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REQUIREMENTS FOR HIGH-EFFICIENCY SOLAR CELLS

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Minimum recombination and low injection level are essential for high efficiency. Twenty percent AM1 efficiency requires a dark recombination current density of 2×10^{-13} A/cm^2 and a recombination center density of less than about 10^{10} cm^{-3}. Recombination mechanisms at thirteen locations in a conventional single-crystalline silicon cell design are reviewed. Three additional recombination locations are described at grain boundaries in polycrystalline cells. Material perfection and fabrication process optimization requirements for high efficiency are outlined. Innovative device designs to reduce recombination in the bulk and interfaces of single-crystalline cells and in the grain boundary of poly-crystalline cells are reviewed.

I. INTRODUCTION

Increasing efficiency and lowering cost have been the main objectives of solar cell research to achieve cost parity with other electrical power generation methods. Single-crystalline silicon cell efficiency approaching 18% (AM1) has been attained under production environment, moving the current research target to 20% or beyond [1]. Poly-crystalline silicon cell approach may lower the manufacturing cost further to a competitive level.

This paper will provide a review of the requirements for achieving high efficiencies. The next section, II, will review the dark d.c. current-voltage characteristics of a cell. Section III describes the dominant recombination mechanisms at thirteen locations in single-crystalline and three additional grain boundary locations in poly-crystalline cells. Section IV outlines the material requirements for minimizing recombination. Section V gives a discussion of process optimizations for high efficiency. Device design optimizations for high efficiency are reviewed in section VI. Section VII gives a summary.

II. D. C. CURRENT-VOLTAGE CHARACTERISTICS

The d.c. current-voltage characteristics of a solar cell in the dark provides a clear indication of its performance under sun light. It can be expressed generally by the diode equation

$$J = J_r[\exp(qV/rkT) - 1] \tag{1}$$

where J is the dark current density (A/cm^2), J_r is the recombination current density coefficient (A/cm^2) which will be called recombination current, q is the charge of the electron, V is the voltage across the cell with p-side positive and n-side negative in the p/n junction cell, r is the recombination law or junction ideality factor, k is the Boltzmann constant and T is the cell temperature.

The highest efficiency is achieved when both J_r and r are small. The dependence on r is illustrated by the illuminated current-voltage characteristic of a solar cell in Fig.1 whose equivalent circuit is also given in this figure. It is evident that the smallest r gives the largest area under the illuminated I-V curve and hence the highest power deliverable to the load. In a practical cell whose efficiency loss comes from electron-hole recombination at traps due to crystalline imperfections, the lowest recombination factor is r=1. This corresponds to low level injection, that is, the photogenerated electron and hole concentration levels are much less than the dark equilibrium majority carrier (electron in n-type or hole in p-type silicon) concentration. The limiting recombination is via imperfection located in the base layer of the cell under the low level condition in a properly designed high efficiency cell.

The other I-V curves in Fig. 1 are from different recombination and conduction mechanisms. The ideal zero recombination case, r=0, is also known as the threshold diode. The r=2/3 case comes from zero imperfection so that the residual recombination is due to the direct recombination of an electron with a hole during which another electron or hole carries away the recombination energy. This is known as the interband Auger recombination. The factor 2/3 arises from the high injection level condition in an interband Auger recombination-limited cell since electron and hole densities are increasing with the terminal voltage V as exp(qV/2kT) while the recombination rate or current is increasing with the product of concentration of two electrons and one hole or one electron and two holes, N^2P or NP^2. Additional discussions and references are given by this author in a recent review article [2]. The r=2 case comes from high-level recombination at the imperfection centers. The SCL curve has the current limited by the space charge of the photogenerated electrons and holes, known as the space-charge-limited case. It is the worse efficiency case and was a limitation of some earlier amorphous silicon cells [3] whose base layer has a rather high resistivity.

Thus, the highest efficiency for the current technology in which electron-hole recombination at the traps due to imperfections dominates is a cell whose r should be made to approach one and whose recombination current density, J_r or J_1, be reduced to as small a value as possible.

In Table I, the theoretical results that relate J_1 to the AM1 efficiency are given. They show that in order to reach a 20% AM1 efficiency given in the column labeled EFF, the recombination current density, J_1, must be less than 0.2 pico-ampere per square centimeter. They also show that for each 2% increase of the efficiency, the recombination current density must decrease by one order of magnitude. It lowers to 0.2 femto-ampere per square centimeter in order for the efficiency to reach 26%. At this low recombination loss level, the recombination events are dominated by the interband Auger mechanism instead of the trap mechanism and the former limits the intrinsic or ultimate efficiency to about 25% for silicon solar cell at AM1 illumination on the earth surface [2].

