SILICON SOLAR CELL EFFICIENCY IMPROVEMENT: STATUS AND OUTLOOK

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INTRODUCTION

The struggle to improve the efficiency of silicon solar cells has been going on as long as these devices have been a commercial product. The reason is simply that efficiency, as well as operating life, is an economic attribute in their application as part of a system. Fig. 1 illustrates the efficiency improvements made during the thirty year existence of the silicon solar cells, from about 6% efficiency at the beginning to 19% in the most recent experimental cells. Clearly the progress has not been a steady one. In the more stationary periods, the effort was more oriented towards improving radiation resistance and yields or the production lines, while, in other periods, the emphasis was more directed to reaching new levels of efficiency through better cell design and improved material processing. The last few years were again in such an "efficiency push" period, and encouraging first results have been forthcoming from the recent efforts. Nevertheless, considerably more efficiency advancement in silicon solar cells is expected, and anticipated attainment of efficiencies significantly above 20% (AM 1.5) is being more and more discussed. Whether this goal will be achieved is an open question, as major advances in material processing and in the resulting material perfection will be required.

The achievements along the road to efficiency improvement are best gauged by an analysis of the contributions of the individual principal loss mechanisms to the overall performance of a given device. Such analyses are presented in Table I, which lists the individual performance attributes of the milestone solar cells of the last fifteen years. Between 1959 and 1978, all solar cell development represented in the table was oriented towards application in space. Therefore, the available performance data are all based on AMO solar radiation, while the data for the more recent cells are based on AM 1.5 sunlight. To permit comparison in Table I, the space cell data were converted to AM 1.5 sunlight, using the spectral responses of the cells.

Table I indicates that the improvements achieved in the 1970s on the space cells included primarily an advancement of the collection efficiency, and a reduction of the "secondary" loss factors, such as residual reflectance, or series resistance losses. In the more recent efforts, directed at efficiency improvement for terrestrial applications, further advances have been made in the reduction of the impact of these secondary losses, but the main emphasis has been placed on the improvement of the voltages.

A study of the data in Table I leads to an evaluation of the status of silicon solar cell technology: the technology is available to decrease all the secondary loss mechanisms to the level where efforts for their further reduction will be fairly unproductive; the basic collection efficiency has been improved to the point where the beginning of its "saturation" with further reductions of minority carrier recombination has been reached; and further improvements are primarily to be achieved in the area of voltage increases through reduced minority carrier recombination.

MINORITY CARRIER RECOMBINATION AND SOLAR CELL EFFICIENCY

A study of the loss mechanisms and of their impacts, as displayed in Table I, reveals that recombination of minority carriers is the major basic effect which presently limits the efficiency of solar cells. Thus, a maximum efficiency value is associated with each level of the recombination rate in the device. The ultimate efficiency is reached when the only effective recombination mechanisms are radiative and direct band-to-band recombination.

An investigation of the relationship between recombination rates and maximum achievable efficiency is most transparent when it is carried out on the "basic" solar cell (Fig. 2). This device contains only those parts which are absolutely necessary for its functioning as a solar cell. These parts are: a volume for the absorption of photons and generation of free charge carriers: a potential barrier for the device to perform as a generator; and contacts for the extraction of a current. The basic analysis even considers the contacts as ideal, and omits a direct consideration of their functioning. The idealized analysis also chooses those impurity concentrations which, in consideration of minority carrier recombination, provide the highest efficiency. It then uses the same impurity density on both sides of the junction.

Recombination takes place both in the volume and at the surfaces of the device. It is practical to start the investigation with the assumption that all surface recombination velocities can be made equal to zero, and that the volume minority carrier lifetimes are equal in all parts of the device. This eliminates most influences of the device structure. Also, other device performance influencing effects are, at first, assumed to contribute zero losses. These considerations lead to curve 1 of Fig. 3, which represents efficiency as function of the minority carrier lifetime in such an idealized device, essentially as an upper limit for the achievable conversion efficiencies. The curve is basically composed of two straight lines in this semilogarithmic plot. Below about 1 ms lifetime, where the curve is represented by the straight line with the greater slope, the recombination is strictly determined by a varying density of recombination centers as described by the Shockley-Read-Hall theory. The resulting variation of the lifetime at constant resistivity is indicated by the vertical part of the dashed line in Fig. 4. Above the value of approximately 1 ms, the lifetime is dominated by Auger recombination, that is direct band-to-band recombination rather than recombination via centers. From this point on, to achieve a higher minority carrier lifetime, the impurity concentration has to be reduced. As maximum solar cell performance is obtained when the contributions of Shockley-Read-Hall type recombination and Auger recombination are equal, the dashed line in Fig. 4 approximately represents this condition above the 1 ms lifetime value. In this case, Shockley-Read-Hall recombination is assumed to be dominated by deep trap levels, which result in the independence of the lifetime from the impurity concentration (saturation lifetime) up to the transition to Auger recombination. Thus, for the 10 and 100 ms lifetimes, the impurity concentration has to be reduced to 1.5×10^{16} and 5×10^{15} cm^{-3}, respectively. Also, because of the difference in Auger coefficients, a small difference in the minority carrier lifetime values for the n and the p region is obtained in these cases.

As Fig. 4 shows, the lifetime values in recently obtained FZ ingots fall well below the Auger line, and are thus dominated by recombination via centers. For the efficiency improvements expected in the future, it will become necessary to reduce the recombination center density so far that Auger recombination will, in effect, become the lifetime limiter.

The data discussed so far are those typically obtained by use of fully analytical modeling. Such modeling is restricted to low level injection. Estimation of the excess minority carrier densities injected across the junction at open circuit voltage shows that the low level injection condition (e.g., $n_p << p_{p,o}$) starts to be violated between the 1 ms and 10 ms bulk lifetime values. This would not be of much consequence were it not for the fact that the minority carrier lifetime values have been chosen to be at the edge of domination by Auger recombination. In consequence, the impurity densities had to decrease for increasing lifetime values, while the excess minority carrier concentrations increase. Thus, the effective lifetimes are determined by the excess carrier concentrations, because of Auger recombination, rather than by the recombination center density. This leads to an efficiency saturation which is indicated in Fig. 3 by the wavy lines. Such an efficiency limitation has recently also been discussed by Green [1] and by Tiedje et al [2], who both found this limitation to be less severe for very thin cells, where it actually can approach the radiative recombination limit near 30%.

It has been seen repeatedly that the influence of the surface recombination velocity on the efficiency has the shape of an S-curve (Fig. 5), with practically no performance impact below a certain value of surface recombination velocity. Above this value, the solar cell performance falls off rather rapidly, until it reaches a lower saturation level. It is thus of interest to determine this threshold value for the surface recombination velocity. Using a range of surface recombination velocity values for each value of minority carrier lifetime, surface recombination threshold values have been determined, defined as that value at which the power output of the device has been reduced by 2.5%, from its s = 0 value. This process has been carried out first for the back surface, and then for the front surface, leading to a total reduction in power output of 5%. Surface recombination on the generally narrow edges of the device has been neglected in this process. The result is curve 2 in Fig. 3. The surface recombination velocity threshold values themselves are given in Fig. 6. Two curves are presented, as the threshold values differ for the front and the base surface recombination velocities for the given device structure, which has a nominal junction depth of 2 μm. It is noteworthy that the surface recombination velocity thresholds lie above 100 cm/s, and in the 30-60 cm/s range for bulk lifetimes of 100 μs and 1 ms, respectively. Such velocity values are attainable with current technology. However, to achieve the highest efficiency values, the surface recombination velocities have to be reduced below the 1 cm/s level.

In the device geometry chosen, the minority carrier lifetime in the front region can be less than assumed for Fig. 3. A sensitivity analysis similar to that carried out for the surface recombination velocities provides the "threshold" value for the front region minority carrier lifetime. It is defined as that value at which the power output is degraded by 1%. The resulting lifetime is shown in Fig. 7 for the various efficiency levels. As Fig. 7 shows, the threshold front region minority carrier lifetimes are approximately two orders of magnitude lower than those required for the base region. These lower front region values are more readily achievable in device fabrication than the original higher ones.

