20936/88

002114

APPLICATION ACCEPTED AND AMENDMENTS

18-7-90

COMMONWEALTH OF AUSTRALIA

Patents Act 1952

APPLICATION FOR A STANDARD PATENT

We, WESTINGHOUSE ELECTRIC CORPORATION, of 1310 Beulah Road, Churchill, Pittsburgh. PA. 15235, United States of America, hereby apply for the grant of a standard patent for an invention entitled:

"METHOD FOR TEXTURING A SILICON SURFACE OF ANY CRYSTALLOGRAPHIC ORIENTATION USING AN ISOTROPIC ETCH AND PHOTOLITHOGRAPHY AND SILICON CRYSTALS MADE THEREOF"

which is described in the accompanying complete specification.

DETAILS OF BASIC APPLICATION:

Country	Date	Number
United States of America	8th September, 1987	094,184

ADDRESS FOR SERVICE ALTERED

Our address for service is:

PETER MAXWELL & ASSOC.
NTH. PARRAMATTA NSW

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AUSTRALIAN PATENT OFFICE Reg 89 (2)

Dated this 9th day of August, 1988

WESTINGHOUSE ELECTRIC CORPORATION
by their Patent Attorneys
HALFORD & MAXWELL:

To: Commissioner of Patents

File: 88 1 170

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500167 11/08/88

W.E. Case 53,907/Australia

FORM 7 REGULATION 11 (2)

COMMONWEALTH OF AUSTRALIA

PATENTS ACT 1952-1954

DECLARATION IN SUPPORT OF A CONVENTION APPLICATION UNDER PART XVI FOR A PATENT

In support of the Convention Application made under Part XVI of the Patents Act 1952-1954 by WESTINGHOUSE ELECTRIC CORPORATION for a patent for an invention entitled "METHOD FOR TEXTURING A SILICON SURFACE OF ANY CRYSTALLOGRAPHIC ORIENTATION USING AN ISOTROPIC ETCH AND PHOTOLITHOGRAPHY AND SILICON CRYSTALS MADE THEREBY"

I, A. Mich, Jr.
of 185 Penhurst Drive, Pittsburgh, Pennsylvania 15235
United States of America, do solemnly and sincerely declare as follows:

1. I am authorized by WESTINGHOUSE ELECTRIC CORPORATION, the applicant for the to make this declaration on its behalf.

2. The basic application as defined by Section 141 of the Act was made in the United States of America on September 8, 1987, by the inventors nominated in clause (3) below.

3. DANIEL LEO MEIER, JAMES BERNARD MCNALLY, LEONARD EARL HOHN, JEONG-MO HWANG of, respectively, 264 Barclay Avenue, Wilkinsburg, Pennsylvania 15221, USA, 680 Westchester Drive, N. Huntingdon, Pennsylvania 15642, USA, 840 Butterfield Drive, N. Huntingdon, Pennsylvania 15642, USA, 4504 Dell Street, Murrysville, Pennsylvania 15668, Korean are the actual inventors of the invention and the facts upon which WESTINGHOUSE ELECTRIC CORPORATION is entitled to make the application are as follows:

The said WESTINGHOUSE ELECTRIC CORPORATION is the assignee of the said DANIEL LEO MEIER, JAMES BERNARD MCNALLY, LEONARD EARL HOHN, JEONG-MO HWANG.

4. The basic application referred to in paragraph 2 of this declaration was the first application made in a convention country in respect of the invention the subject of the application.

Declared at Pittsburgh, Pennsylvania

This 5th day of August, , 19 88.

A. Mich, Jr.
Chief Counsel

To,
THE COMMISSIONER OF PATENTS,
COMMONWEALTH OF AUSTRALIA.

(12) PATENT ABRIDGMENT (11) Document No. AU-B-20936/88
(19) AUSTRALIAN PATENT OFFICE (10) Acceptance No. 602114

(54) Title
METHOD FOR TEXTURING A SILICON SURFACE OF ANY CRYSTALLOGRAPHIC ORIENTATION USING AN ISOTROPIC ETCH AND PHOTOLITHOGRAPHY AND SILICON CRYSTALS MADE THEREBY

International Patent Classification(s)
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(56) Prior Art Documents
AU 252815 41342/64 C30B 15/36, 29/06

(57) Claim

1. A method for etching a silicon dendritic web crystal for use in a photovoltaic cell characterized by the steps of applying a predetermined pattern of material resistant to etching to a surface of the silicon crystal, the pattern substantially covering all of the surface; etching the surface with an isotropic etching material until the etching material substantially fully undercuts the pattern of material resistant to etching, thus forming a plurality of peaks with sloping sides on the silicon crystal, the isotropic etching material and pattern cooperating so that the sloping sides having a slope which substantially traps within the silicon crystal all of the light striking the silicon crystal.

.../2

2. The method of claim 1 characterized in that the step of applying a predetermined pattern of material resistant to etching comprises preparing the surface with an adhesion promoting agent; applying a coat of the material resistant to etching over the entire surface wherein said material resistant to etching is a photoresist material; prebaking the coated crystal; placing a mask over the coated surface, the mask comprising a plurality of spaced apart parallel strips of opaque material; exposing the masked surface to light; developing the photoresist formulated material with a developer and washing away undeveloped photoresist formulated material leaving generally parallel strips of material resistant to etching on the surface: and post baking the parallel strips of material resistant to etching to affix them to the surface.

602114 P/00/011
Form 10

PATENTS ACT 1952

COMPLETE SPECIFICATION

(ORIGINAL)

FOR OFFICE USE

Short Title:

Int. Cl:

Application Number:
Lodged:

Complete Specification—Lodged:
Accepted:
Lapsed:
Published:

Priority: 8th September, 1987

This document contains the amendments made under Section 49 and is correct for printing.

Related Art:

TO BE COMPLETED BY APPLICANT

Name of Applicant: WESTINGHOUSE ELECTRIC CORPORATION

Address of Applicant: 1310 Beulah Road,
Churchill. Pittsburgh. PA 15235
UNITED STATES OF AMERICA.

Actual Inventor: DANIEL LEO MEIER, JAMES BERNARD MCNALLY, LEONARD EARL HOHN, JEONG-MO HWANG

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Complete Specification for the invention entitled: "METHOD FOR TEXTURING A SILICON SURFACE OF ANY CRYSTALLOGRAPHIC ORIENTATION USING AN ISOTROPIC ETCH AND PHOTOLITHOGRAPHY AND SILICON CRYSTALS MADE THEREBY".

The following statement is a full description of this invention, including the best method of performing it known to ~~me~~* us:-

* Note: The description is to be typed in double spacing, pica type face, in an area not exceeding 250 mm in depth and 160 mm in width, on tough white paper of good quality and it is to be inserted inside this form.

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The present invention relates to a process for making silicon crystals for photovoltaic cells.

Solar or photovoltaic cells are semiconductor devices which function by absorbing light and converting a substantial fraction of the energy of the absorbed light into electrical energy. Such cells are typically made of silicon crystals. However, not all the light that is incident to the surface of a solar cell is absorbed by the semiconductor material. A fraction of the incident light is reflected from the top surface of the cell. Another fraction is transmitted through the entire thickness of the semiconductor material. This transmitted fraction becomes progressively larger as the thickness of the cell becomes smaller.

