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STATUS OF WRAPAROUND CONTACT
SOLAR CELLS AND ARRAYS

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ABSTRACT

Wraparound contact solar cells have both negative and positive electrodes on the back side of the device. A brief history of the development of the wraparound contact cell is given. Fabrication techniques and the performance of the present high efficiency devices are discussed.

Solar cells with wraparound contacts provide the following advantages in array assembly.

(1) Eliminate the need for discretely formed, damage susceptible series tabs.

(2) Eliminate the n gap problem by allowing the use of uniform covers over the entire cell surface.

(3) Allow a higher packing factor (more cells per unit area) by reducing the additional series spacing formly required for forming, and routing the series tab.

(4) Allow the cell bonding to the interconnect system to be a single-side function wherein series contacts can be made at the same time parallel contacts are made. Automated assembly becomes feasible thereby reducing labor and costs.

Particular emphasis will be placed upon cell lay-down and cell blanket fabrication for the 25 kW SEP array which is expected to be the first large-scale space application of the wraparound contacted cell.

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WRAPAROUND CONTACT SOLAR CELLS are photovoltaic devices with both positive and negative electrodes on the back (nonilluminated) side of the cell. There are two types of wraparound cells, the wraparound junction and the wraparound insulator types shown in figure 1. As shown, either the junction or an insulator layer extends over the edge and wraps around to the back of the cell. In both types the metal contacts also wrap around. A wide variety of cell geometries is possible. Some of them are shown in figure 2.

Wraparound contact offer several important advantages. The active illuminated area can be increased by removing the main bus bar from the front of the cell. This can result in a 5 to 7 percent increase in short circuit current and power output as long as voltage and curve factor are not reduced by the wraparound design. Other advantages include easier cover glass application and more complete protection and simplier cell interconnection and array assembly. These are discussed in greater detail in the following sections of this paper.

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Despite the potential advantages there have been several barriers to the use of wraparound cells. The major disadvantages of wraparound cells encountered in the past are 1) lower efficiency than conventional cells, 2) lack of production capability and space flight testing, and 3) higher cost than conventional cells. Now wraparound technology has been brought to a stage where these negative factors are being overcome. As a consequence, wraparound cells will find increasing use in space missions, particularly for uses as represented by the Solar Electric Propulsion (SEP) array.

The purpose of this paper is to present the status of wraparound contact cell and array technology. The early history of the wraparound cell and the systematic development efforts which have attacked and solved the problems and broken the barriers to the use of wraparound cells in space are presented. Future development trends are also discussed. The 25 kilowatt array for solar electric propulsion, the first space use of wraparound cells, is also described.

EARLY CELL DEVELOPMENT

The first practical solar cell was demonstrated in 1954 (1)*. It was a wraparound junction cell without wraparound metal. Serious defects which limited efficiency were high series resistance, recombination losses and reflection losses. The first commercially produced cells were similar to this cell, circular with deep p on n wraparound junctions without wraparound metal. Fabrication difficulties resulted in low production yields. The series resistance problem was solved by putting the p contact on the front of the cell. These separate front and back contacts became the convention throughout the industry. Thus at an early stage in solar cell development the benefits of wraparound contacts were lost. In 1958 the first U.S. satellite, Explorer 1, was launched. After 1958 development efforts concentrated on conventionally contacted, rectangular cells for space use. Grid fingers further reduced series resistance and made shallower junctions possible. Other developments included better antireflection coatings and n on p cells with coverglasses to reduce radiation damage in earth orbit. After these early advances in the 1950's, little major progress in silicon solar cell technology was made in the 1950's. Average efficiency of conventionally contacted production quality cells was about 11 percent air mass zero (AMO).

*Number in parentheses designate references at end of paper

In 1964 the NASA Goddard Space Flight Center sponsored an effort (2) in which a few hundred wraparound cells were made and assembled into modules. The cells had wraparound junctions and metallization. They had 5 percent greater active area than conventional cells and efficiences of about 10 percent AMO. The purpose of the work was to demonstrate the feasibility of wraparound cells and their usefulness for advanced array assembly methods. There were no spacecraft at that time which required wraparound cells, so no further work was supported.