Finally, there is an optimum device thickness connected with every minority carrier lifetime value. This thickness constitutes the peak value of a rather flat maximum. Figure 8 presents the optimum base thickness as function of the minority carrier lifetime for the efficiency values of Fig. 3. It is seen in Fig. 8 that a 500 μm thick device is best for lifetime values above 1 ms, with the optimum thickness dropping off rapidly for lower lifetime values. The application of texturing was found to permit the use of a reduced thickness, as would be expected from it as well as from other light trapping measures. But it is also seen that the texturing provides only a small efficiency improvement at the highest efficiency values, as indicated by the cross in Fig. 3.

To obtain a conception of realistically achievable efficiencies, the values of curve 2 in Fig. 3 have been reduced by another 10%, in order to account for the effects of the secondary losses. It is known that these losses, in combination, are reduceable to this level by application of the best current technologies. This 10% reduction leads to curve 3 in Fig. 3. It shows that with a base minority carrier lifetime of 100 μs, an efficiency of 19.8% should be achievable, which is a value not much above the one achieved so far in the best devices with somewhat lower lifetimes. It also shows that a lifetime value near a millisecond will be needed to achieve 22% efficiency. While millisecond lifetimes should be achievable by a combination of today's best technologies in semiconductor material processing, the achievement of efficiencies above 22% will require a considerable advancement of the material science of silicon.

CONCEPTS FOR HIGH EFFICIENCY SOLAR CELL DESIGN

Evaluating the current status of silicon solar cell technology (summarized in Table II) makes it evident that the technology is available to reduce all the contributions from secondary loss mechanisms to the level of maximally 2 to 3% each. This will be close to the practically achievable limits. Secondary loss mechanisms are those which are determined by technology factors, and which have a fundamental limit of zero, with the exception of the collection efficiency. These secondary losses include the reflectance, shading due to front surface metal coverage, Joule losses due to series resistance, excess junction current, etc.

The evaluation also shows that the (internal) collection efficiency is, in all modern cells, significantly above 90%. It has also been found that the collection efficiency increases only slowly with further reductions of minority carrier recombination, giving the effect of an apparent "saturation."

In contrast to the collection efficiency, the open circuit voltage continues to increase significantly with continued reduction of minority carrier recombination. This is the performance attribute which has the largest margin for improvement at the current status of solar cell technolo-gy. The curve factor, finally, increases together with the open circuit voltage, although its increase proceeds at a smaller rate.

A review of the progression towards the current high level of silicon solar cell performance indicates that this level has been accomplished only by taking a global view of the device. The expression "global view" means simultaneously considering the influence of all loss mechanisms, and reducing each of them to the lowest possible level (Table III). In fact, where there are several performance determining mechanisms, which act on the same attribute and which cannot be reduced to zero, then the optimum performance is generally obtained when the different contributions are brought to equal, low levels. This rule, for instance, applies to the contributions to the saturation current from the base and from the front region. A device where the saturation current is clearly dominated by one or the other region is not optimized until the higher contribution is brought down to the level of that from the other region.

The efforts towards efficiency improvement have so far led to a number of "add-ons" to the basic cell. They include: (1) a grid metallization structure to reduce the front layer sheet resistance; (2) a single or dual layer anti-reflection coating; (3) texturing of the front surface to enhance the anti-reflection effect and to increase the effective internal optical path length; (4) an optical reflector at the back surface to increase the optical path length ("light trapping"); (5) passivating layers at the front and back surfaces to lower the effective surface recombination velocities; (6) potential steps or drift field regions; (7) isolating layers; and (8) reduced area metallization (dot contacts)--the last three also primarily for the reduction of the effective surface recombination velocity. This could lead to a complicated device structure (Fig. 9). At least part of the purpose of applying the measures (3) to (8) is to reduce the recombination rates of minority carriers, and their effects and limitations will be considered in the following.

The discussions up to this point have shown that the reduction of minority carrier recombination is the key element in achieving significant further improvements in silicon solar cell performance. Contemplation of the subject reveals that there are essentially three principal paths available to the reduction of recombination (Table IV). The first is the normally considered avenue of decreasing the density of recombination centers. This has to be accomplished in the volume of the device and on its surfaces. The second avenue is the reduction of the volume of the material, or of its surface area, both of which contain the recombination centers. For the volume, the concept is to utilize "thin layers" which means that their thickness is smaller than the diffusion length, while, for surfaces, it is principally to reduce the total surface area which contains recombination centers For solar cells this would be possible only by using optical concentration. A secondary approach is to reduce areas of unavoidably high surface recombination velocity in favor of surfaces with a lower surface recombination velocity. The typical example of this approach is the reduction of the ohmic contact area ("dot contacts"). The third avenue, finally, is that of reducing the density of the excess minority carriers, as the recombination currents both for the volume and for the surfaces are proportional to the excess minority carrier concentration. The density of the excess minority carriers can be reduced, e.g., if their flow towards the outside of the volume in which recombination occurs, can be accelerated. This particular approach is available for minority carriers generated by the absorption of light, which means for the improvement of the collection efficiency. A second method is to "shield" the areas with higher excess minority carrier density from the areas with higher recombination rates by steps of the electrostatic potential in the appropriate direction. This leads to a lower density of the excess minority carriers within the region of higher recombination rates. The third approach is to isolate regions or surfaces with high recombination rates, such as the metal/semiconductor boundaries at the contacts, from the regions with higher minority carrier density by an intervening "thick layer." The effect of this "isolating layer" is that the region with the higher excess minority carrier density "sees" the bulk recombination rate of the intervening layer rather than the higher surface recombination rate at the other boundary of the thick layer. The final approach utilizes an increased dopant concentration. This is particularly effective in the case of injection of minority carriers across a forward biased potential barrier.

Having recognized the principal concept for the reduction of minority carrier recombination, the question turns to the implementation of these concepts. A number of device structures and of design concepts are available, each of which addresses one or two of the principal paths to recombination reduction.

Reducing the volume of the semiconductor in which excess minority carriers are present, as a means for reducing recombination, is elucidated by considering the relationship for the diode current (Table V). This current is proportional to the transport velocity which, for infinitely thick layers, equals the ratio of diffusion length to minority carrier lifetime. For layers which are thin compared to the diffusion length, however, the transport velocity approaches the ratio of the layer thickness to the minority carrier lifetime. Thus, continued reduction of the thickness further reduces the recombination current. In a solar cell in the open circuit condition, where the diode current has to equal the light generated current, the injected excess minority carrier density is proportional to the inverse transport velocity, that is proportional to the minority carrier lifetime and inversely proportional to the layer thickness. When the lifetimes become very large or the layer thicknesses very small, the injected excess minority carrier density can exceed the magnitudes required for the low-level injection condition to hold, as discussed before, and a transition to Auger dominated recombination can occur. Thus, a reduction of volume recombination may not be achieved beyond the point of transition to Auger recombination.

For the principle of the reduction of the recombination volume, only reduction of the layer thickness has been discussed. An area reduction appears to be potentially effective only if the device cross section for the light generated current could be made different from that for the diode current.

A second item for the reduction of recombination is the reduction of surface area which contains a substantial number of recombination centers Table VI). While in principle devices can be made smaller, the reduction of the "open" surfaces is difficult for solar cells, as the area is needed for the absorption of photons from the incident solar radiation flux. Optical concentration also may not be a remedy to this situation, as it leads to an increased light generated current density, which again can more easily drive the device into the Auger recombination regime.

Surface area reduction can be very effective, however, where the contact areas are concerned, as these represent surfaces of high recombination rates. While means seem to be available to reduce the surface recombination velocities at the open surfaces, particularly if they do not have to effectively pass incident photons, the contact recombination velocities do not seem to be substantially reducible in practical devices. Thus the approach is being pursued to reduce the weighted average surface recombination velocity, by reducing the area of high s and replacing it with an increased area of low s. Limits to the method are approached when the spacing between the areas of high surface recombination velocity reaches the magnitude of the diffusion length. Also, when the individual contact areas become very small, their spreading resistance becomes substantial, so that they start to make a significant contribution to the series resistance.