In a practical cell design, the amount of reflected light has been reduced by application of an anti-reflective coating to the illuminated surface of the cell. The transmitted light has also been captured by depositing a highly reflective metal, such as aluminum, on the back surface of the cell. The light that is reflected from this reflective metal on the back surface makes a second pass through the cell and more light will be absorbed by the cell. However, the light that reaches the front surface of the cell at the end of the second pass is transmitted through the front surface and is lost.

Reducing the reflection losses from the front surface of a solar cell is always important in any cell design. Reducing the transmission losses becomes increasingly important as the cell thickness is reduced in general below about 300 μm. In an ideal situation, the reflection and transmission losses should be reduced to zero, with all incident light effectively "trapped" and absorbed in the semiconductor material and converted to electrical charge carriers. The object of this invention is to trap the maximum amount of incident light and convert it to electrical charge carriers.

Figure 1 shows an ideal model depicting a silicon crystalline lattice appropriate for semiconductor devices. As shown, the crystal is cubical, with the corners of the cube being defined by a silicon atom. The face shaded in solid cross hatching represents the (100) face and the face shaded in broken cross hatching represents the (111) face.

In the past, it has been shown that it is possible to texture the surface of semiconductor materials such as silicon, provided this surface lies in a (100) crystallographic plane. An anisotropic etch, for which the etch rate in the <111> direction is much slower than the etch rate in the <100> direction, is used to create pyramidal structures on the (100) surface. The faces of the pyramids are the four (111) planes that are exposed by the anisotropic etch. This approach has produced cells with reduced reflectivity and increased carrier collection efficiency. The reflectivity is reduced because light incident on one side of a pyramid can be reflected onto another pyramid instead of being lost. The collection efficiency is increased because light enters the silicon at an oblique angle, and the absorption of the longer wavelength light occurs closer to the junction instead of deep in the base where the carriers have a greater chance of being lost.

A variety of anisotropic etching solutions has been used, including NaOH, KOH, ethylene diamine, and hydrazine, but NaOH and KOH are the most popular. All produce the desired results with silicon having a (100) surface. However, anisotropic etches fail to produce the desired texturing on crystals which do not have a (100) surface. In particular, they are not effective for dendritic web silicon, which has a substantially (111) surface.

In general a method or process for etching a silicon dendritic web crystal for use in a photovoltaic cell, when performed in accordance with this invention, comprises the steps of applying a predetermined pattern of material resistant to etching to a ~~(111)~~ surface of the silicon crystal, the pattern substantially covering all of the ~~(111)~~ surface; etching the ~~(111)~~ surface with an isotropic etching material until the etching material substantially fully undercuts the pattern of material resistant to etching, thus forming peaks with sloping sides on the silicon crystal, the isotropic etching material and pattern cooperating so that the sloping sides having a slope which substantially traps within the silicon crystal all of the light striking the silicon crystal.

The invention as described in the claims will become more apparent by reading the following detailed description in conjunction with the accompanying drawings in which:

Figure 1 is a schematic drawing showing the (100) and (111) planes in a silicon crystal lattice.

Figures 2a and 2b are schematic drawings showing conceptually the principles of the presently claimed process.

Figure 3 is a schematic drawing showing the path taken by light rays entering crystals produced according to the presently claimed process.

Figures 4a and 4b are schematic representations of a cross-section and elevation view of an etched crystal produced according to the presently-claimed process.

Figures 5a and 5b are schematic representations of a cross-section and elevation view of another etched crystal produced according to the presently-claimed process.

Figures 6-11 are graphs demonstrating the improved results predicted for cells produced from crystals manufactured according to the presently-claimed process.

The present invention provides a method for texturing a silicon surface of any crystallographic orientation, including (111) surface. The problem of texturing a (111) silicon surface is solved by a combination of photolithography and isotropic, as opposed to anisotropic, etching. Figure 2 shows conceptually the way the present invention obtains a sawtooth structure on the face of the crystal. Strips of photoresist having a width of w_1 and a spacing of w_s are defined by standard techniques on the flat silicon surface. An isotropic silicon etch, commonly consisting of a mixture of concentrated hydrofluoric, nitric and acetic acids, is used to etch both downward into the silicon and laterally beneath the photoresist lines. Because the etch is isotropic, it etches laterally as rapidly as it does vertically, thereby undercutting the photoresist and leaving a "sawtooth" pattern shown in Figure 2b, with the period of the pattern and the spacing between adjacent "teeth" being determined by the choice w_1 and w_s. Alternatively, an array of four-sided pyramids can be etched by using a "checkerboard" pattern of photoresist.

Figure 3 shows a model profile of a silicon material for a photovoltaic cell that can be obtained using the present invention. The back surface of the cell has been textured as described above to give a "sawtooth" structure. The path of light incident normally on the cell is also shown. The back of the cell is preferably made nearly perfectly reflecting, for example, by the deposition of a highly reflective metal such as aluminum over the back surface. Ray 2, reflected from the back textured surface of the cell, is incident on the front surface of the cell from within the silicon and undergoes total internal reflection, continuing on as ray 3. This ray is again reflected from the reflective back surface and leaves the silicon as ray 4. With such a "sawtooth" type of back surface, the distance that light travels in the silicon is expected to be six times as great as the physical thickness of the cell.

As can be seen from Figure 3, some of the reflected light will be absorbed close to the collecting junction at the front of the cell. This relaxes the requirement on the minority carrier diffusion length for efficient carrier collection. In addition, the open circuit voltage (V_{oc}) for a thin dendritic web silicon cell (50 μm) will improve significantly compared to a cell of standard thickness (150 μm) because of the reduced volume for recombination in the thin cell. In order to realize the increase in V_{oc}, the back surface of the cell is well-passivated by, for example, a thermally-grown oxide.

The method or process for etching a silicon dendritic web crystal for use in a photovoltaic cell comprises the following steps:

First, any growth oxide should preferably be removed from the web silicon. While in some cases growth oxide may simply be wiped off, often an acid must be used. One such acid that has proven useful is hydrofluoric acid. Growth oxide exhibits a dark blue appearance and interferes with the adhering capabilities of the photoresist. This step may be omitted, for example, if the silicon is grown under conditions in which no growth oxide is present.

Next, an adhesion promoter is preferably applied to the surface of the crystal in order to encourage the photoresist to adhere to the surface of the crystal. In one preferred embodiment, a promoter composed of 20 ml hexamethyldisilazene (HMDS, manufactured by Petrarch Systems, Inc.) and 980 ml of xylene, was applied by dipping the crystal in the promoter for 1 minute. The crystal was then blow dried and baked at 165°C for 60 minutes in nitrogen.

