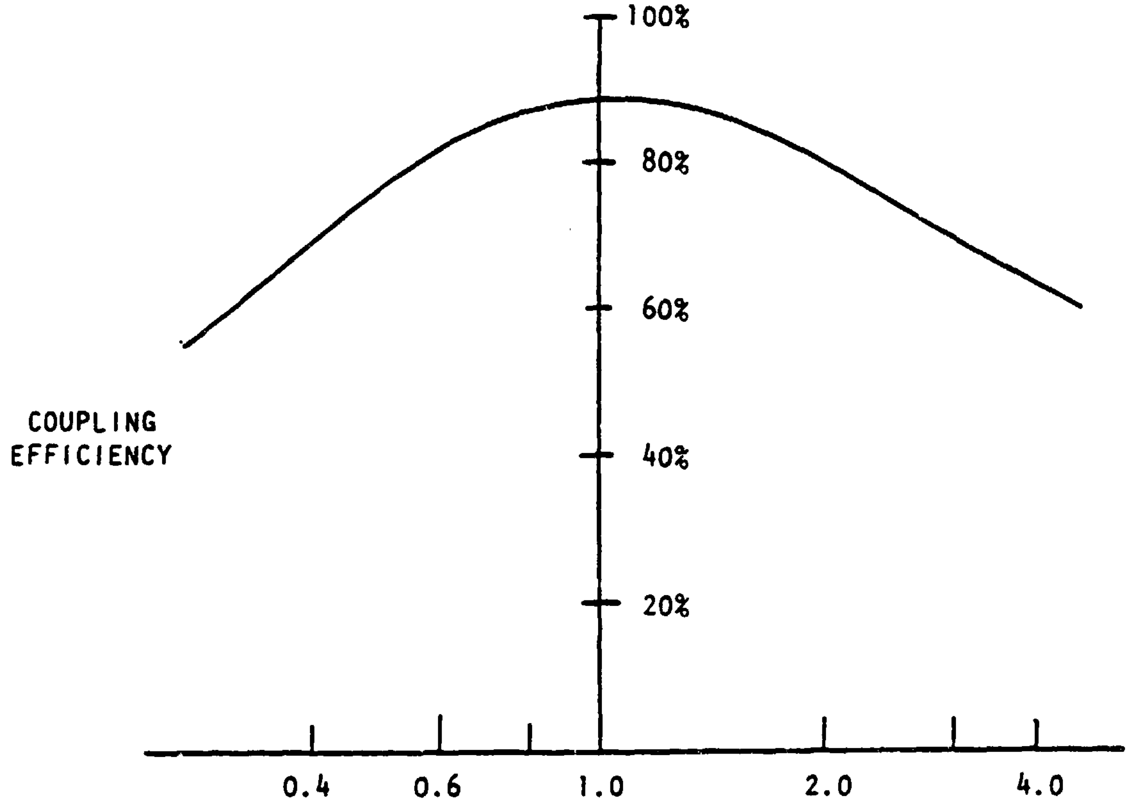

Figure 9. Endfire Coupling Efficiency as a Function of the Ratio R of the Beam Width Plasmon Field Penetration Depth.

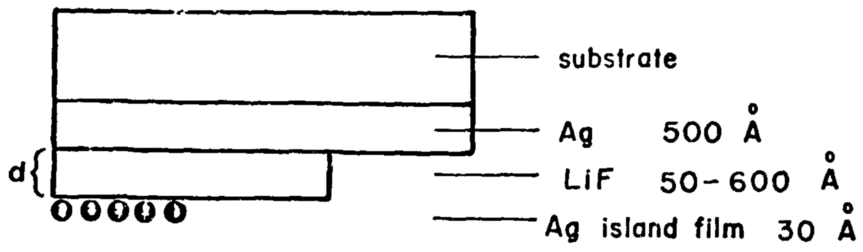

Figure 10. Light Coupling by Metal-Island Films. Sample Cross-section at Top. Measurement Schematic at Side.