WRAPAROUND CELL DEVELOPMENT

EXPLORING AND UPGRADING WRAPAROUND TECHNOLOGY - In 1971 the NASA Lewis Research Center began a series of development contracts to improve the performance of wraparound cells. The first contracts were exploratory in nature, their purpose being to establish achievable performance, to develop production techniques, to evaluate different wraparound methods and cell designs and to obtain information on production costs of wraparound cells. Two solar cell manufacturers were funded for this work. Results of one contract indicated that production costs were close to those of conventional cells (3). It was determined that further developments needed to achieve high volume production included wraparound junction diffusion and contact application techniques. Both junction and insulator wraparounds were evaluated in the other contract (4). Thin layers of insulator materials (SiO_2 and Al_2O_3) were vacuum evaporated but had pinholes which resulted in partially shorted cells. These wraparound junction cells also had increased series resistance due to loss of rear P contact area. Cell handling methods, tooling and the effect of edge damage and surface finish on curve factor and metal adherance were investigated. The tradeoffs between junction depth, curve shape and series resistance were explored and optimized. In each contract, one thousand cells were made with average efficiency of about 11 percent.

In the next phase of this work (5), beginning in 1973, various technological advances were incorporated into the wraparound junction cell. These included shallow junctions to improve blue response, back surface fields to improve voltage and current, thin, closely spaced grid lines to increase active area and current, and antireflective coatings with low absorption and refractive index better matched to silicon. Shallower junctions were achieved but were degraded by the standard titanium contact method and demonstrated the need for an alternate contact technique.

Shallower junctions required finer grid line geometries which led to the use of bimetal masks. Due to economic considerations photoresist masks and multilayer antiflection coatings were not used. Evaporated tantalum pentoxide was used for the AR coating.

Back surface fields were made with both aluminum and boron with the former giving slightly better results. This work demonstrated that the back surface field effect could still be achieved even when n pads on the back surface were present. Edge defects, poor adherance of the contact metal to the edge of the cell and increased series resistance due to a loss of back contact area were still problems. A center spine wraparound configuration (fig. 2) was adopted. It had the advantage of minimizing the amount of metal on the edge which could encounter a defect but the disadvantage of increasing contact area on the front of the cell. Wraparound cells 2 by 2 cm in size averaging about 11 percent AMO efficiency were made. The need for improved fill factor and volume production capability were recognized.

EXTENDING WRAPAROUND TECHNOLOGY - In the continuation of this work (6), beginning in 1975, a chromium-palladium-silver contact system with good edge adherance was developed and adapted to mass production. The adherance of the CrPdAg contact was not dependent on the angle of incidence of the evaporated metal and the silicon wafer as previous contact metals had been. This enabled rotation of the cell during contact evaporation and allowed simpler tooling that made possible high volume production of wraparound contact cells.

This new contact metallurgy plus the technology improvements previously developed were incorporated into a 2 by 4 by 0.02 cm cell with a wraparound center spin configuration. One thousand of these cells were produced using normal volume production procedures. Their average efficiency was 11.2 percent AMO. These cells satisfied the requirements of the Solar Electric Propulsion project of the NASA Marshall Space Flight Center, described below.

This cell, although better than any wraparound high volume produced at that time, still had limitations. The use of a spine type top contact nullified the increased active area advantage of the wraparound. In addition, there were limitations on the size and location of the rear n pads due to back contact losses and series resistance increases. Thus the wraparound junction cell had reached its performance limit. Its best technical features were the shallow, gaseous-diffused junction, the evaporated CrPdAg contacts which produced narrow, closely spaced grid lines, and evaporated Ta_2O_5 antireflection coatings. It was recognized that successful dielectric isolation would remove these limits by not requiring a wraparound junction and insulating the n and p contact metals from each other. With a wraparound insulator the center spine is not needed and the n contact overlays the p contact without decreasing its area and increasing series resistance.

Beginning in 1975 (7) a series of programs funded by NASA Lewis Research Center developed low cost techniques for fabrication of space solar cells. Feasibility for a cell fabrication process based on screen printed contacts and BSF layers and spin-on antireflection coatings and dopants on a texturized surface was shown. In 1976 these low cost techniques were extended to a wraparound contact cell (8). About 1850 cells were made using a low cost process sequence. They had an average efficiency of about 10.9 percent AMO. These cells were 2 by 4 by 0.025 cm and incorporated most of the low cost technology previously mentioned. The performance of these cells was limited by the large area grids which masked active area and by the spin on antireflection coating which had poor short circuit enhancement.

The low cost approach resulted in two key technologies which can be described as breakthroughs.