Following the adhesion promoter sequence, a photoresist is applied, preferably in a substantially uniform thickness. In one preferred embodiment, WAYCOAT IC photoresist was applied to the crystal, and centrifugal force used to provide uniform thickness by spinning the crystal at 3000 rpm for 30 seconds. The coated crystal was then prebaked at 90°C for 15 minutes in nitrogen. Applying the photoresist in this way yields a 1.3 μm thickness of photoresist. Other thicknesses are possible by varying the speed and length of time at which the crystal is spun, or by other methods of application well known to those skilled in the art.

Next, a mask having the desired pattern is applied to the photoresist. In cases where a "sawtooth" pattern, as shown in Figures 4a, 4b, 5a and 5b is desired, the mask has parallel, spaced-apart narrow strips. In cases where an array of pyramids is desired, a mask having a "checkerboard" pattern of intermittently spaced square solids and square openings is used. These squares could be of uniform size and spacing or of non-uniform size and random spacing, as needed, to optimize the fraction of light trapped within the silicon. A sawtooth pattern is generally preferable to a pyramid pattern, since the surface between each pyramid tends to be flat, thereby refracting more light at an angle less than the critical angle for total internal reflection than the sawtooth patterns, which have a smaller proportion of "flat" surface area.

Once the desired mask is applied to the photoresist, the photoresist is exposed to light. It is possible to use a so-called positive or negative photoresist with the present invention, although the negative resists have proven to be preferable, as they tend to withstand the acid etching more favorably than the positive resists. When a negative resist is used, that portion of the resist which is shielded by the mask is dissolved by the developer, and that portion of the photoresist exposed to the light polymerized to be resistant to developer. When a positive resist is used, the opposite occurs, as the photoresist that is exposed is dissolved and the shaded portion remains following the developer application. In a preferred embodiment producing crystrals such as those shown in Figures 4a, 4b, 5a and 5b, a mask with parallel strips was used and a negative photoresist, WAYCOAT IC, was exposed using ultraviolet light at 2.55 mW/cm^2 for 30 seconds.

Following exposure of the photoresist, it is necessary to develop the photoresist. In a preferred embodiment producing crystals such as those shown in figures 4a, 4b, 5a and 5b, because a negative photoresist was used, a negative developer, WAYCOAT was also used, for 30 seconds. After developing the photoresist, it is necessary to dissolve away the undesired portion of the photoresist. In this case, this was accomplished by rinsing the photoresist with butyl acetate for 15 seconds. Because a negative developer was used, the unexposed portion of the photoresist was dissolved away.

Following the rinsing step, it is desirable to postbake the developed photoresist in order to harden the photoresist and drive off any solvents remaining on the photoresist. Postbaking may be accomplished by heating the exposed photoresist at 165°C for 15 minutes in nitrogen.

After the postbaking sequence, the crystal surface is etched to produce the desired pattern using an isotropic etch. Because the etching action is exothermic, it is possible for the etching process to proceed too quickly unless the temperature of the etching solution is carefully controlled. It has been determined that preferred results are achieved if the etch process begins slowly. This is achieved by starting the etching process with isotropic etching solution having a temperature of 5°C ± 3°C. This temperature may be achieved by placing the etching solution in an ice bath or any other chilling means known in the art.

Once the etching solution is sufficiently chilled, the etch process may begin. Peaks are produced by etching the surface of the crystal sufficiently long so as to undercut the photoresist as shown in Figure 2. Etch rates may vary depending on temperature conditions, type of etch used, etc. It is desirable to etch sufficiently long to produce peaks, but not so long that the peaks become rounded or flat. As a general rule, it is preferable that the amount of crystal etched in the vertical direction approximate 10% of the total thickness of the crystal. Experience has shown that an etch time of about one minute is sufficient to achieve the desired amount of etching. One way of determining when the etch is complete is to observe the photoresist. When the photoresist has lifted from the surface of the silicon, this indicates that the photoresist has been sufficiently undercut by the etching solution to create the desired peaks.

In one preferred embodiment of the invention, a sawtooth pattern is etched in a silicon crystal using a solution in the ratio 10 parts concentrated hydrofluoric acid, 1 part concentrated nitric acid, and 3 parts concentrated acetic acid, by volume. The etch time was 60 seconds, and the temperature of the etch solution was approximately 5°C at the beginning of the etching step.

In cases where the photoresist does not lift from the surface of the silicon at the end of the etching step, it is necessary to strip the photoresist from the crystal. The photoresist is stripped using a mixture in the ratio of 4 parts concentrated sulfuric acid to 1 part hydrogen peroxide for 60 seconds at 80°C.

The detailed shape of the etched profile can be altered somewhat by the width and the spacing of the photoresist strips. For example, the distance over which the profile is relatively flat can be reduced by spacing the strips more closely together.

Dendritic web silicon material, approximately 100 µm thick, has been etched as described above to produce a textured surface. Figures 4a, and 4b show a cross-sectional view and an elevated view of such a sample which has been prepared with 30 μm wide photoresist strips spaced 30 μm apart. Observe that the profile obtained approximates the sawtooth profile of Figure 2b. The full thickness of the web sample is shown in Figure 4a so that the depth of the etched pattern can be compared to the overall web thickness.

Another web silicon sample has been textured using a mask with 10 μm wide strips spaced 10 μm apart, so that the depth of the etch is less than that shown in Figure 4a and 4b. The results are shown in Figures 5a and 5b. This texturing has also been applied to float zone silicon wafers with either a (111) surface or a (100) surface. Results similar to those given in Figures 4a, 4b, 5a and 5 were obtained, thereby demonstrating that the technique is applicable to silicon with a surface orientation other than (111). Indeed, the process disclosed herein will perform with any material capable of being etched with an isotropic etch.

Under ideal conditions, a peak with an angle of 90° at the apex, and sides sloped at a 45° angle relative to the normal direction to the original flat surface of the crystal are produced as shown in Figure 2b. However, experience has shown that the inclined surface of the peaks tend to be rounded, as shown in Figures 4a, 4b, 5a and 5b. In order to achieve light "trapping" within the crystal, it is necessary for the inclined surfaces of the peaks to be inclined at an angle of at least 15° relative to the horizontal. Inclined surfaces with angles of at least 15°, approximated by drawing an imaginary line from the apex of a peak through the center of an adjacent trough, as shown in Figures 4a and 4b, are possible according to the present invention.

The present process can be used to etch the front surface, (that closest to the light source), the back surface, or both surfaces of the crystal. Experience has shown that etching the front surface is preferable to etching only the back surface of the crystal.

It may be desirable in some cases to coat the back surface of the etched crystal with a reflective coating, such as aluminum. It may also be useful to coat the front surface, that is, the surface facing the light source, with an anti-reflective coating. In this way, even more light can be transmitted through the front surface and not be lost through the back surface, in an effort to approach the ideal situation of "light trapping".

It may not be necessary to cover the textured surface shown in Figure 3 with a highly reflective metal. It appears that in most cases, essentially total internal reflection will occur at the back surface as well as at the front surface without a reflective metal coating. This means that the benefits of texturing could also be realized with a bi-facial cell design, in which the back surface has metal grid and not full area coverage with reflective metal. With cell structures such as these, or with front and back texturing, it may be possible to approach complete light trapping.