The figures in the table are obtained by a simple calculation to maximize the output power to the load, P=IV, using Eq.(1) with r=1. The short circuit current, J_{SC}, is taken to be a constant 36.0 mA/cm^2 while the cell temperature is assumed to be at 297.15K or 24C. V_{OC} is the open circuit voltage. FF is the fill factor, sometimes called the curve factor (CF) and it is defined by $FF=P_{MAX}/(J_{SC}V_{OC})$ where P_{MAX} is the maximum available power.

III. RECOMBINATION LOCATIONS AND MECHANISMS

In order to reduce and eliminate recombination losses, a review of the recombination locations and dominant recombination mechanisms is given in this section. The single-crystalline cell will be discussed first followed by an extension to poly-crystalline cells.

A. SINGLE-CRYSTALLINE CELL

A conventional single-crystalline cell structure is used whose cross-sectional view is given in Fig. 2. Thirteen recombination locations are identified and numerically labeled. These are now described by deviding the cell into four electrically active layers in the four-layer model.

EMITTER QUASI-NEUTRAL LAYER

1. Contact Metal to Silicon Emitter Interface

   Thermal recombination dominates at the interface traps, especially when the interfacial contact layer is imbedded with oxide islands which can give rise to silicon and oxygen dangling bonds that are efficient electron-hole recombination sites. These are similar to the interface traps which also degrade the performance of metal-oxide-silicon field-effect transistors. This recombination is also known as the Shockley-Read-Hall (SRH) thermal recombination mechanisms in which the recombination energy is dissipated by lattice vibration or phonon emission.

2. Anti-Reflection Coated Oxide to Silicon Emitter Interface

   SRH thermal as well as the interband- and bound-Auger recombination mechanisms can be important, the former at the oxide/silicon interface traps due to dangling silicon and oxygen bonds and the latter due to the high concentration of majority carrier or dopant impurity at the silicon surface under the oxide/silicon interface.

3. Bulk Emitter Layer

   SRH thermal and the interband- and bound-Auger recombination mechanisms can be important due to the high dopant impurity density which can result in high density of traps in the emitter layer.

4. Emitter Perimeter

   Saw damage and exposed chemically-etched surface at the emitter perimeter will have both high density of dangling silicon bonds and non-dopant impurities which may be electron-hole recombination traps.

EMITTER SPACE CHARGE LAYER

5. Emitter Bulk Space Charge Layer

Dominant recombination in this layer is mainly through the thermal SRH mechanism at traps due to residual non-dopant impurities. A $r=2$ value can be expected for the most dominant traps with bound state energy level at the midgap position of the silicon energy gap. Generally, $1 < r < 2$ has been observed.

6. Emitter Perimeter Space Charge Layer

The dominant recombination is also the thermal SRH mechanism at the traps due to dangling silicon bonds at the exposed surface and silicon and oxygen dangling bonds at partially oxide-covered silicon surface.

BASE QUASI-NEUTRAL LAYER

7. Bulk Base Layer

The 20% efficiency is limited by the extrinsic recombination mechanism due to thermal SRH recombination at residual non-dopant impurity traps and at physical defects or dangling silicon bonds. The ultimate efficiency of 25 to 26% is limited by the intrinsic recombination mechanisms of interband Auger recombination and interband radiative recombination of electrons with holes directly.

8. Back Contact Metal to Silicon Interface

This is similar to the front contact metal to silicon interface described for location 1 previously. However, its recombination rate could be higher due to the lower dopant impurity concentration than that of the diffused front surface, the latter may have a potential barrier repulsive to minority carriers. The thermal SRH mechanism dominates. Two device designs have been employed to reduce this loss. One is the use of a very thick silicon wafer. The other is the use of a built-in electric field from the dopant impurity concentration gradient to repulse the photogenerated minority carriers. This is known as the back surface field cell and discussed in the following subsection with location numnbers 10 to 13.

9. Base Layer Perimeter

Thermal SRH recombination dominates at the traps due to dangling silicon bonds at the exposed and saw damaged surface and silicon and oxygen dangling bonds at the partially oxide-covered surface from etching residuals.

BACK-SURFACE-FIELD LAYER

The cross-sectional view of the Back-Surface-Field (BSF) solar cell structure is shown in Fig. 3. The BSF layer can be fabricated either by alloying aluminun into a p-type silicon bulk since aluminum is a dopant acceptor impurity with solubility above 10^{18} Al/cm^3, or it can be fabricated by solid state diffusion of either boron into a p-type substrate or phosphorus, arsenic or antimony into a n-type substrate. The aluminum alloying is an earlier technique which is not as effective due to deep and less controlled penetration of the alloy layer into the silicon base [4] while the diffused BSF layer in 18% silicon cells has been demonstrated more recently but is less reproducible due to the imperfections introduced during high temperature diffusion.

10. Bulk N+ (or P+) Layer

This is a highly doped layer where the recombination losses are mainly due to the thermal SRH mechanism at traps arisen from the heavy doping.

11. Back Contact Metal to Silicon Interface

Recombination at this interface is identical to that at the similar front interface. However, its effect on efficiency is less since it is away from the region where electrons and holes are generated by light.