First, the screen printed wraparound dielectric, which was fast and easy to apply, provided a very good, adherent, pinhole-free insulating layer. The second breakthrough technology was the screen-printed aluminum back surface field. It provided excellent voltage enhancement with a fast, easy and extremely reproducible process.

WRAPAROUND ADVANCEMENTS - The best features of the vacuum process wraparound junction technology (6) and the low cost wraparound insulator technology (8) described above were combined in the next phase of the work. Beginning in early 1977 the best cell technologies shown in table I were explored and integrated to produce cells with efficiencies in excess of 15 percent AMO (9, 10). It is expected that this combined technology fabrication process will result in high efficiency wraparound contact (HEWAC) cells with average efficiency of 14.5 percent AMO in production quantities. The HEWAC cell has eliminated the features of wraparound cells which limited performance in the past: e.g., no center spine or bus bar that removes active area, no need to remove p contact area to make room for n contacts and no pinholes or shorting of the insulator to limit cell performance. The HEWAC cell has incorporated the best aspects of cell technology e.g., thin grid fingers, high performance Ta_2O_5 antireflection coatings, texturizing, past back surface field and shallow junctions. The HEWAC cell represents the culmination of a long series of development efforts.

FUTURE CELL DEVELOPMENT TRENDS

Future space missions such as solar electric ion propulsion for comet rendezvous and orbitting solar power satellites are under study. These missions may use thin, light weight solar cells in large arrays which can best use the advantages of wraparound contacts previously discussed. Creating wraparound contacts in silicon wafers with only 50 μm thickness presents a new set of technological problems. These problems include developing fabrication processes with acceptable yields, maintaining high cell efficiency and building a cell structure that can withstand the rigors of array assembly and the space environment. These problems have been investigated for conventional contact cells with good results (11). Extending this work to a wraparound design or extending the HEWAC technology to a thin cell appears likely in the future.

A new category of solar cells, rear junction devices, are thin and light in weight and have both contacts on the nonilluminated side. Rear junction devices include the interdigitated back contact cell (12) and the tandem junction cell (13). Their principal feature is a comblike interlocking p and n junction region on the back of the cell as shown in figure 3. Results to date indicate that they may also produce light weight, high performance space quality cells. Four mil thick cells have been made with 10 percent efficiency and with better metalization are expected to yield 12.5 percent air mass zero efficiency (13).

Wraparound and rear junction cells are examples of a broad class of devices in which the positive and negative electrodes are coplanar on the back of the cell. A new name, "Coplanar Back Contact" (CBC) cells has been coined to describe these devices. CBC cells include the interdigitated back, the tandem junction, the wraparound insulator and the wraparound junction cell. All the advantages of wraparound contact cells previously discussed also apply to CBC cells. Future development work may expand and/or refine CBC design.

ADVANTAGES OF WRAPAROUND CONTACT CELLS IN ARRAY FABRICATION

Wraparound contact solar cell development has been supported by NASA primarily to facilitate low-cost fabrication of large area solar arrays for space. The individual cell covering operations and the cell bonding operations are considerably simplified compared to conventional contact solar cells. This simplification results in the wraparound contact cell design being amenable for use in future highly automated cell assembly laydown operations that are necessary for low-cost large area solar array fabrication.

SOLAR CELL COVERING - From the individual operation viewpoint, the wraparound contact solar cell is easier to cover than the conventional contact cell. This is because the total wraparound contact cell front surface is covered by the glass and the orientation of the cover with respect to the "n" contact and the avoidance of an n gap need not be considered. Two adjacent edges of the solar cell and of the cover are held in matching position while the cover adhesive cures. Automated glass covering of solar cells with both conventional contact and wraparound contact designs has been demonstrated with the need for the covering machine to sense the position of the front surface "n" contact bar being eliminated with the wraparound contact cell. The possible future use of clear plastic film materials as a means of covering multiple solar cell assemblies and encapsulating electrical modules is also facilitated by the absence of front contact bonds when wraparound contact cells are used.

SOLAR CELL BONDING - The individual cell bonding operation using the wraparound contact cell is simplified when the cell assembly is used as part of an appropriate solar array system. The SEP (Solar Electric Propulsion) solar array utilizes a flexible printed circuit substrate in which the etched metal interconnect traces are encapsulated between two sheets of Kapton polyimide film (fig. 4). The use of the printed circuit or integral interconnect system has major advantages:

(1) Weight and assembly functions are eliminated by not requiring an adhesive to mechanically mount interconnected cells to the substrate. The electrical joint is the mechanical joint.