The present process can be used on any type of crystal, regardless of the orientation of the face being etched. Thus, the present invention offers a substantial advancement over prior systems, which only produce peaks on crystals having a (100) plane etching surface.

The presently claimed process also can be used in areas other than producing photovoltaic cells. For example, the saw-toothed pattern produced according to the presently-claimed invention can be used to carry very small fiber optics cables between the peaks.

The anticipated improvement in solar cell parameters as a result of incorporating the sawtooth back have been calculated for a range of cell thickness and minority carrier diffusion lengths. The continuity equation, which describes the movement of minority carriers in the base of a solar cell, has been solved using a Green's function technique for the light-trapping geometry shown in Figure 3. This allows a calculation of J_{sc} and V_{oc}. The calculated values J_{sc} as a function of cell thickness are given in Figures 6 to 11 for minority carrier diffusion lengths of 50, 100, 200 and 340 µm, respectively. In these Figures J_{sc} calculated for a sawtooth reflecting back is compared with J_{sc} calculated for a flat reflecting back (double pass) and with J_{sc} calculated for a non-reflecting back (single pass). The relatively small losses associated with reflection from the front surface, shadowing from the grid, and recombination in the emitter are not taken into account in these calculations.

The recombination velocity associated with the back surface (s_{back}) is taken to be zero. The calculated values remain valid provided the recombination velocity is much less than the diffusion velocity, which is typically 3000 cm/sec. Since a recombination velocity of 300 cm/sec or less is obtainable with an oxide-passivated surface, the assumption that s_{back} is effectively zero is realistic. Also shown in these Figures is a line representing the current equivalent of the AM1.5 100 mW/cm^2 spectrum. This gives the total current available with perfect light-trapping and no carrier recombination. The dashed curve gives the calculated J_{sc} values, assuming the (imperfect) light trapping associated with the sawtooth back and no recombination.

Figures 10 and 11 give the calculated values of J_{sc}, V_{oc}, and efficiency η for a sawtooth-back cell as a function of cell thickness. The diffusion length is taken to be 100 µm (typical for web cells) in Figure 10 and 340 µm (best measured value for a web cell) in Figure 11. With reflection and shadowing losses taken to be 7% in J_{sc}, the calculated optimum efficiency is 15.8% for 100 µm diffusion length and 18.0% for 340 µm diffusion length. A comparison of calculated efficiency for thin cells having a sawtooth back with cells of standard thickness having a flat reflecting back is given in Table 1 for a range of diffusion lengths. These calculations indicate that web cells having an efficiency of 18% are achievable.

Table 1 shows a comparison of calculated efficiency for thin cells having a sawtooth reflecting back with cells of standard thickness having a flat reflecting back.

TABLE 1

Diffusion Length (μm)	Cell Thickness (μm)	Cell Back	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
50	150	Flat	30.0	0.519	0.780	12.2
50	50	Sawtooth	33.3	0.529	0.780	13.8
100	150	Flat	33.1	0.542	0.780	14.0
100	50	Sawtooth	35.9	0.562	0.780	15.8
200	150	Flat	35.6	0.571	0.780	15.9
200	50	Sawtooth	36.8	0.597	0.780	17.1
340	150	Flat	36.5	0.597	0.780	17.0
340	50	Sawtooth	37.0	0.624	0.780	18.0

Assumptions:

1. AM 1.5 spectrum with 100 mW/cmY^2 intensity
2. Surface recombination velocity at back surface is zero
3. Reflection and shadowing result in 7% loss in J_{sc}
4. Losses associated with emitter are negligible
5. Base resistivity is 4 ohm-cm (p-type) for V_{oc} calculation
6. Back surface is perfectly reflecting

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for etching a silicon dendritic web crystal for use in a photovoltaic cell characterized by the steps of applying a predetermined pattern of material resistant to etching to a surface of the silicon crystal, the pattern substantially covering all of the surface; etching the surface with an isotropic etching material until the etching material substantially fully undercuts the pattern of material resistant to etching, thus forming a plurality of peaks with sloping sides on the silicon crystal, the isotropic etching material and pattern cooperating so that the sloping sides having a slope which substantially traps within the silicon crystal all of the light striking the silicon crystal.

2. The method of claim 1 characterized in that the step of applying a predetermined pattern of material resistant to etching comprises preparing the surface with an adhesion promoting agent; applying a coat of the material resistant to etching over the entire surface wherein said material resistant to etching is a photoresist material; prebaking the coated crystal; placing a mask over the coated surface, the mask comprising a plurality of spaced apart parallel strips of opaque material; exposing the masked surface to light; developing the photoresist formulated material with a developer and washing away undeveloped photoresist formulated material leaving generally parallel strips of material resistant to etching on the surface: and

post baking the parallel strips of material resistant to etching to affix them to the surface.

3. The method of claim 2 characterized by the step of stripping the material resistant to etching after the etching by utilizing a stripping solution.

4. The method of claim 3 characterized in that the stripping solution is made up of four parts concentrated sulfuric acid and one part hydrogen peroxide.

5. The method of claim 2 characterized in that the parallel strips of material resistant to etching are disposed at right angles as well as being parallel to provide checker board pattern of material resistant to etching when the undeveloped material is washed away and a plurality of pyramid shaped peaks with slopes on four sides are formed when the etching is completed.

6. The method of claim 1 characterized in that the etching material is a solution comprising, by volume, ten parts of concentrated hydrofluoric acid, one part of concentrated nitric acid, and three parts of concentrated acetic acid.

7. The method of claim 2 characterized in that the light applied to the masked crystal is ultraviolet.

8. The method of claim 2 characterized in that the slope of the sides is at least 15 degrees.

9. The method of claim 5 characterized in that the slope of the sides is at least 15 degrees.

10. A method of etching a silicon dendritic web crystal as hereinbefore described with reference to the accompanying drawings.

DATED this 28th day of June, 1990.

WESTINGHOUSE ELECTRIC CORPORATION
Patent Attorneys for The Applicant:
PETER MAXWELL & ASSOCIATES.