The next possibility for decreasing recombination rates involves a reduction of the number of excess minority carriers available in regions of higher recombination center density. The first approach to this is "shielding" these areas by interspersing a suitable step in the electrostatic potential, often called a "high/low junction," or a drift field (Table VII). The effect of reduced recombination expresses itself in the transport velocity for minority carriers across a real or imagined boundary within a given region of the device. The reduction of the transport velocity by the addition of a potential step is equal to the negative exponential of the height of the potential step or, expressed differently, to the ratio of the majority carrier concentrations at the two sides of the potential step.

Such potential steps can be incorporated in a semiconductor device in many different forms. They may be layers containing a drift field resulting from a doping gradient. When such layers are relatively thin, they are often called high/low junctions. Such potential steps may be "accumulation layers" near the surface of a device, and are present particularly in the cases where an insulator covers the surface of the semiconductor, particularly when it is interposed between a metal and the semiconductor. Depletion layers increase the transport velocity and should, therefore, be avoided. Going beyond depletion leads to inversion layers which act more like floating pn junctions which also have been proposed for shielding purposes in solar cells. The floating junctions seem to be most effective when they act as true "emitters," which means injection only from the emitter, no recombination current into the emitter. This may be the only beneficial application of an "emitter" in a solar cell. The final form of a potential step is achieved in the transition to a material with a different bandgap, i.e., a wider bandgap. The transition to the wider bandgap layer is generally arranged so that it results in a high/low junction of the proper direction. These wide bandgap layers, when applied to the open part of the front surface, are generally designed so as not to collect a significant amount of current, but to transmit the photons to the active semiconductor volume. They are then called "window layers."

The use of potential steps has several limitations. Firstly, the use of moderately high doping at the low side of high/low junctions, in order to achieve a high open circuit voltage (V_{OC}), reduces the available step height. This condition is further accentuated by the need to avoid the heavy doping effects on the high side, which can seriously influence the device performance. Similar considerations apply to accumulation layers, where it is in some cases also difficult to provide enough charge to adequately "accumulate" in a more heavily doped semiconductor. An item to also watch is the capability for avoiding "absorption without collection" in window layers. In addition, at the transition between the active semiconductor and the window layer, a high concentration of interface states can substantially increase recombination.

A third approach is to isolate the active volume of the device from a region with a high recombination center density by interspersing an "isolating layer." If such an interspersed layer is thicker than the difussion length within it, then the transport velocity at the interface between the active volume and the isolating layer is determined only by the ratio of diffusion length to minority carrier lifetime, and is practically independent of the transport velocity at the other boundary of the isolating layer, which, e.g., may be the high effective surface recombination velocity of a metal/semiconductor interface (Table VIII). The limit to the effectiveness of such an isolating layer is that the L/τ ratio has to be adequately high, certainly higher than the transport velocity at the outside boundary of the isolating layer. Also, if such an isolating layer is placed in the optical path, it can severely degrade the collection efficiency.

More and more use is being made of such isolating layers. They appeared first in connection with the high/low junctions applied in the base of solar cells, which frequently go under the name "BSF structures." The use of such isolating layers has also been proposed for the front region of the device, where they are limited to the area shaded by the ohmic contacts (Fig. 10), while another recent high efficiency design uses an isolating layer in the base without application of the high/low junction (Fig. 11).

A commonly used approach to reducing the density of injected excess minority carriers, e.g., n_p, and to consequently achieving higher open circuit voltages, is to decrease the thermal equilibrium minority carrier concentration $n_{p,0}$ (Table IX). $n_{p,0}$ is inversely proportional to the majority carrier concentration and consequently the dopant concentration. This reduces the saturation current, and yields a higher V_{OC}. At the open circuit condition, however, the excess minority carrier concentration is returned to the same value as present in the case of lower dopant concentration. The limits of achieving improvements through higher dopant concentrations are reached by the onset of Auger recombination, and deleterious effects are experienced through bandgap narrowing.

After all these avenues available through device structuring possibilities are exhausted, then the only recourse left for the reduction of recombination becomes the decrease of the recombination center density itself (Table X). For those of these centers which are located in the volume of the material (bulk centers), the interest focuses on the original material processing (crystal growth), and on the further role of these previously introduced centers during device processing. In the original material processing, attention needs to be directed to the reduced incorporation of impurities which cause recombination centers; to the avoidance of crystal defect introduction, particularly through control of the thermal environment during crystal growth; to the roles of oxygen and carbon which are present in the silicon in relatively high concentrations; and to the formation of defect complexes, and particularly to their roles in forming or neutralizing recombination centers.

The second area, device processing, is equally important for the reduction of the recombination center density in the final device. The first and most obvious point of attention is the prevention of the introduction of new lifetime killing impurities. A second approach is to remove existing defects in the material at various stages during the device process, using treatments which are generally connected with the name "gettering." One of the major problems in device processing, particularly during the application of high temperature processes, is the transformation of existing inactive defects into recombination centers. On the other hand, it is desirable to foster the transformation of recombination centers to electrically inactive defects. These transformations may involve changes in existing complexes, or the formation of new ones. The transformations are often connected with the name "passivation," and one of the major open questions in this area is the role which hydrogen can play.

Somewhat related to the question of reducing the bulk recombination center density is that of dealing with the surface recombination centers. What is meant here is the actual reduction of the density of recombination centers at the surface, rather than the effect of a reduced surface recombination velocity which often is connected with the introduction of a potential step just below the surface (Table XI). The usual recombination center density of untreated silicon surfaces is in the 10^{15} cm^{-2} range. This number happens to be near the density of dangling bonds which would be expected to exist at a perfect silicon surface. If these dangling bonds should actually be responsible for the recombination centers, then the question arises of how these dangling bonds interact with other chemical species, and particularly which of these interactions result in a substantial decrease in the recombination center concentration. In addition, there is the question of which other defects form surface traps which act as recombination centers. Definitive answers to these questions may lead to the methods for effectively avoiding the introduction of these defects, or for their elimination, once they are in existence.

The whole question complex on the reduction of the recombination center density leads to the conclusion that considerable progress in the silicon material science is needed, as well as in the technology of crystal preparation and of device processing.

The preceding discussions lead to the conclusion that a high efficiency solar cell design will by necessity combine at least several of the methods known for the reduction of recombination (Table XII). It will further have to strike the right compromise between the conflicting design requirements, as a particular method may improve certain attributes of the device, but have a negative impact on others. And finally, all the second order effects need to be included in the design considerations, and the best available technologies for their reduction be applied in order to achieve the highest efficiency extractable from the silicon solar cell. The general high efficiency design concept, thus, will pursue the two-pronged approach of decreasing the recombination loss of minority carriers, and particularly that of the carriers injected under forward bias, and of simultaneously reducing all the secondary effects to near negligible values. Several cell design approaches seem to exist for each of these performance attributes, and the designer will have to select those which will yield the highest overall device performance, when applied in combination. And, of course, this device will have to be fabricated at a competitive price.

CONCLUSION

It has been seen that the achievement of higher efficiencies in silicon solar cells depends on the reduction of all secondary losses to negligible values, which is about possible with current technology, and then on the reduction of minority carrier recombination (summarized in Table XIII). For the latter, four principal approaches are available, three of which are essentially remedial, handled through device design, and one is fundamental, namely the reduction of the recombination center density.

All the reduction of recombination via recombination centers will only lead to the dominance of Auger recombination, which appears to impose the ultimate practical limitation on solar cell efficiency. As there exist still some doubts on the magnitude of the Auger coefficients, this ultimately achievable efficiency can also not be certain at this time. Some rather fundamental research will be needed to gain the complete understanding of the band-to-band recombination effects which carry Auger's name.