12. Back Oxide to Silicon Interface

Recombination at interface traps on the back interface here is similar to that at the front interface discussed for location 2 above. The effect on efficiency is again smaller than that from the front interface. However, recombination losses at both locations 11 and 12 cannot be neglected in high efficiency cell designs.

13. Back Surface Field Perimeter

Recombination in this layer is dominated mainly by the thermal SRH mechanism due to the presence of surface and interface traps similar to those present at the other part of the perimeter surface, such as locations 4, 6 and 9. However, a high interfacial recombination loss can seriously offset the effect of shielding the back contact/ and oxide/ silicon interface recombination sites from the photogenerated minority carriers [4].

B. POLY-CRYSTALLINE CELLS

All of the above recombination locations and mechanisms are important in poly-crystalline cells. Most are emphasized since there are more non-dopant impurity traps and more physical defects in the polycrystalline silicon material. In addition to these, an important and frequently dominating loss of photogenerated electrons and holes is recombination at the grain boundaries separating the single-crystalline grains in the poly-crystalline materials. We envision three grain boundary locations which have somewhat different recombination mechanisms and rates. These are discussed using Fig. 4.

14. Grain Boundary in the Bulk Film

Grain boundary has high density of dangling silicon bonds which are recombination sites for electrons and holes. Grain boundaries penetrate through the entire poly-crystalline silicon film passing through the four layers: the N+ emitter layer, the N+/P emitter junction space charge layer, the P quasi-neutral base and the P/P+ BSF layer. In each layer, the recombination rate at the grain boundary traps is different although all with the same thermal SRH recombination mechanism.

15. Grain Boundary Intersect at the Oxide/Silicon-Emitter Interface

Again the thermal SRH mechanism and the interband- and bound-Auger mechanism may dominate the electron-hole recombination. However, the high density of dangling bond traps at the grain boundary would further increase the recombination loss at this intersection.

16. Grain Boundary Intersect at Contact-Metal/Silicon-Emitter Interface

The high density of traps in the grain boundary would also increase the recombination loss at this contact.

IV. MATERIAL IMPERFECTIONS

If quantum mechanical electron bound states are present at an imperfection in a crystal, it will trap or bound an electron and effecting the recombination of a hole with the trapped electron. A similar electron-hole recombination can occur at an imperfection which has a hole bound state or can trap a hole. Such an electonically active imperfection is commonly known as an electronic (either electron or hole) trap. Imperfections can also act as atomic traps which can trap and release other atoms or ions, for example the hydrogen trapping property of the group-III acceptors (B, Al, Ga and In) recently discovered by us [6]. An imperfection in a crystal can be an electronic trap, an atomic trap, either an electronic trap or an atomic trap differing in atomic configuration, both an electronic trap and an atomic trap, and neither an electronic nor an atomic trap. It is evident that a combination of these properties to eliminate the electronic trapping property or the electronic bound state would be the goal for improving efficiency. The oxygen and silicon dangling bond type of imperfection at the oxide/silicon interface is an example in which its electronic trap or electron-hole recombination properties can be eliminated by atomic or hydrogen trapping which is known as hydrogenation of the dangling bonds. In addition, imperfections may also aggregate to form extended conduction paths or insulating regions which may seriously reduce the cell efficiency by distorting the ideal current-voltage characteristics of the solar cell junction.

Material imperfections can be divided into two groups, the chemical impurities and the physical defects. These are briefly discussed below.

A. CHEMICAL IMPUIRITIES

1. Recombination Sites

Metals (Au, Ti, V, Mo, W, Zn, Ag and others) and non-metals (S, Se, Te and others) are known electronic traps in silicon. Au is a dominant residual trap in unprocessed single crystal silicon and after high temperature integrated circuit processing. Ti, Mo and W were shown to be among the dominant residual impurities in solar cell grade single crystal and these metals cannot be easily and completely gettered out of the cell layers during cell fabrication.

2. Low Resistance Paths

Copper segregates onto dislocations to form resistance paths which may parallel the p/n junction of the cell, causing shorts or low resistive shunts that reduce the cell efficiency.

3. Carrier Fluctuation

Random clusters of dopant impurities (B, Ga, Al, P, As and Sb) may occur at high concentrations which could cause large spatial fluctuation of the electron and hole concentrations. Such fluctuations could significantly degrade the ideal current-voltage characteristics of a high-efficiency cell.

4. Insulating Clusters

Oxygen and nitrogen in silicon may form silicon-oxide and silicon-nitride clusters of random sizes. They are insulating or having a large energy gap and hence high potential barrier that prevent the transport of electrons and holes. These insulating layers will also degrade the current-voltage characteristics and reduce efficiency. There were indications that they may also serve as sinks for the recombination impurities to reduce the trap density in the active region of a integrated circuit transistor. This property is less effective since the thickness of the electronically active layer in solar cell is much larger (about 100 micro-meters) than that in integrated circuits (a few micro-meters or less).