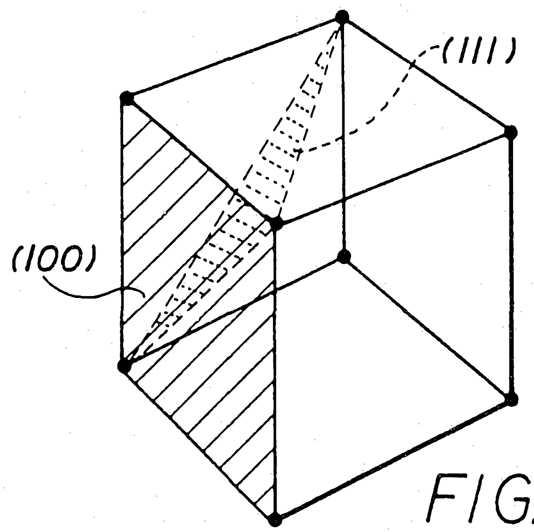
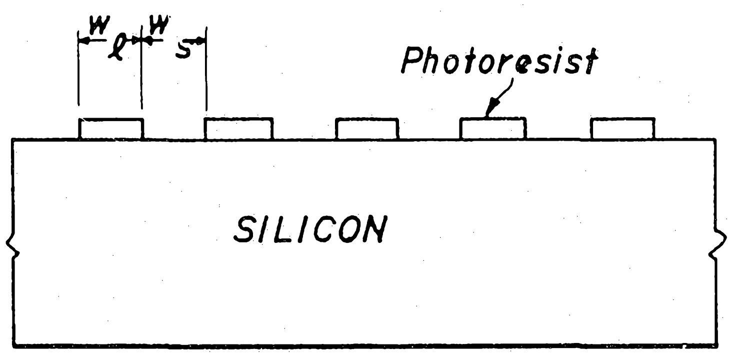
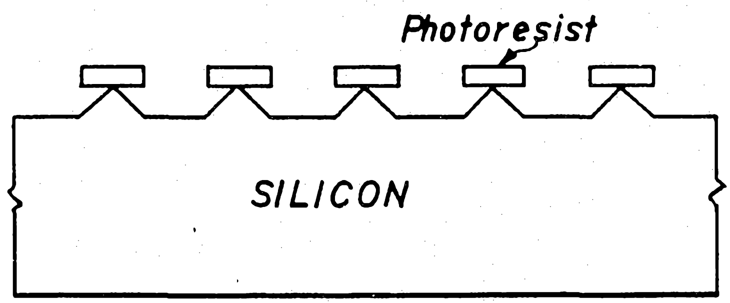


FIG. 1



AFTER PATTERN DEFINITION BY PHOTOLITHOGRAPHY

FIG. 2a



AFTER ISOTROPIC SILICON ETCH

FIG. 2b

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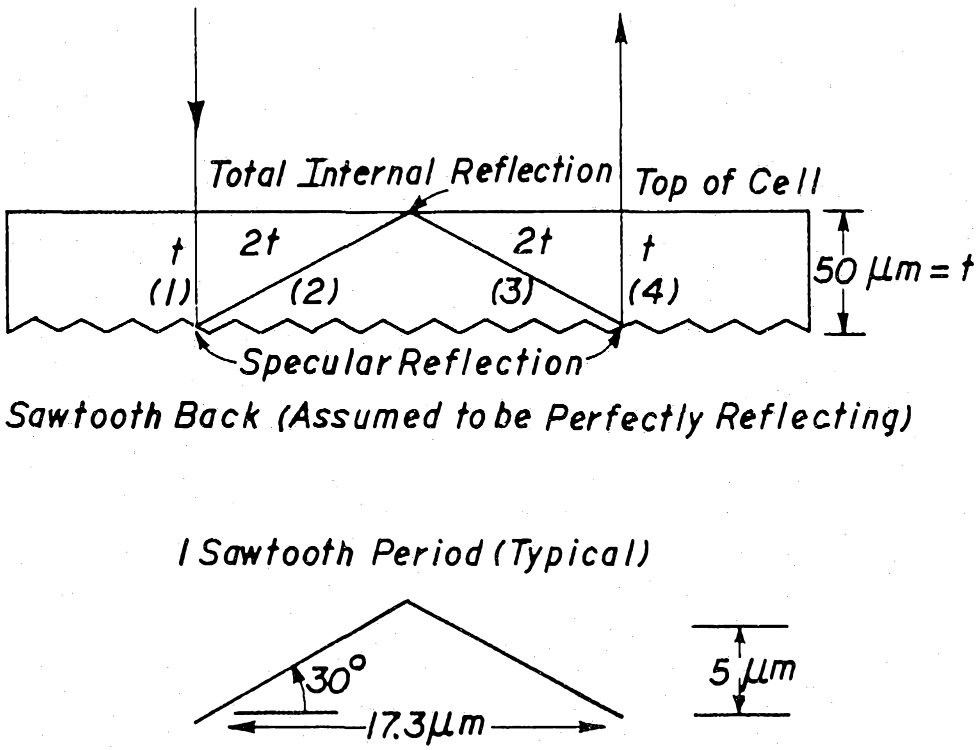

FIG. 3

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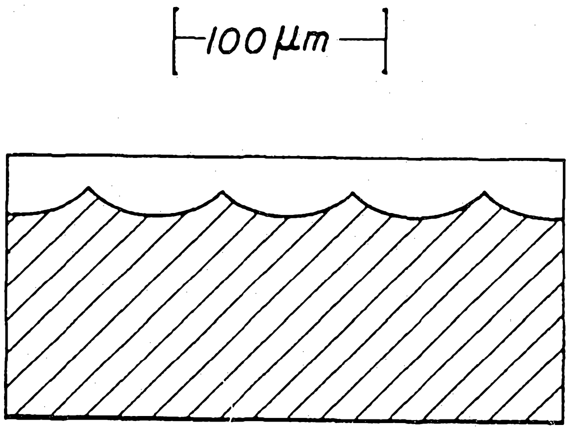