Several of the "remedial" methods for reduction of recombination involve high majority carrier concentrations. The onset of Auger recombination tends to force the efficiency versus carrier concentration curves towards zero slope, and the onset of bandgap narrowing then to a negative slope. Again, the bandgap narrowing effect does not seem fully explained, with the result that the various bandgap models in existence now lead not only to different solar cell performance expectations, but also to different cell designs for optimum performance. Again, fundamental research is needed.

Outside of these fundamental research needs, substantial silicon material research, both bulk and surface, will be needed to reach substantially higher efficiency levels. And then we should not forget the inventiveness which could bring forward new, more effective remedial design concepts.

REFERENCES

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2] Tiedje, T., Yablonovitch, E., Cody, G. D., and Brook, B. G., "Limiting Efficiency of Silicon Solar Cells," ibid., pp. 711-716.

PRIMARY CAUSES OF LOSSES	SYMBOL	DESIGN PARAM	1970 COM'L CELL	"VIOLET CELL"	"BLACK CELL"	1978 SPACE CELL	1984 EXPER'L CELLS SPIRE	WESTINGH	M.A.GREEN	GOALS 20%	22.6%
		BASE: WIDTH	?	300 μm	300 μm	300 μm (A)	380 μm	375 μm	280 μm	200 μm	200 μm
		$\tau_{n,p}$	3 μs	?	?	?	~40 μm	~23 μm	~25 μm	95 μs	950 μs
		τ_{n,p^+}	—	—	—	?		(10.1 μs)	(10 1 μs)	0.26 μs	2.6 μs
		FRONT: WIDTH	0.4 μm	~0.15 μm	~ 0.2 μm	~0.2 μm	~0 2 μm	~0 3 μm	~0.3 μm	2 μm	2 μm
		$\tau_{p,n}$	?	?	?	?			lns - 15 μs	0 1 μs	10 μs
		S	?	?	?	?	~10^4 cm s^{-1}	~10^4 cm s^{-1}	10^3 cm s^{-1}	10^3 cm s^{-1}	10^2 cm s^{-1}
		TREATM.	SiO	Ta_2O_5 + GLASS	TEXT'D + Ta_2O_5 + GLASS	TEXT'D + Ta_2O_5	TEXT'D + SiO_2 + TiO_2	TiO_2/SiO_2	ZnS/ MgF_2	DUAL AR	DUAL AR
1. LIGHT GENERATED CURRENT:											
FUNDAMENTAL LIMIT (AM1)	$I_{L,td}$		44 mA cm^{-2}								
A. OPTICAL SURFACE PROPERTIES (REFLECTION)	(1-R)		0.905	0.90	0.9:	0.96	0.975	0.966	0 954	0.97	0.97
B. CONTACT COVERAGE	S		0.96	0.95	0.95	0.96	0.965	0.97 (A)	0.948	0.966	0.966
C. INCOMPLETE ABSORPTION (THICKNESS)	η_{COLL}		0.72	0.95 } = 0.90	0.96	0.96 (A)	0 956	0.956	0.973	0.92	0.95
D. RECOMBINATION OUTSIDE DEPLETION REGION (BULK AND SURFACE, INCLUDING CONTACTS)				0.95	0.94	0.94	0.91	0.915	0.93		
E. ("DEAD LAYERS")	(1-A)			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
OVERALL COLLECTION EFFICIENCY:	γ		0.63	0.77	0.84	0.84	0.82	0.82	0 82	0.86	0.89
LIGHT GENERATED CURRENT (AM1)	$I_L = \gamma \cdot I_{L,td}$ (mA cm^{-2})		28.1	34.0	37.1	37.0	36.2	36.0	36.0	37.9	39.2
2. OPEN CIRCUIT VOLTAGE:											
FUNDAMENTAL LIMIT:	$(VF)_{fund}$ = 0.76		0.836 V (j_0 = 4.2·10^{-16} A cm^{-2})								
A. RECOMBINATION OUTSIDE DEPLETION REGION (BULK AND SURFACE, INCLUDING CONTACTS) B. BANDGAP NARROWING	$(VF) = (VF)_{techn}/(VF)_{fund}$		0.522	0.528	0 533	0 555	0 565	0.57	0 59	0 60	0.65
C. "CURRENT LEAKAGE"	(R_{sh})		1.0	1 0	1.0	1 0	1.0	1.0	1.0	1.0	1.0
OPEN CIRCUIT VOLTAGE:	$V_{oc} = (VF) \cdot E_g$ (V)		0.574	0.581	0.586	0.610	0.622	0.627	0.653	0.661	0.715
3. FILL FACTOR:											
FUNDAMENTAL LIMIT:	$(CF)_{fund}$		0 865								
A. B. } SAME AS OPEN CIRCUIT VOLTAGE	$(CF) = (CF)_{techn}/(CF)_{fund}$		0.82	0.823	0.823	0 824	0 83	0.833	0.839	0.84	0 85
C.	(R_{sh})		1.0 (A)	1.0	1 0	1 0	1 0	1.0	1 0	1 0	1 0
D. RECOMBINATION IN DEPLETION REGION	$(CF)_{add'l}$		0.91	0.97	0 97	0 97	0 985	0.98	0 982	0.97	0.97
E. SERIES RESISTANCE	(R_s)		0.96	0.985	0.984	0 98 (A)	0 98	0.98	0 984	0.98	0.98
FILL FACTOR	(FF)		0.716	0.78	0.78	0.78	0.801	0.800	0.811	0.80	0.81
RESULTING CONVERSION EFFICIENCY	η		11.6	15.4	17 0	17.6	18 1	18.1	19 1	0.200	0.226