5. Electronic Trap Passivation

It has been known that atomic hydrogen is very effective in passivation of electronic traps at non-dopant impurities and grain-boundary. The former is a result of hydrogen-impurity bond formation known as hydrogenation of the impurity which renders the impurity electronically inactive or causes its electronic bound state to disappear. Grain boundary passivation by hydrogen has been known for many years and is presumbly due to the hydrogen bond formation with the dangling silicon bonds in the grain boundary.

B. PHYSICAL DEFECTS

Physical defects are missing host atoms and extra host atoms in interstitial sites. Most of the missing host defects are known electronic traps which can be readily deactivated by hydrogenation electrically. Some of these are the vacancy, divacancy and vacancy clusters, vacancy-impurity clusters, grain boundaries and perimeter damages.

V. PROCESS OPTIMIZATION

There are various ways to reduce the imperfection density and the recombination losses via selection of fabrication processes. A few possibilities are reviewed.

A. CLEAN PROCESS

A major part of the recombination impurity may be introduced during wafer handling prior to high temperature processing. Clean handling is critical to reduce the residual recombination impurity to less than about 10^{10} cm^{-3} which would give a lifetime of about 300 microseconds and a recombination current density of about $2x10^{-13}$ A/cm^2 needed to reach 20% AM1 efficiency. The density was based on a electron trapping diameter of 10A and base doping density of 10^{16} cm^{-3}.

B. LOW TEMPERATURE

Recombination losses at physical defects and defect-impurity complexes are important limiting factor in high efficiency cells due to the very low density requirement we just indicated on the recombination impurities. Silicon dangling bonds and other physical defects are less likely to form at lower processing temperatures. The current silicon solar cell processing temperature of 800 to 900C may already be in the optimum range.

C. PASSIVATION

Passivation of the impurity and defect recombination centers by atomic hydrogen is a distinct possibility to further reduce the residual electrically active recombination centers. Hydrogenation of the residual dangling bonds at the oxide/silicon interface and some metallic recombination impurities and silicon vacancy clusters in the silicon bulk have been demonstrated in silicon single crystals but yet to be in silicon device or solar cells. Hydrogen passivation of the silicon dangling bonds at grain boundary and in amorphous silicon has been well known for many years. In view of the very low density requirement of the high efficiency cells, the dangling bond density in the starting silicon and in the finished cell before passivation must be very low and then a nearly complete passivation by hydrogen of the residual bonds may be attained which is necessary for the very high efficiency cells. Passivation by hydrogen may be a viable process for solar cells whose active layers are thick (tens to hundreds of micrometers) since the diffusion and migration rate of atomic hydrogen is very high at temperatures slightly above room temperature. This high mobility, although an advantage for deactivating the dangling bonds of the recombination traps, may also be a limiting factor on the cell reliability such as the goal of 20-year or the more recent 30-year operating life.

D. GETTERING

Gettering of the recombination impurities to reduce recombination or J_I has been successfully demonstrated in the laboratory and gettering has sometimes been employed in the production of silicon transistors and integrated circuits. The sink for the recombination impurities during a high temperature gettering procedure is usually a surface oxide glass, a damaged surface layer, a high concentration diffused surface layer or even a polysilicon surface layer. The last has been the most effective. Gettering relies on the high mobility or diffusivity of the recombination impurities in silicon at the gettering temperatures, usually nearly the diffusion or the oxidation temperature. It also relies on the assumption that the sink has a much higher solubility than silicon at the gettering temperature and the gettering volume or layer thickness is sufficiently large so that it is not saturated by the gettered impurity. Gettering can be made effective in many silicon transistor and integrated circuit fabrication processes since the active silicon layers are usually very thin so that a relatively short gettering time and low gettering temperature are adequate. Gettering may not be as effective in solar cell, especially for improving the efficiency to beyond 20% since the active layer in solar cell is very thick and may be ten or more times larger than diffusion length of the to-be-gettered recombination impurities for a one-hour high temperature gettering. Considerable research efforts have been spent to show that the important recombination impurities, Ti, Mo, and W, in silicon solar cell only diffuses toward the surface sinks by a small amount, up to about five microns, in the cell fabrication temperature range of 800 to 1000C. This is highly inadequate for gettering these impurities by a surface sink in a 100-micrometer active layer of a high efficiency silicon solar cell.

VI. DEVICE DESIGNS

Innovative device designs have been proposed and demonstrated by a number of silicon solar cell researchers to reduce recombination losses in order to improve the efficiency to 20% and beyond. Some of these are described below. More detailed descriptions of these cell structures and the experimental results can be found in the articles of the special issue of Solar Cell [1] and in references cited in [2].

A. REDUCTION OF INTERFACE RECOMBINATION LOSSES

Polysilicon emitter and polysilicon base contacts have been proposed and demonstrated to reduce the interfacial recombination losses at these contacts which were discussed as recombination locations 1 and 11.