(2) Thin foils of the interconnect metal are accommodated, protected and held in exact registration by the encapsulating layers through the assembly process.

(3) A wide variety of interconnect stress relief-geometric patterns can be incorporated by precise step and repeat camera photographic processes to form the circuitry for the entire electrical module.

Although, as shown in figure 4, conventional contact solar cells can be accomodated by the integral interconnect design, the wraparound contacted cell offers additional advantages:

(1) The need for discretely formed, damage susceptible series tabs is eliminated.

(2) The n gap problem is eliminated by allowing the use of uniform covers over the entire cell surface.

(3) A higher cell packing factor is allowed by reducing the additional series spacing formerly required for forming and routing the series tab.

(4) Cell bonding to the interconnect system becomes a single sided function wherein series contacts can be made at the same time as parallel contacts. Automation of cell bonding is simplified reducing labor and costs.

In the finished substrate design, the interconnect metal is exposed on both sides of the substrate at metal pad locations. The interconnect pad locations coincide with the locations of the wraparound contact solar cell backside contacts, both n and p. The resulting combination of the wraparound contact solar cell design and the substrate design allows the solar cell assembly to be indexed face down on a supporting tool and to be covered with the flexible substrate. The interconnect pads can contact the solar cell contacts below and a bonding tool has access to the interconnect pads from above. All bonds are then made from one side of the substrate.

Modules built using this technology have been thermal tested by the Marshall Space Flight Center in the SEP Solar Array Technology Program. The purpose of the testing was to determine the mechanical and electrical integrity of the cell interconnect system when exposed to thermal cycles over a wide temperature range (-135° to +80° C). The best module tested had 5 percent bond failures after 7400 cycles. This percentage is not excessive for this stage of development. These test results are promising and provide confidence that the reliability required by most missions can be achieved at reasonable costs in a development program.

PRESENT MODULE FABRICATION WITH WRAPAROUND CONTACT CELLS

The methods presently used in the SEP solar array program for wraparound contact cell laydown employ a hand-loaded vacuum tool in which individual cell assemblies are placed face down between shim projections in the face of the tool. The cell assembly is a covered solar cell. The total projections fix the correct relative position of the total number of cells that the tool will hold. The tool is then fixed on a parallel-gap weld station. The array substrate is manually positioned over the solar cells and fixed in place. A numerically controlled system then automatically steps the table under the weld electrodes and initiates the welding operation. Following the weld pulse, the cells and substrate are similarly stepped to the next position until all the cell bonds for the cells on the tool are completed. Thus present module fabrication uses only one weld at a time. The substrate with cells is lifted and the empty welding tool is manually removed and reloaded. The full tool is replaced on table, the substrate is again manually positioned, and numerically controlled welding sequence is repeated. The size of the substrate module (28 in. by 7 ft for SEP) that is handled as a unit is limited to that which can be reasonably moved about and pulse illumination tested with available light sources. It is also made as large as possible to limit the number of modules that are handled to fabricate a large area solar array.

FUTURE AUTOMATED FABRICATED WITH WRAPAROUND CONTACT CELLS

Techniques for roll-laminating large printed circuit solar array substrates are being developed by the Lockheed Missile and Space Co. (LMSC) for NASA. Figure 5 illustrates the process. These substrates are 34 inches wide and up to 350 feet in length. Strips of this length can be processed by roll-laminating or by electrodepositing metal on the Kapton film. Following the etching of the cell interconnect circuit, the Kapton coverlay is roll laminated over the circuit to complete its encapsulation. A laser skiving operation is used to remove the Kapton plus adhesive from the pads in the interconnect system (both sides of the substrate) so that welding electrodes and the cell surface have access to the metal interconnect. Solar cell module assembly is now ready for cell assembly laydown.

Studies of the automation of the cell assembly laydown operation show that the wraparound contact cell is quite compatible with the various automation techniques proposed. This is because only one side of the cell assembly need be presented for all the bonding operations. The initial degree of automation in large area solar array fabrication is expected to accomplish the automation of the operations described above under "Present Module Fabrication" for an electrical module of sufficient size to demonstrate feasibility of processes, i.e., cell and substrate registration and cell to interconnect welding. The first operation of this future automated process involves the automatic dispensing of individual cell assemblies. This operation uses cell assembly storage cassettes, rolls, tapes or cartridges. These devices are manually loaded by the cell vendor or may be automatically loaded by the cell vendor in the last step of an automated acceptance and cell performance grading operation.