(A) = ASSUMED

Table I

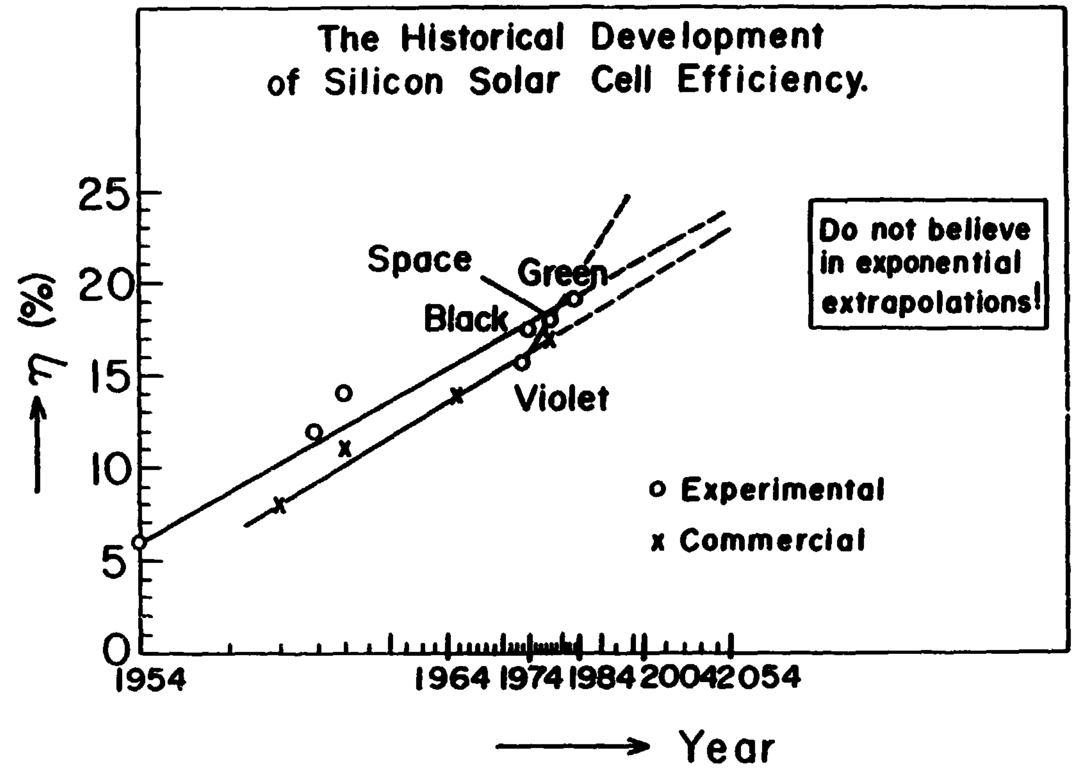


Figure 1

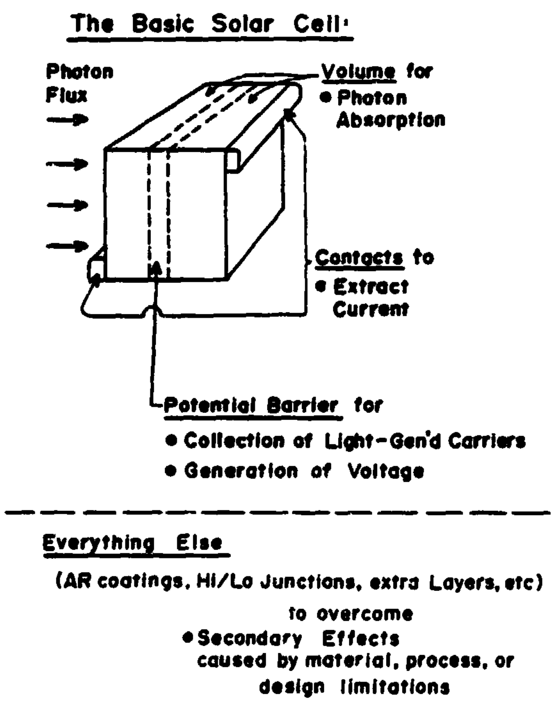


Figure 2

STATUS OF Si SOLAR CELL TECHNOLOGY

- TECHNOLOGY IS AVAILABLE TO REDUCE THE CONTRIBUTION OF EACH SECONDARY LOSS MECHANISM (REFLECTION, CONTACT SHADING, SERIES RESISTANCE, ETC.) TO THE MAXIMALLY 2-3% LEVEL.
- INTERNAL COLLECTION EFFICIENCY IS GENERALLY >90%; "SATURATES" WITH FURTHER REDUCED RECOMBINATION.
- OPEN CIRCUIT VOLTAGE CONTINUES TO SUBSTANTIALLY INCREASE WITH DECREASING MINORITY CARRIER RECOMBINATION, UP TO BASIC RECOMBINATION LIMIT (RADIATIVE AND AUGER).
- CURVE FACTOR (FUNDAMENTAL PART OF FILL FACTOR) CAN INCREASE (WITH V_{OC}) BY A FEW PERCENT.