FIG. 4a

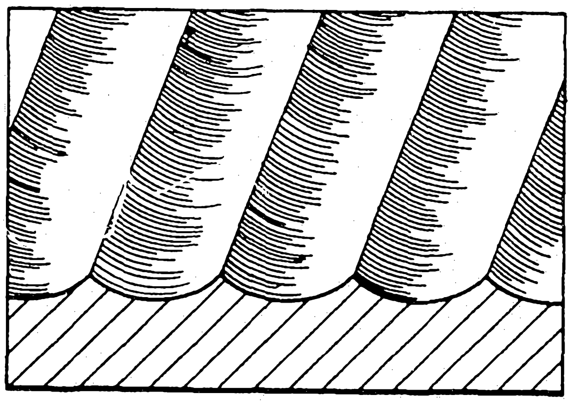


FIG. 4b

20936/88

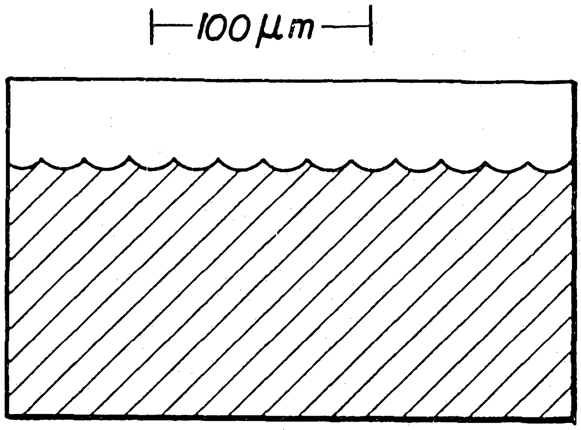


FIG. 5a

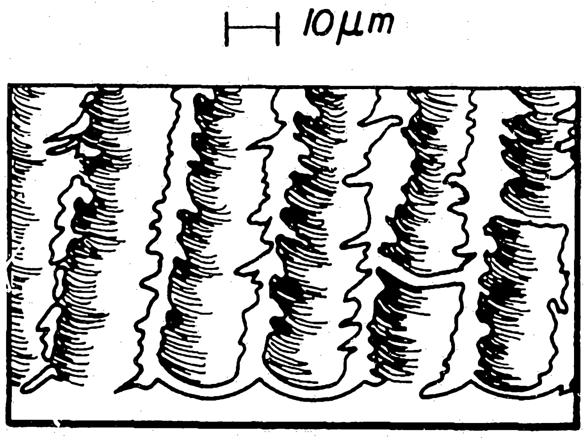


FIG. 5b

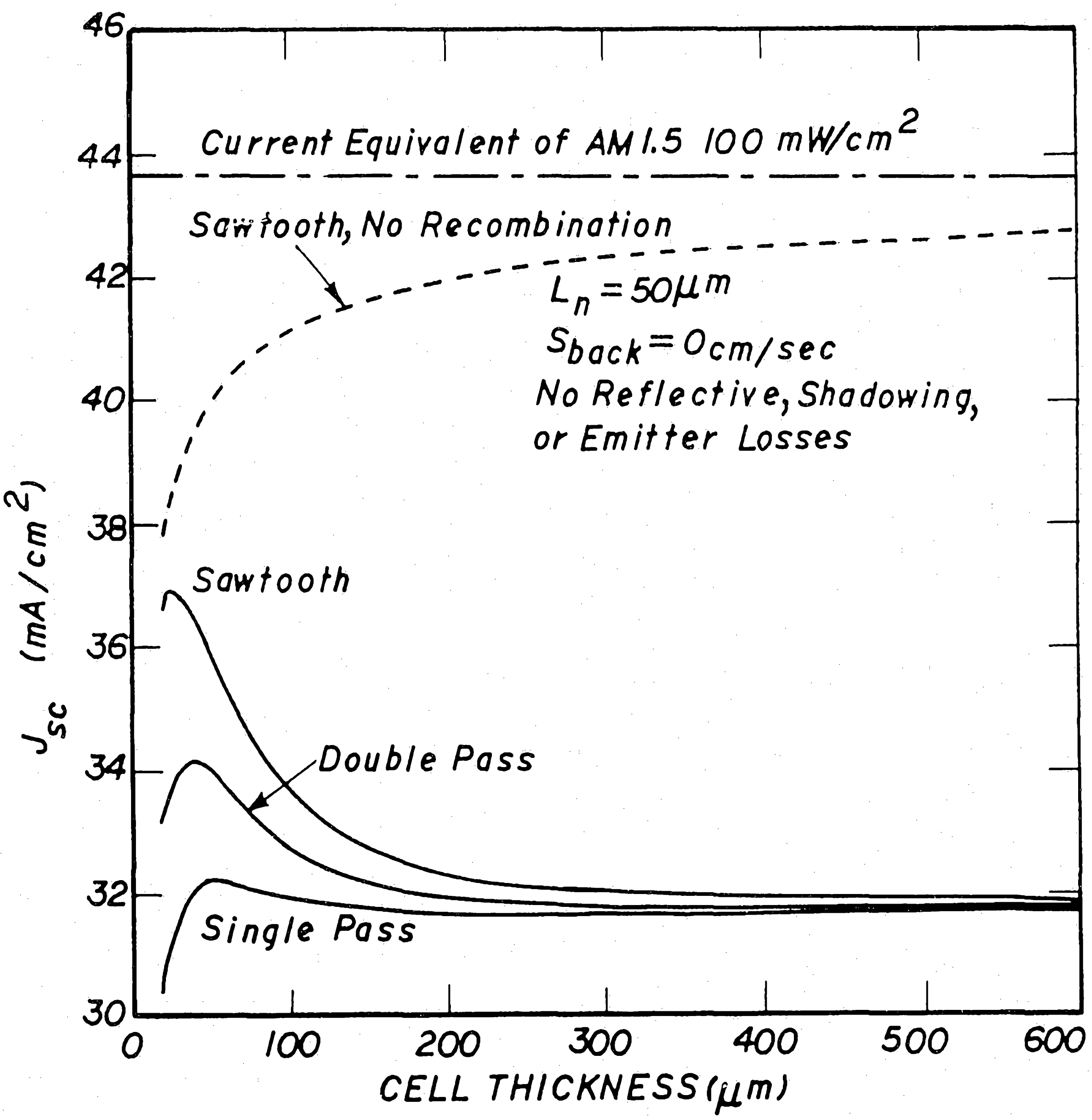

46
44
42
40
38
36
34
32
30
Current Equivalent of AM1.5 100 mW/cm2
Sawtooth, No Recombination
Ln = 50μm
Sback = 0cm/sec
No Reflective, Shadowing, or Emitter Losses
Sawtooth
Double Pass
Single Pass
Jsc (mA/cm2)
0
100
200
300
400
500
600
CELL THICKNESS (μm)