The polysilicon emitter concept may be thought of as an extension of the thin-oxide-barrier between the emitter metal contact and the silicon emitter used by Green to attain 19% AM1 efficiency. The reliability and reproducibility of the thin tunneling oxide barrier are yet to be demonstrated for the very large area cells while the polysilicon emitter is expected to be much superior due to the higher temperature of formation and the thicker film of the polysilicon emitter.

Oxidized front and back silicon surfaces have also been employed to reduce the interfacial recombination losses at the exposed front surface (location 2) and a major part of the back surface (location 12) just described. The improvement is especially dramatic for the front surface which was demonstrated by removing the front oxide, resulting in a large rise of the dark recombination current, J_1, and a noticeable lowering of the efficiency. The oxide passivation concept has been extended and implemented to the back surface with observable improvement but the effect is less due to shielding by the BSF layer.

The high/low junction shield concept was first employed for the back surface by the NASA-Lewis group {see references in [4]}. This was extended to the front emitter layer by us [7] and included some innovative high efficiency cell designs by others supported by the JPL/DOE program. It is probable that the nearly 20% cell of Green had such a high/low emitter junction which is inevitably present in a doubly diffused emitter that consists of a first low-concentration and deeper (0.2 micron) diffusion and a second high-concentration shallower diffusion (0.1 micron or less).

B. REDUCTION OF BULK RECOMBINATION LOSSES

Thin [8] and graded [9] base, especially using epitaxial layers on highly doped substrate, should be effective in reducing the base recombination losses which are thought to be the main remaining loss after emitter recombination losses are eliminated in high efficiency (20%) to very high efficiency (>20%) cells. Design demonstrations were given by us recently [8] which showed that 20% cells can be attained by reducing the active base to about 50 microns even for a not-too-high minority carrier lifetime, 20 microseconds, or a base recombination impurity density of 10^{12} cm^{-3}. This recombination impurity concentration requirement is 100 times less severe than 10^{10} cm^{-3} quoted in the early part of this paper for a thick base cell. It dramatically illustrates one attractive cell design concept for high efficiency, the thin graded base, which has yet to be fully explored experimentally.

C. REDUCTION OF PERIMETER RECOMBINATION LOSSES

Perimeter recombination losses (locations 4, 6, 9 and 13) can drastically reduce the cell efficiency [5]. Dicing the cell by chemical etch instead saw cut could reduce the recombination trap density on the perimeter surface. Etched groove which is subsequently oxidized can further reduce perimeter recombination losses. Diffusion isolation of the cell edge may be most effective at the expense of a small reduction of the effective cell area. The main point is that to reach efficiencies of more than 20%, the perimeter recombination loss, previously unimportant in 17% or less cells, may become a limiting factor.

D. GRAIN BOUNDARY PASSIVATION IN POLYSILICON CELLS

In poly-crystalline silicon solar cells, high efficiency cell structures may be fabricated using the high diffusivity of phosphorus and hydrogen along the grain boundary plane. Fig. 5 shows a P+/N/N+ cell structure where use is made of the fast phosphorus diffusion along the grain boundary from the back surface during the N+ BSF diffusion. Fig. 6 shows the opposite of Fig. 5 in which the phosphorus diffusion down the grain boundary is from the front surface during the N+ emitter diffusion in an N+/P/P+ cell structure. For ease of illustration, the grain boundaries are shown perpendicular to the film plane and equally spaced. Grain size and boundary are randomly distributed in realistic situations. For both of these two structures, the grain boundary diffusion of phosphorus has helped to form a high/low junction shield labeled 1 on these figures (N+/N in the P+/N/N+ cell in Fig. 5 and P+/P in the N+/P/P+ cell in Fig. 6). These high/low junction potential barriers shield the photo-generated minority carriers from reaching the grain boundary which contains a high density of recombination centers. The region labeled 2 in Fig. 6 is a N/P junction which shields the grain boundary from the minority carriers. The intersection at the oxide surface, labeled 3, could allowed enhanced hydrogen diffusion down to the grain boundary in order to passivate the grain boundary traps by hydrogenation, which would be futher enhanced if the oxide on the end of the grain boundary can be removed by a preferential etchant.

VII. SUMMARY

The requirements for high-efficiency silicon solar cells are: (1) low resistivity bulk to maintain low injection level in the base in order to have the r=1 ideal Shockley dark diode law, (2) low recombination center density in the base, after emitter and interface recombination losses are reduced or eliminated, and low recombination center density in grain boundaries of polysilicon cells such as by phosphorus and hydrogen diffusion passivation, (3) low temperature and clean fabrication processing to reduce impurity and physical defect recombination sites, and (4) innovative cell designs to shield the high trap density sites from photo-generated minority carriers by potential barriers of high/low junctions and polysilicon/silicon contacts barriers.