The next operation requires the automatic placing of the cells in proper position on a welding support tool and the holding of this position until bonding is complete. This may be a batch operation with one or more support tools shuttling between loaders and the weld station or a complete electrical module too' that is loaded prior to the start of welding. Tapes carrying the solar cell assemblies may be used to feed the upside down cells into a support tool just in front of the welder. This must occur under the substrate as the welder moves over the fixed substrate or an alternate approach has a table supporting the substrate as the substrate moves under the welder and over the cell support surface that is being fed cell assemblies for welding. The control and positioning of the array substrate over the solar cell must be indexed to the position of the interconnect trace in the substrate. This may be accomplished optically with special tabs in the interconnect trace being used to key the proper registration of the substrate.

As the technology of automated solar array module fabrication matures, gang welding with multiple welding heads will progress from four-head stations where all bonds on a single cell are made in one step to 40-head stations with the automatic supply and registration capability for the substrates and the wraparound contact cells being scaled up also. It is expected that the balance of continuous flow operations and line flow operations where sequential steps in the overall assembly task are performed at discrete, automatic work stations will be changing as the automated array fabrication system develops. Reduction of labor by automation of solar cell module assembly operations will contribute substantially to the reduction of overall solar array costs. The Skylab solar arrays which were built in the late 1960's cost NASA approximately $600/W (1972 dollars). The SEP solar array with automated assembly techniques will cost less than $400/W (1978 dollars). The influence of reduced labor on the reduction of solar array costs is illustrated in table II where the cost of fabricating a SEP solar cell module is compared with a typical cost for fabrication of a module of conventional design. The costs shown for the SEP module reflect todays' methods of fabrication as described in the previous section "Present Module Fabrication with Wraparound Contact Cells." Automated fabrication techniques of the types discussed above will further reduce these costs. Even though wraparound contact cells cost more than conventional contact cells, their development has promoted reduction of costs in other expensive array fabrication areas thereby contributing to the reduction of overall solar array costs. Continued development of the wraparound contact cell can be expected to reduce the price difference between the two types of cells, and further reduce the dollars per square foot difference in price.

SUMMARY

The wraparound contact cell has progressed from a primitive laboratory device to a space quality cell today. In the early 1970's efficiencies of only about 10 percent were available. A continuing development program has attacked and solved the problems with the early wraparound cell so that today efficiencies in excess of 15 percent have been achieved. Future development will see wraparound or coplanar back contact cells decrease in thickness and weight and decrease in cost.

The wraparound contact cell is highly amenable to automated low cost solar array fabrication and it's first use will be in the SEP solar array. Wraparound contact cell covering with glass or organic films is facilitated in both manual and automated operations. The wraparound contact cell enhances array panel designs for fully automated assembly. The parallel and series cell bonds can be made simultaneously resulting in significant savings in assembly time. This savings is observed with the present array assembly techniques. Wraparound contact cells will be easily handled, transferred and bonded as the development of line flow and continuous flow automated array assembly techniques takes place.

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TABLE I. - WRAP-AROUND CONTACT SOLAR CELL PROCESSING FEATURES

Cell feature	Vacuum process W/A junction technology (ref. 6)	Low-cost W/A insulator technology (ref. 8)	Combined low cost-vacuum process technology (ref. 10)
Junction	Gas diffusion*	Spin-on dopant	Gas diffusion*
Contacts	Evaporated CrPdAg* thin grids*	Print-on past thick grids	Evaporated CrPdAg* thin grids*
P^+ back	Evaporated Al	Print-on Al*	Print-on Al
Surface treatment	Chemical polish	Texturized*	Texturized
AR coating	Evaporated Ta_2O_5*	Spin-on AR coating	Evaporated Ta_2O_5*
Wrap-around method	W/A junction	Planar junction with W/A print-on* insulator	W/A print-on insulator*
Efficiency	11.2 percent AMO	10.9 percent AMO	Est. 14.5 percent AMO

*Best technology.