FIG. 6

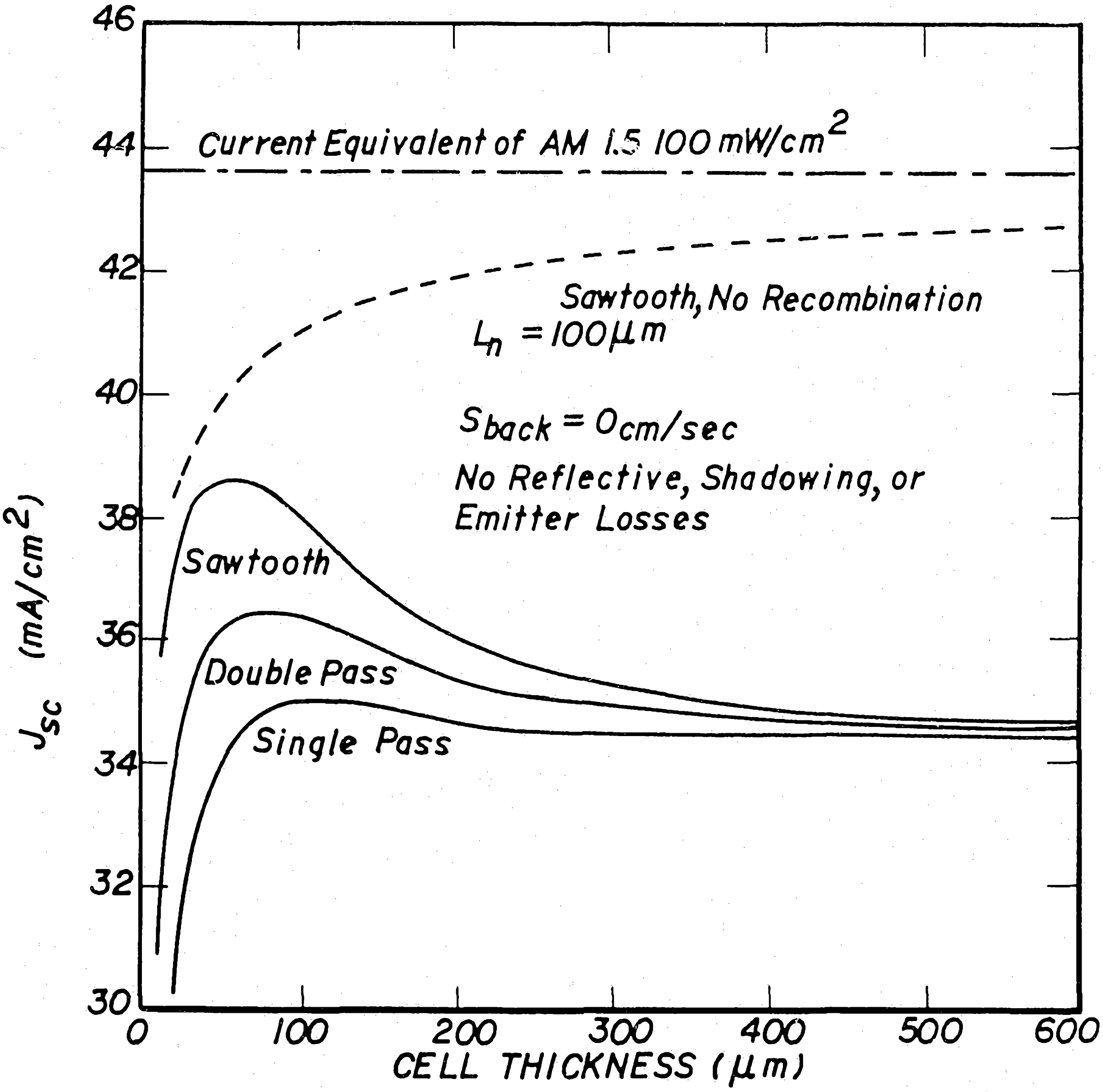

46
44
42
40
38
36
34
32
30
Current Equivalent of AM 1.5 100 mW/cm2
Sawtooth, No Recombination
Ln = 100µm
Sback = 0cm/sec
No Reflective, Shadowing, or
Emitter Losses
Sawtooth
Double Pass
Single Pass
Jsc (mA/cm2)
0
100
200
300
400
500
600
CELL THICKNESS (µm)