ACKNOWLEDGMENT

We would like to thank Dr. Ralph Lutwack for inviting us to this workshop as well as for earlier supports which started our solar cell effort. This work was made possible by the supports from the Jet Propulsion Laboratory and the U.S. Department of Energy during the past ten years. We would also like to thank Professor Fredrik A. Lindholm of the University of Florida for continued interaction and collaboration in the last ten years on solar cell studies.

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TABLE I High efficiency requirements from theory of an ideal Shockley diode dark current-voltage characteristics.

HIGH EFFICIENCY REQUIREMENTS

SOURCE	J_1 (A)	J_{SC} (mA)	V_{OC} (mV)	FF	EFF (%)
Theory	2.0×10^{-16}	36.0	840	0.8664	26.0
Theory	2.0×10^{-15}	36.0	780	0.8588	24.0
Theory	2.0×10^{-14}	36.0	720	0.8501	22.0
Theory	2.0×10^{-13}	36.0	660	0.8402	20.0

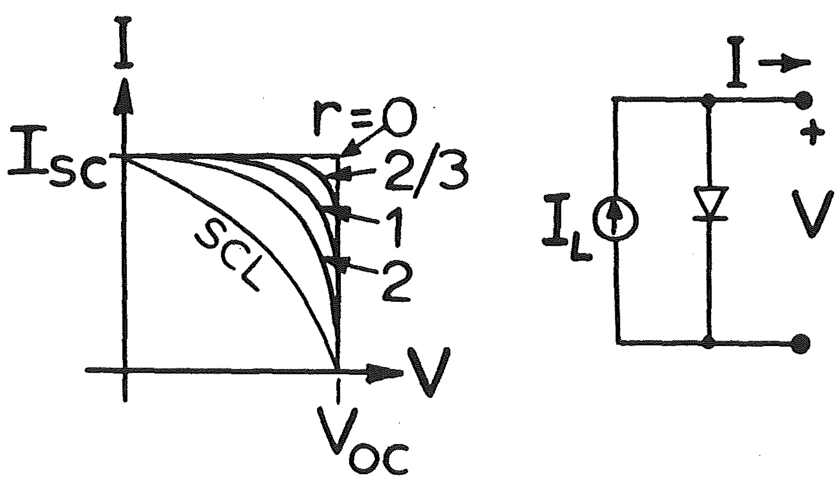

Figure 1 Current-Voltage characteristics of five illuminated diodes with different recombination mechanisms and their equivalent circuit diagram.

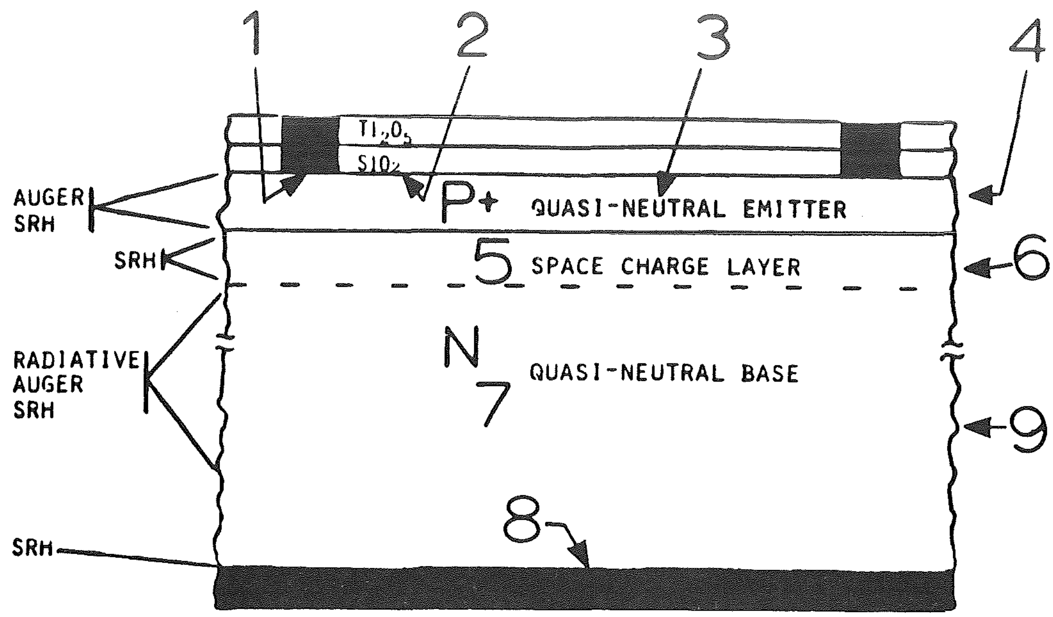

Figure 2 Nine important recombination locations and dominant mechanisms in a typical single-crystalline solar cell.