TABLE II. - SOLAR CELL MODULE COST COMPARISON

Component	Cost (dollars/square foot)	
	SEP Solar array[a]	Conventional solar array[b]
1. Substrate (materials and labor)	[c]100	140
2. Cell interconnect hardware	Included in component 1	380
3. Cell to interconnect bonding	[c]60	190
4. Cell laydown	Included in component 3	50
Module fabrication subtotal	160	760
5. Cells and covers	[c]2000	1500
6. Acceptance test	20	20
7. Quality Assurance	30	30
Subtotal	2050	1550
Total module cost	2210	2310

[a]Lightweight flexible substrate, integral interconnect, wraparound contact cell.
[b]Rigid substrate, conventional interconnect, conventional cell.
[c]Automation of process will reduce these costs.

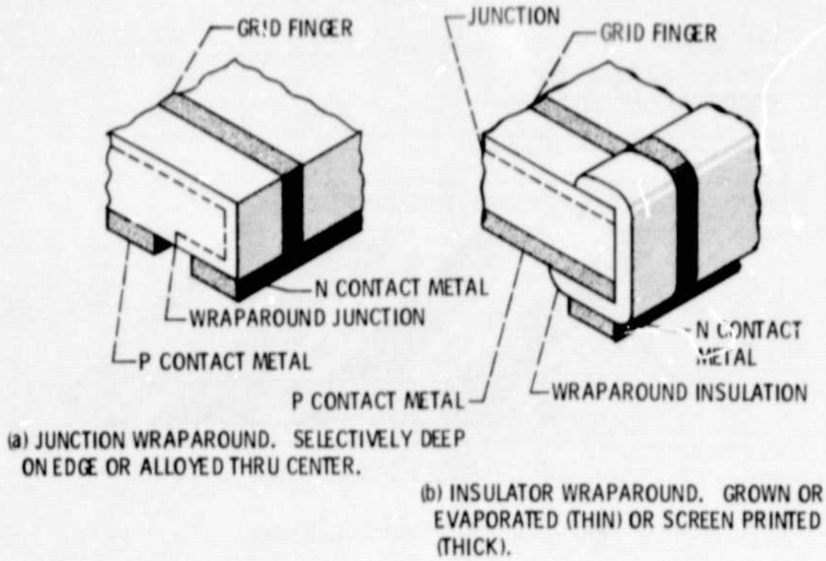

Figure 1. - Types of wraparound contact solar cells (close-up view of cell corner).

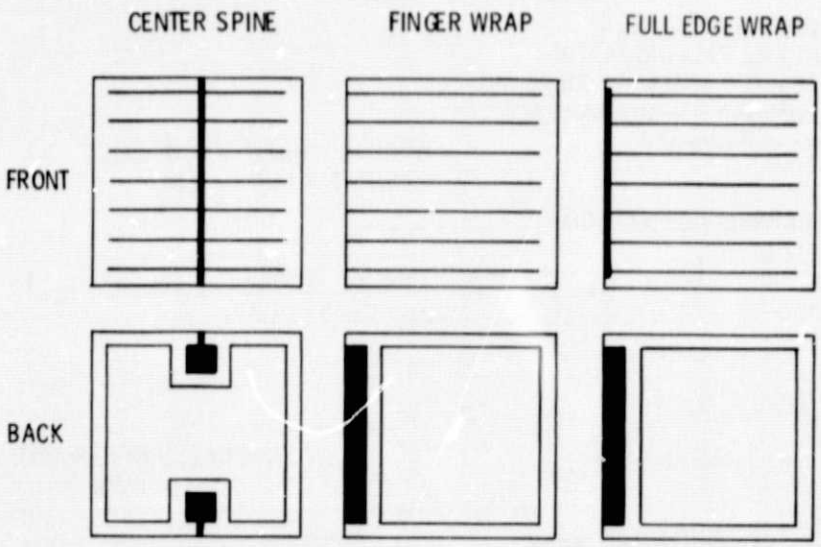

Figure 2. - Contact geometries of wraparound cells.

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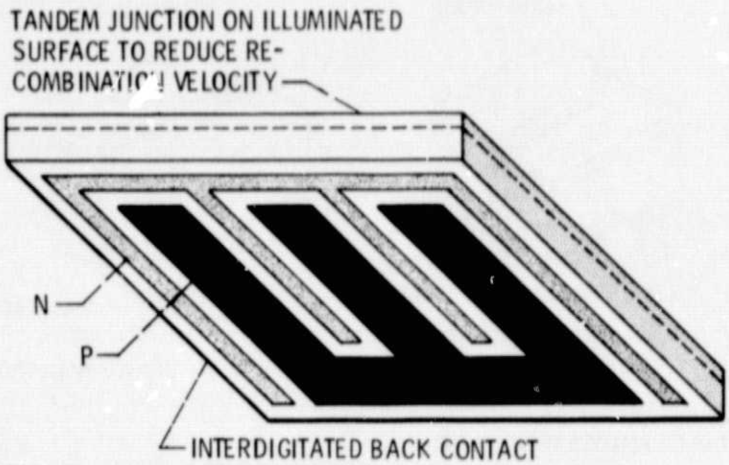

Figure 3. - Rear junction device.