Table II

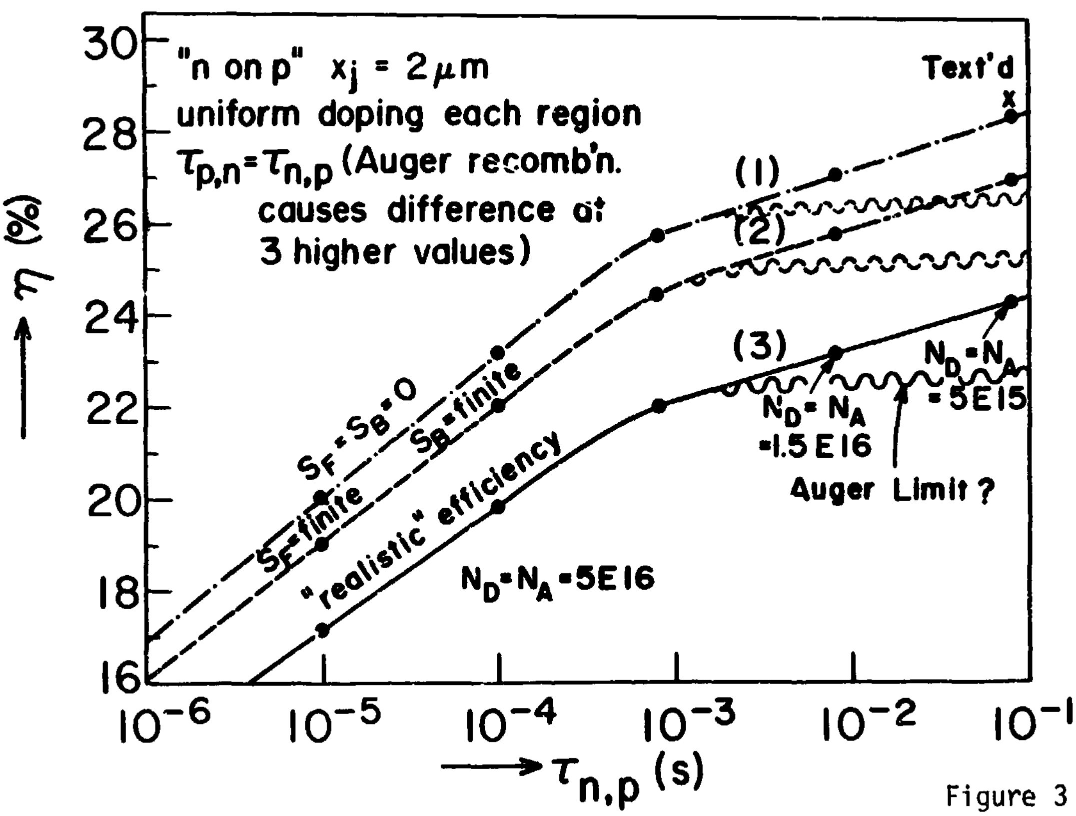


Figure 3

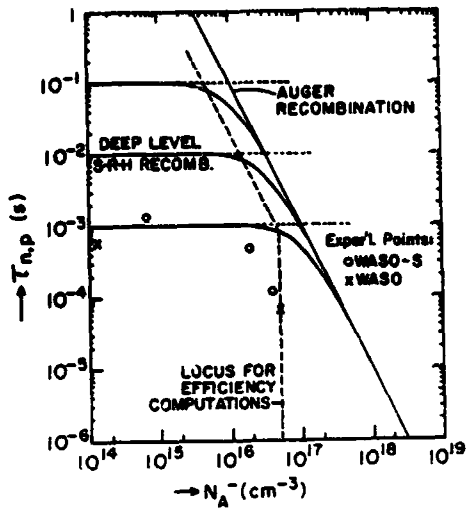


Figure 4

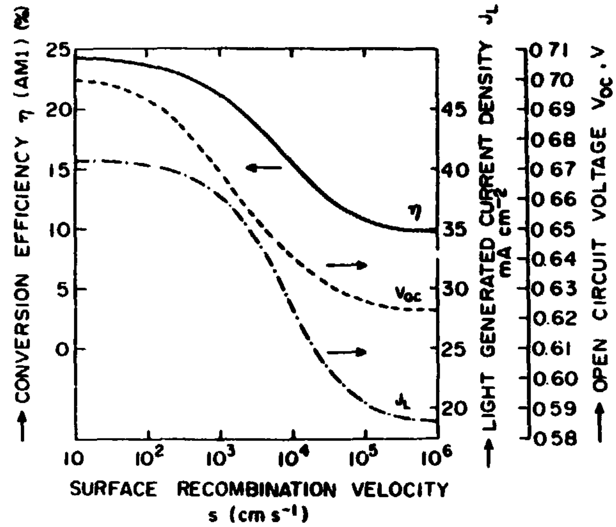


Figure 5

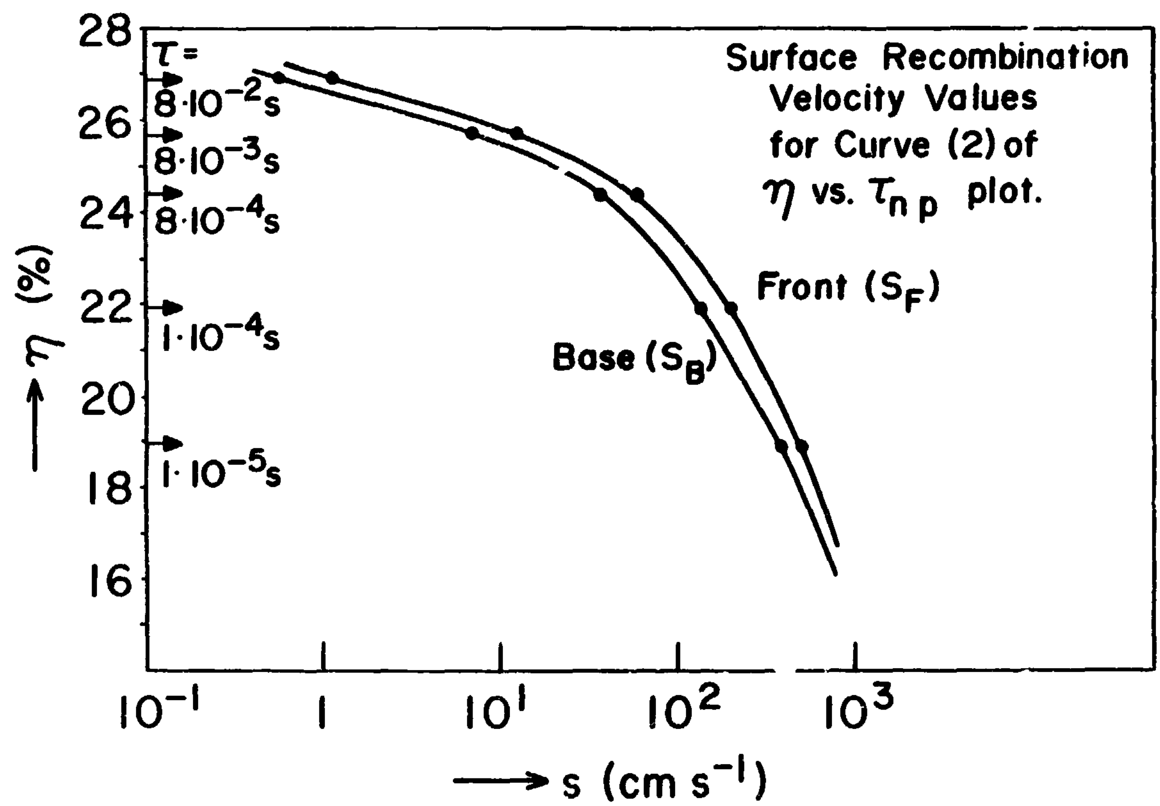


Figure 6

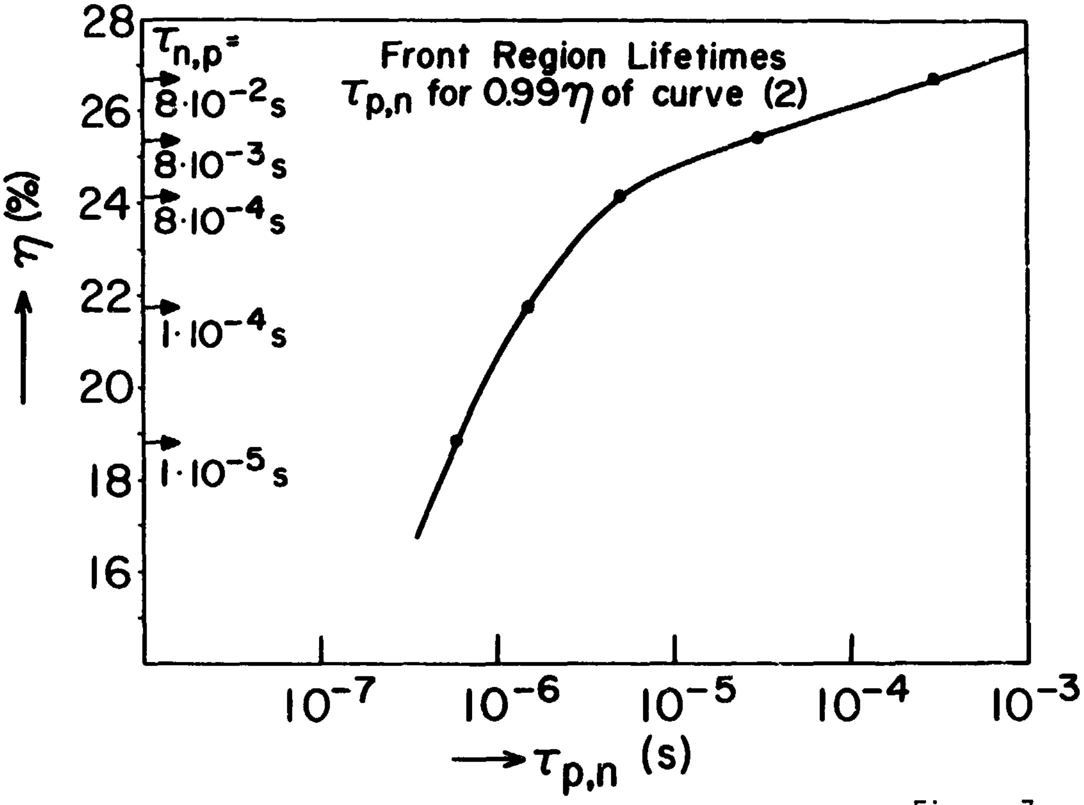


Figure 7

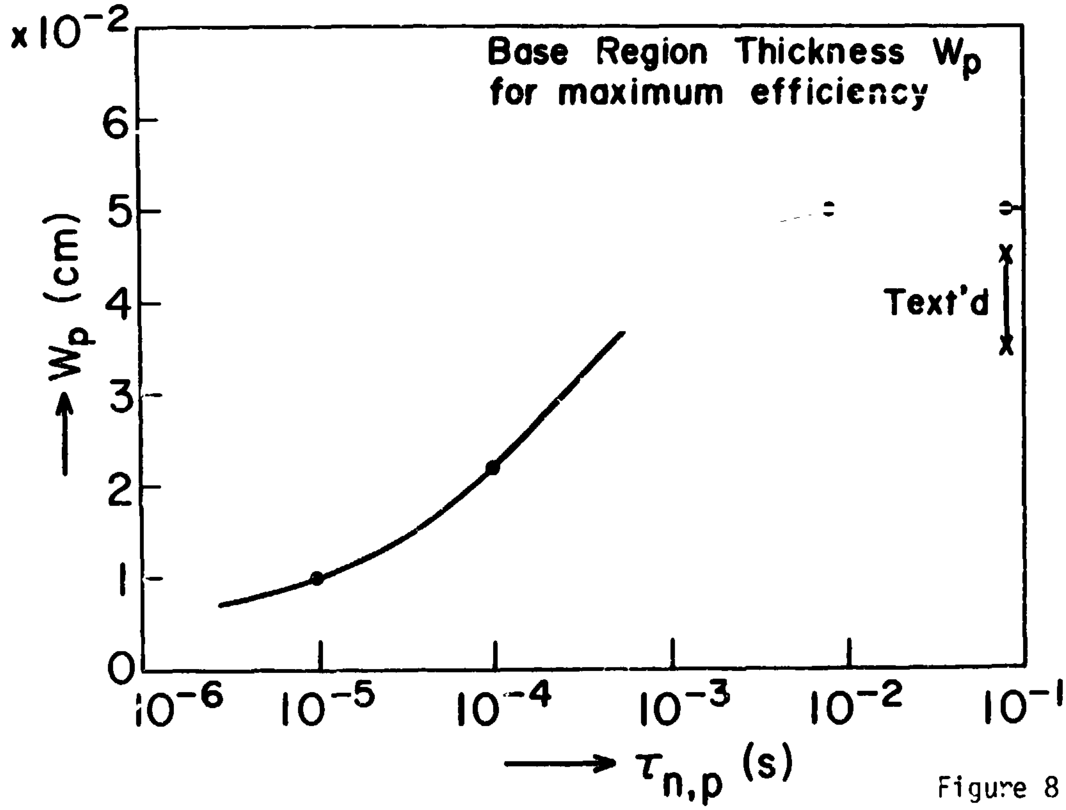


Figure 8

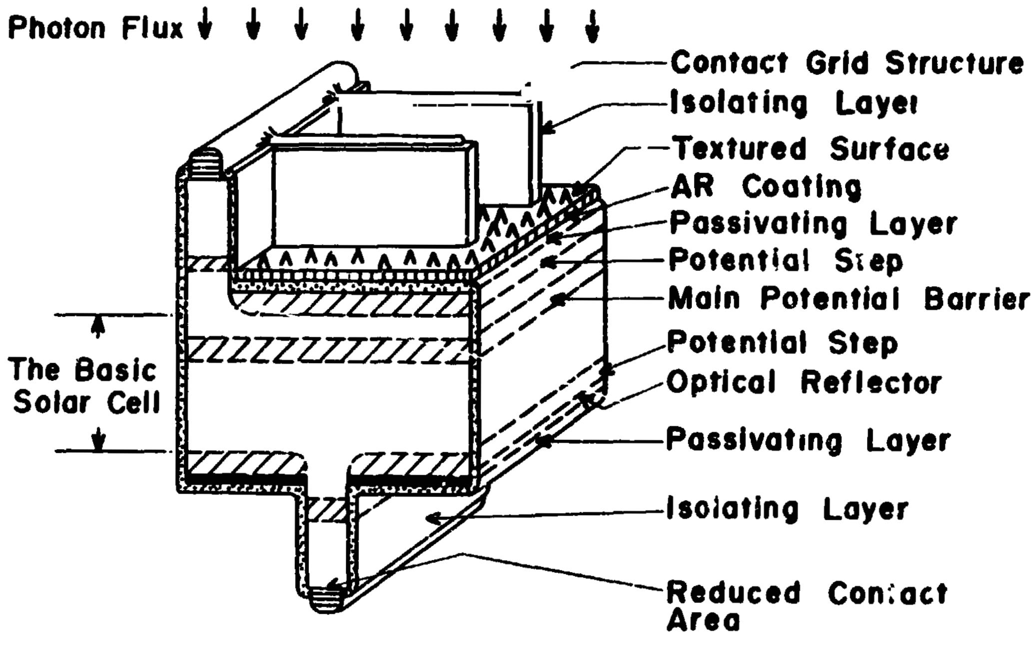
HIGH EFFICIENCY REQUIRES

A GLOBAL VIEW OF THE DEVICE, SO THAT ALL TECHNOLOGY-DETERMINED LOSSES WILL BECOME LOW.

IF ONE LOSS MECHANISM DOMINATES —> NOT OPTIMIZED
—> REDUCE IT

[OLD OPTIMIZATION RULE:
CONTRIBUTIONS FROM DIFFERENT COMPONENTS
ARE EQUAL AT MAXIMUM OR MINIMUM.]

Table III



Schematic View of the Solar Cell "That Has Everything"

Figure 9

THE THREE PRINCIPAL PATHS TO REDUCED RECOMBINATION

DECREASE

1. DENSITY OF RECOMBINATION CENTERS

- IN BULK N_t (cm^{-3}) ⟶ HIGHER τ
- AT SURFACES $N_{s,t}$ (cm^{-2}) ⟶ LOWER s

2. VOLUME OR AREA CONTAINING RECOMBINATION CENTERS.

- "THIN" LAYERS
- "DOT CONTACTS"

3. DENSITY OF EXCESS MINORITY CARRIERS

- FAST REMOVAL TO OUTSIDE (FOR η_{coll})
- "SHIELDING" WITH POTENTIAL STEPS } FOR η_{coll}
- "ISOLATING" FROM HIGHER RECOMBINATION RATE } FOR η_{coll}
- HIGH DOPANT CONCENTRATION

} FOR V_{oc}

Table IV

REDUCE VOLUME:

(I.E., THICKNESS OF LAYERS)

PRINCIPLE: $j_d = qn_p \frac{L}{\tau} \Big|_{d>>L} \longrightarrow j_d = qn_p \frac{d}{\tau} \Big|_{d<<L}$

("THICK" LAYER) ("THIN" LAYER)

LIMIT: $I_d = I_L$ for V_{oc}:

$$n_p = \frac{j_L}{q} \cdot \underbrace{\left(\frac{\tau}{d}\right)}_{\text{VARIABLE}} \not\ll p_{p,o}$$