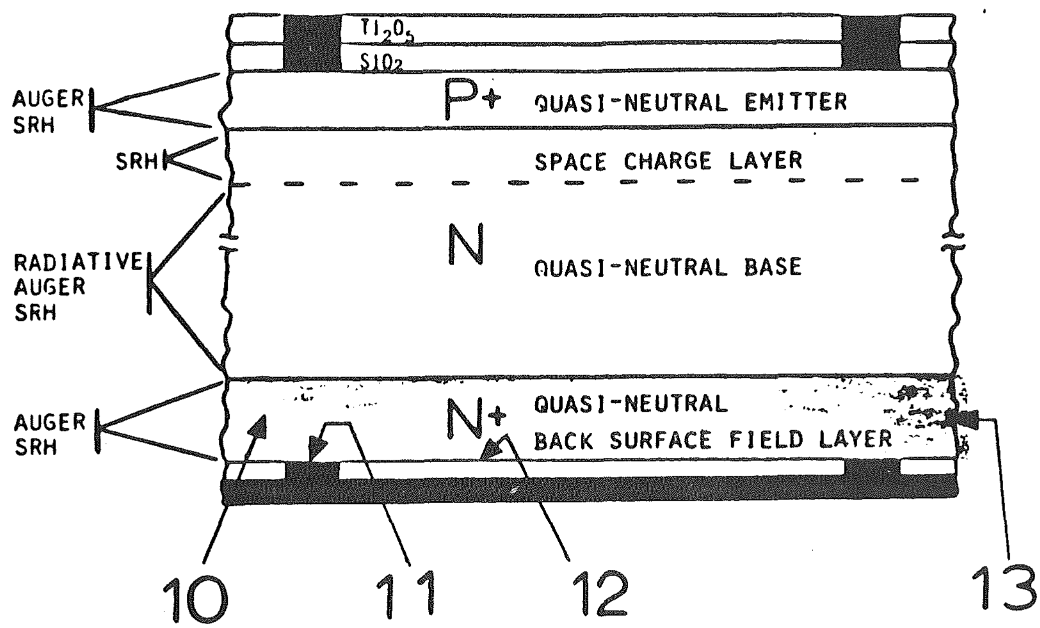

Figure 3 Four recombination locations in the back surface field layer of a single-crystalline solar cell.

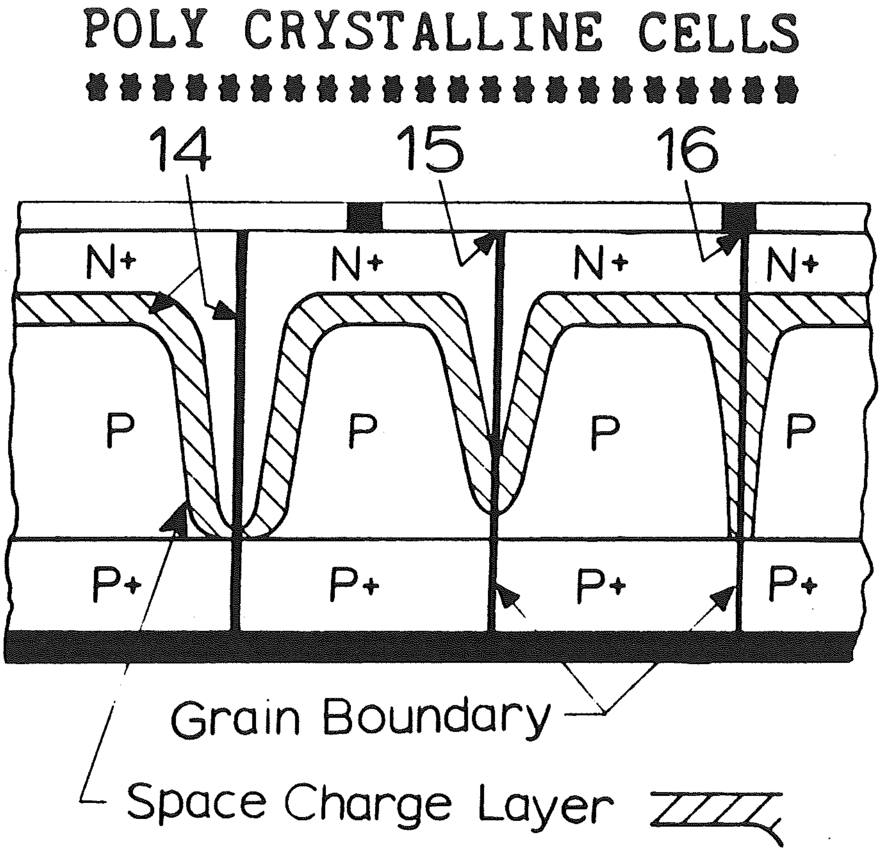

Figure 4 Recombination locations in the grain boundaries of a poly-crystalline solar cell.