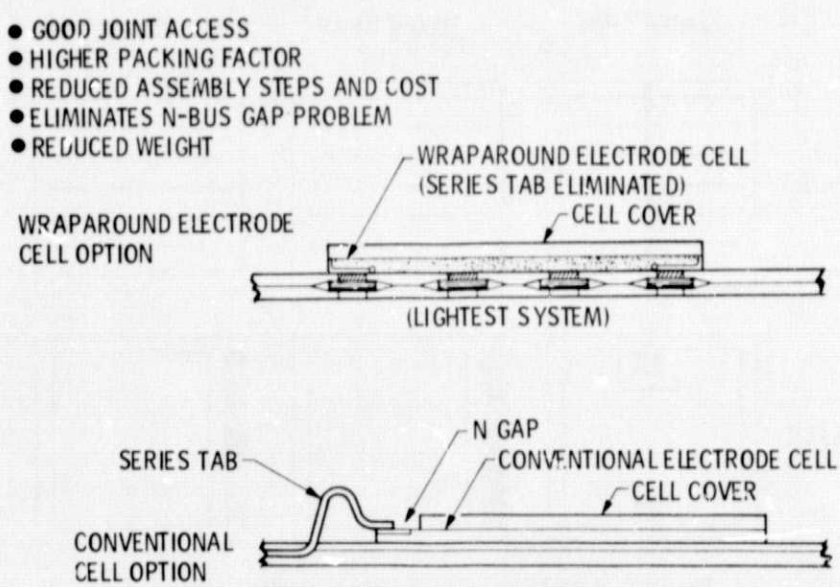

Figure 4. - Integral interconnect substrate design.

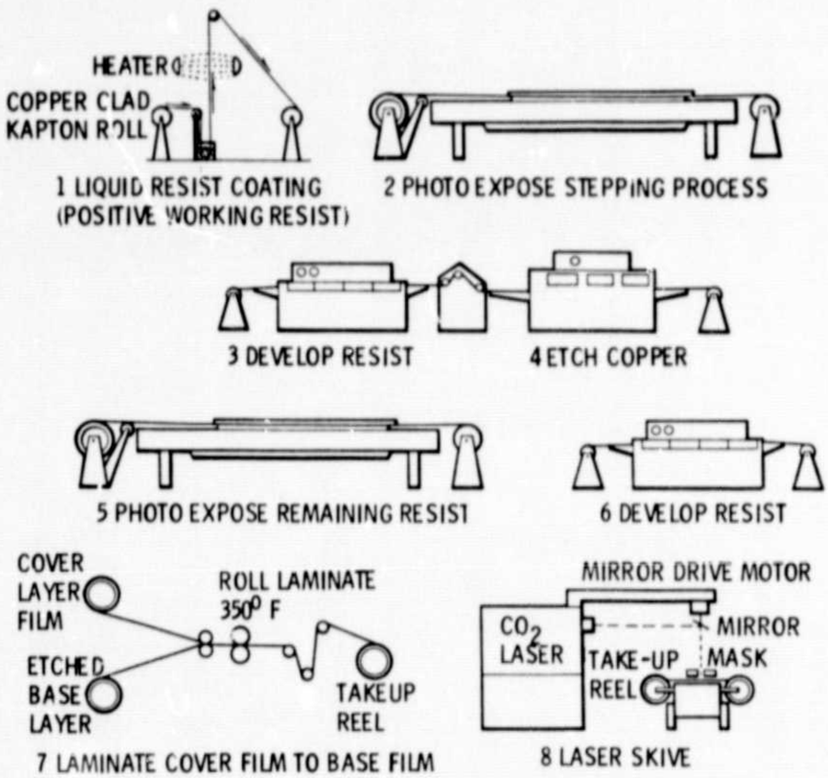

Figure 5. - Manufacturing concept for substrate fabrication.