NO LONGER LOW LEVEL INJECTION

$$\tau_{Auger} = \frac{1}{C_{Auger}(p_{p,o}+n_p)^2} < \tau_{S-R-H}$$

$(Aj_d = Aj_L)$

(AREA REDUCTION COULD BE EFFECTIVE ONLY, IF j_d/j_L RATIO COULD BE CHANGED, WITH I_d/I_L CONSTANT.)

Table V

REDUCE SURFACE AREA:

OPEN SURFACES:

LIMIT: ● NEEDED FOR PHOTON ABSORPTION

(CONCENTRATION: INCREASED j_L:

$$n_p = \frac{j_L \tau}{q\ d} \overset{?}{<<} p_p)$$

CONTACT AREAS: "DOT" CONTACTS

UTIL E AVERAGE EFFECTIVE s:

$$j_{r,s} = qn_p(x_s)\ \frac{A_1 s_1 + A_2 s_2}{A_1 + A_2}$$

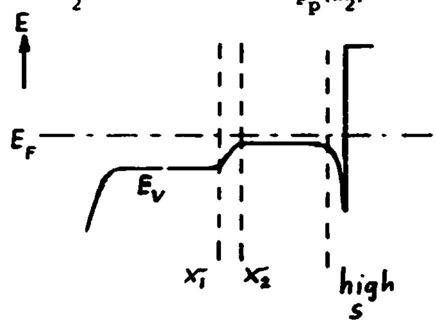
LIMITS:
- LESS EFFECTIVE WHEN SPACING < L
- SPREADING RESISTANCE INCREASES R_s

Table VI

SHIELDING WITH POTENTIAL STEPS:

GENERALLY REDUCES TRANSPORT VELOCITIES (FOR RECOMBINATION CURRENTS)

BY: $\frac{u_1}{u_2} = e^{-\frac{q\Delta(E_F - E_V)}{kT}} = \frac{p_p(x_1)}{p_p(x_2)}$; (FOR p-TYPE,



$$j_r(x_1) = qn_p(x_1)u_1(x_1)$$

$$= qn_p(x_1)\ \frac{p_p(x_1)}{p_p(x_2)}\ u_2(x_2)$$

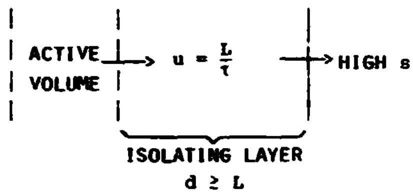
FORMS OF POTENTIAL "STEPS":
- DRIFT FIELD REGIONS
- HIGH/LOW JUNCTIONS
- ACCUMULATION LAYERS (USUALLY UNDER INSULATORS, INCLUDING "TUNNEL CONTACTS").
- "FLOATING" pn JUNCTIONS (OR INVERSION LAYERS).
- BANDGAP CHANGES (USUALLY ΔE_G WITH HIGH/LOW JUNCTION, "WINDOW LAYER").

LIMITS:
- INCREASED DOPING AT "LOW" SIDE REDUCES AVAILABLE STEP HEIGHT.
- "HEAVY DOPING" EFFECTS ON "HIGH SIDE" LIMIT USEFUL STEP HEIGHT.
- ABSORPTION W/O COLLECTION IN "WIND ' LAYERS."
- INTERFACE STATES AT TRANSITION TO "WINDOW LAYER."