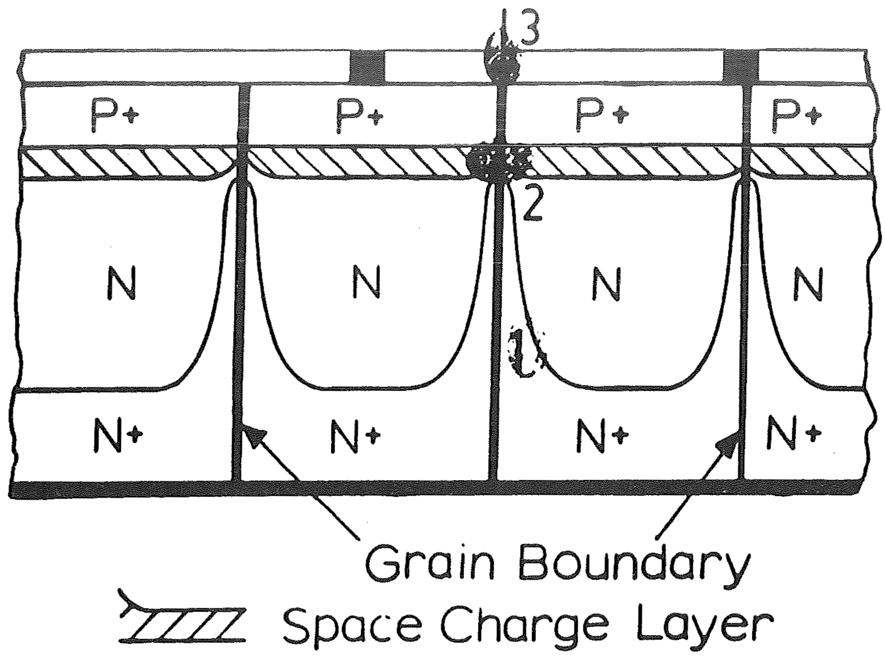

Figure 5 Passivation or shielding of the grain boundaries by phosphorus and hydrogen diffusion in a n-type polysilicon solar cell.

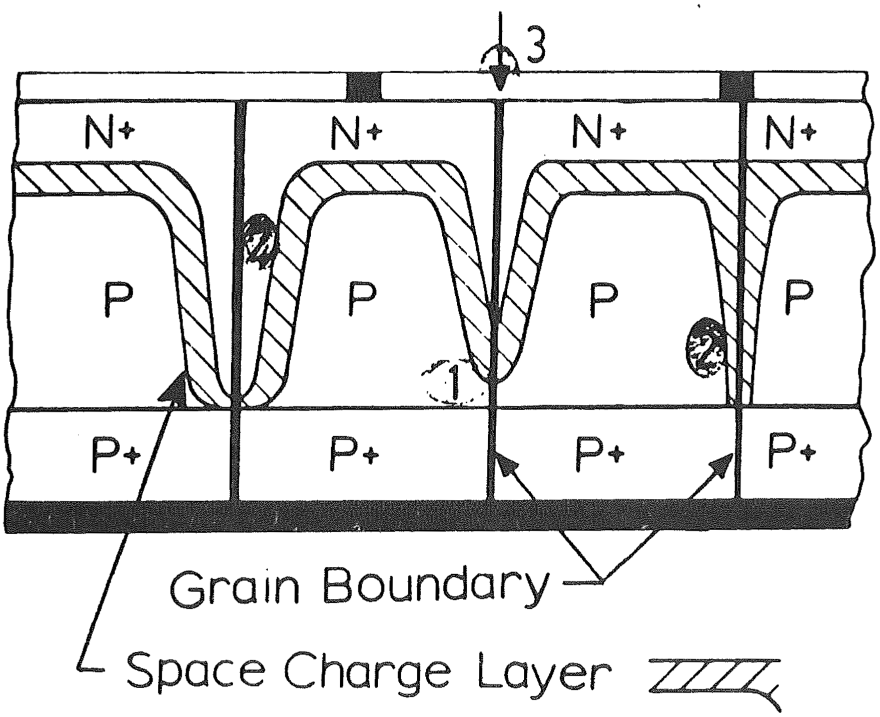

Figure 6 Passivation or shielding of the grain boundaries by phosphorus and hydrogen diffusion in a p-type poly-silicon solar cell.

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DISCUSSION

PRINCE: You gave us a very thorough discussion of the various recombination processes, 13 in single-crystal and 16 in polycrystal. Have you ordered these in some way to tell us which are the most important ones that must be eliminated, or are you going to have that information in your paper, or can you reference some papers that have this information?

SAH: I think for single-crystal material, the impurity recombination in the base would be the remaining one. After most of the impurity recombination in the base is removed, then a limit will be reached that will not be possible to reduce much further due to the radiative intra-band Auger recombination. At that point, cells with efficiencies of 23 to 24% or more will be obtained. In the polycrystalline cells, the grain boundary is the most serious problem. One needs to eliminate the recombinations in the grain boundary by, perhaps, specially designed devices, structure design, or by hydrogenation. I think that if the dangling bonds in the grain boundary were tied up with hydrogen, they will not be electrically active as recombination sites.