Table VII

ISOLATING WITH "THICK LAYERS"

PRINCIPLE:



LIMITS:

- ADEQUATELY HIGH L/τ.
- AFFECTS COLLECTION EFFICIENCY, IF IN IPTICAL PATH.

Table VIII

HIGH DOPANT CONCENTRATION

PRINCIPLE:

$$j_d = q\, n_p \cdot \frac{L}{\tau} = q\, n_{p,o}\, e^{\frac{qV}{kT}} \cdot \frac{L}{\tau}\,;$$

$$V = \text{HIGH IF } n_{p,o} = \text{SMALL:}\quad n_{p,o} = \frac{n_i^2}{p_{p,o}}$$

LIMITS:

- HEAVY DOPING EFFECTS.

Table IX

REDUCE VOLUME RECOMBINATION CENTER DENSITY:

- ORIGINAL MATERIAL PROCESSING:
  - FEWER IMPURITIES
  - ROLES OF OXYGEN, CARBON?
  - FEWER CRYSTAL DEFECTS (THERMAL ENVIRONMENT IN X-TAL GROWTH?)
  - ROLES OF DEFECT COMPLEXES
- DEVICE PROCESSING:
  - NO NEW IMPURITY INTRODUCTION
  - REMOVE EXISTING DEFECTS (GETTERING)
  - AVOID TRANSFORMATION OF DEFECTS TO RECOMBINATION CENTERS (EFFECTS OF THERMAL PROCESSES?)
  - FOS[illegible] TRANSFORMATION OF RECOMBINATION CENTERS TO HARMLESS DEF[illegible] (PASSIVATION; CHANGES OF COMPLEXES?; ROLE OF HYD[illegible]GEN?)

Table X

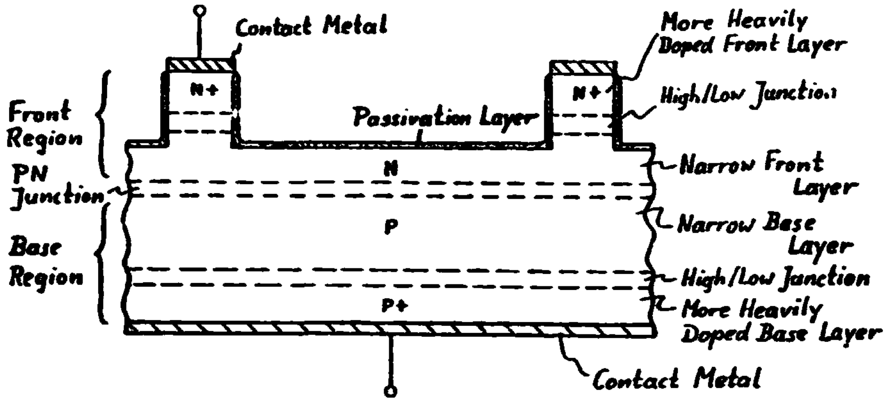
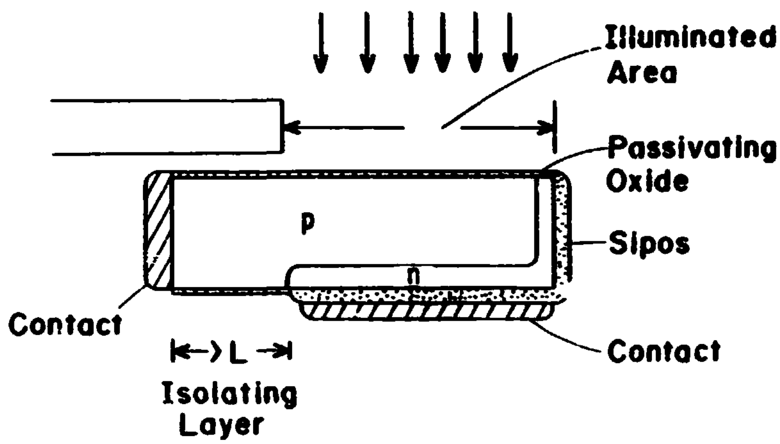


Figure 10



THE EXXON HIGH EFFICIENCY DESIGN

Figure 11

REDUCE SURFACE RECOMBINATION CENTER DENSITY:

- PASSIVATION OF DANGLING BONDS.

  (WHICH LAYERS ARE MORE EFFECTIVE IN REDUCING S_0, WHICH IN SUPPORTING ACCUMULATION LAYERS?)

- WHAT OTHER DEFECTS FORM SURFACE TRAPS

  (HOW CAN THEY BE AVOIDED OR ELIMINATED?)

Table XI

A HIGH EFFICIENCY CELL DESIGN

- COMBINES SEVERAL OF THE METHODS FOR REDUCTION OF RECOMBINATION.
- STRIKES THE RIGHT COMPROMISE BETWEEN CONFLICTING DESIGN REQUIREMENTS.
- REDUCES ALL SECOND ORDER EFFECTS.

Table XII

THE GENERAL HIGH EFFICIENCY DESIGN CONCEPT

EFFECT	LOCATION	AVAILABLE MEASURES: PRINCIPLE	AVAILABLE MEASURES: METHOD
● REDUCE RECOMBINATION LOSS OF MINORITY CARRIERS, PARTICULARLY INJECTED CARRIERS (HIGH V_{oc}):			
BULK RECOMBINATION	BASE FRONT	REDUCE N_t	PROCESSING
		REDUCE VOLUME	APPLY LIGHT TRAPPING
SURFACE RECOMBINATION	OPEN SURFACE	REDUCE $N_{t,s}$	PASSIVATION LAYER
		SHIELDING	DRIFT FIELD
		ISOLATION	WINDOW LAYER
	CONTACT	REDUCE AREA	"DOT CONTACT"
		SHIELDING	TUNNEL CONTACT WITH ACCUMULATION LAYER
		SHIELDING	HIGH/LOW JUNCTION, BSF
		SHIELDING ISOLATION	HIGH/LOW JUNCTION, WITH THICK p^+ OR n^+ LAYER, OR WIDE BANDGAP LAYER
		ISOLATION	THICK LAYER ALONE
● SECONDARY EFFECTS			
REFLECTION	FRONT	AR	MULTI-LAYER AR
		TEXTURE	TEXTURE + SINGLE AR
CONTACT	FRONT	REDUCE METAL COVERAGE	WRAP-AROUND DESIGN
		REDUCE METAL COVERAGE KEEP LOW	FINE LINE GRID
R_S	FRONT BACK	KEEP LOW	DEGENERATE SURFACE LOW METAL SHEET-RESISTANCE GOOD INTERCONNECT DESIGN
EXCESS CURRENT	JUNCTION	KEEP LOW	GOOD PROCESSING

Table XIII

DISCUSSION
(WOLF)

SPITZER: Given all the tradeoffs on grid design, passivation, and the other things that are necessary to make a 20% efficient cell, the question is, can screen-printed contacts be used for the 15% module, or will they not offer enough for high-efficiency features?

WOLF: I have been talking against screen printers at a number of meetings. The biggest problem I see in them is that in screen printing and sintering you don't get better resistivity or better conductivity. Even with silver it seems you get conductivity only about one-third, in general, of what you get if you electroplate or deposit silver. You are limited by how thick you can make the layer in one pass. The sheet resistance becomes limited by the bulk conductivity you can get. The second problem is, you cannot make them very narrow. It seems that 5 mils might be achievable with today's technology. These are the two things I see against screen-printed contacts.

SPITZER: Then, probably no.

WOLF: I would think if you go for high efficiency, at least consider a secondary later. I always find the first thing is to show we can really make high efficiency, so let's use the best technology we know we can apply to get to high efficiency then later let's think of how can we make them cheaper.

Now I want to introduce the next speaker. Here is a little contradiction. I have been saying that all the secondary problems are minor, our current technology is solved; just worry about recombination. Arnie Lesk from Solavolt is going to tell us about all the problems that still exist in trying to make low-resistance contacts. So, basically, I guess it is not easy, and there are still a lot of problems connected with it.