FIG. 7

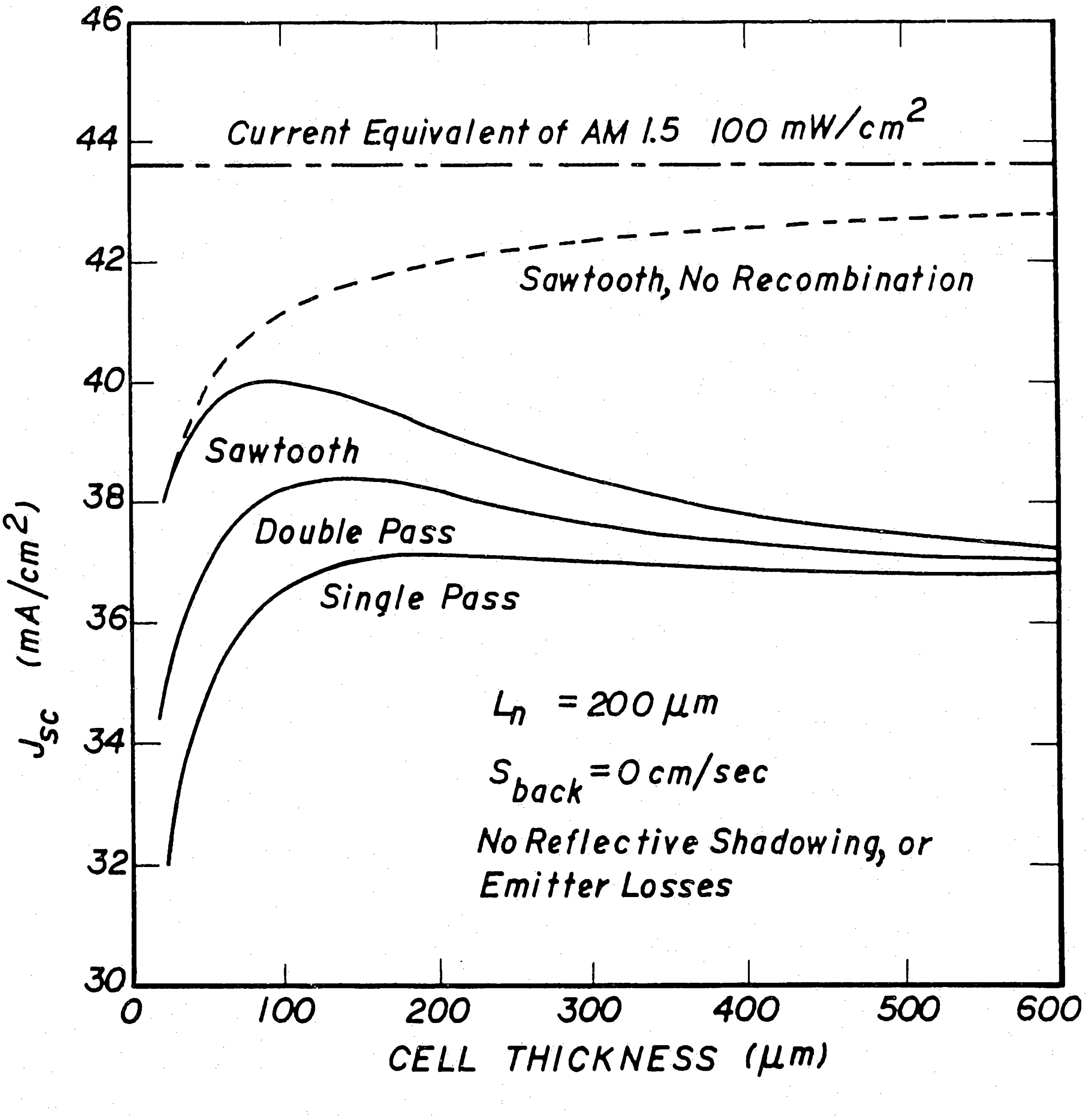
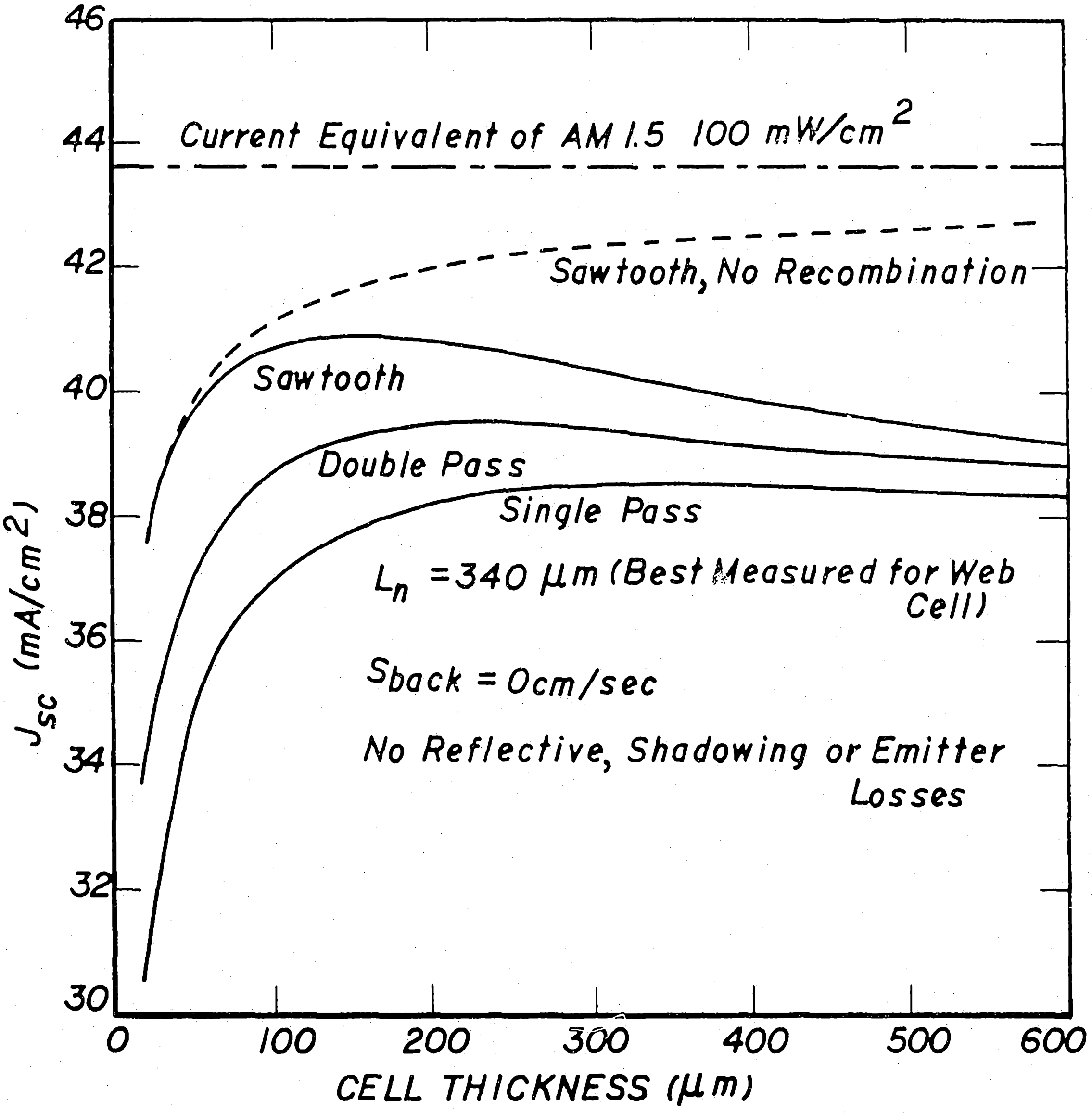
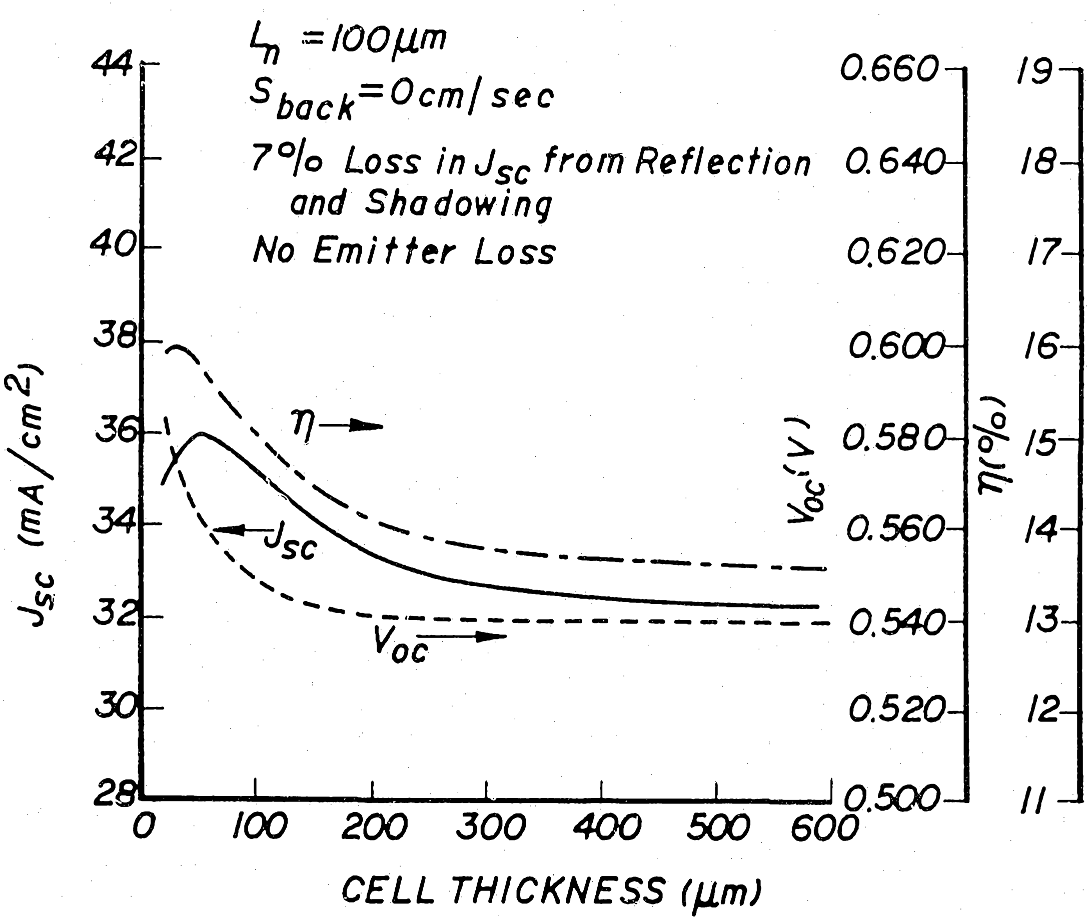

46
44
42
40
38
36
34
32
30
0
100
200
300
400
500
600
Current Equivalent of AM 1.5 100 mW/cm²
Sawtooth, No Recombination
Sawtooth
Double Pass
Single Pass
L_n = 200 μm
S_{back} = 0 cm/sec
No Reflective Shadowing, or
Emitter Losses
J_{sc} (mA/cm²)
CELL THICKNESS (μm)

FIG. 8



Current Equivalent of AM 1.5 100 mW/cm2
Sawtooth, No Recombination
Sawtooth
Double Pass
Single Pass
Ln =340 µm (Best Measured for Web Cell)
Sback = 0cm/sec
No Reflective, Shadowing or Emitter Losses
Jsc (mA/cm2)
46
44
42
40
38
36
34
32
30
0
100
200
300
400
500
600
CELL THICKNESS (µm)

FIG. 9



L_n =100μm
S_{back}=0cm/sec
7% Loss in J_{sc} from Reflection and Shadowing
No Emitter Loss
η
J_{sc}
V_{oc}
J_{sc} (mA/cm²)
V_{oc} (V)
η(%)
44
42
40
38
36
34
32
30
28
0.660
0.640
0.620
0.600
0.580
0.560
0.540
0.520
0.500
19
18
17
16
15
14
13
12
11
0
100
200
300
400
500
600
CELL THICKNESS (μm)

FIG. 10

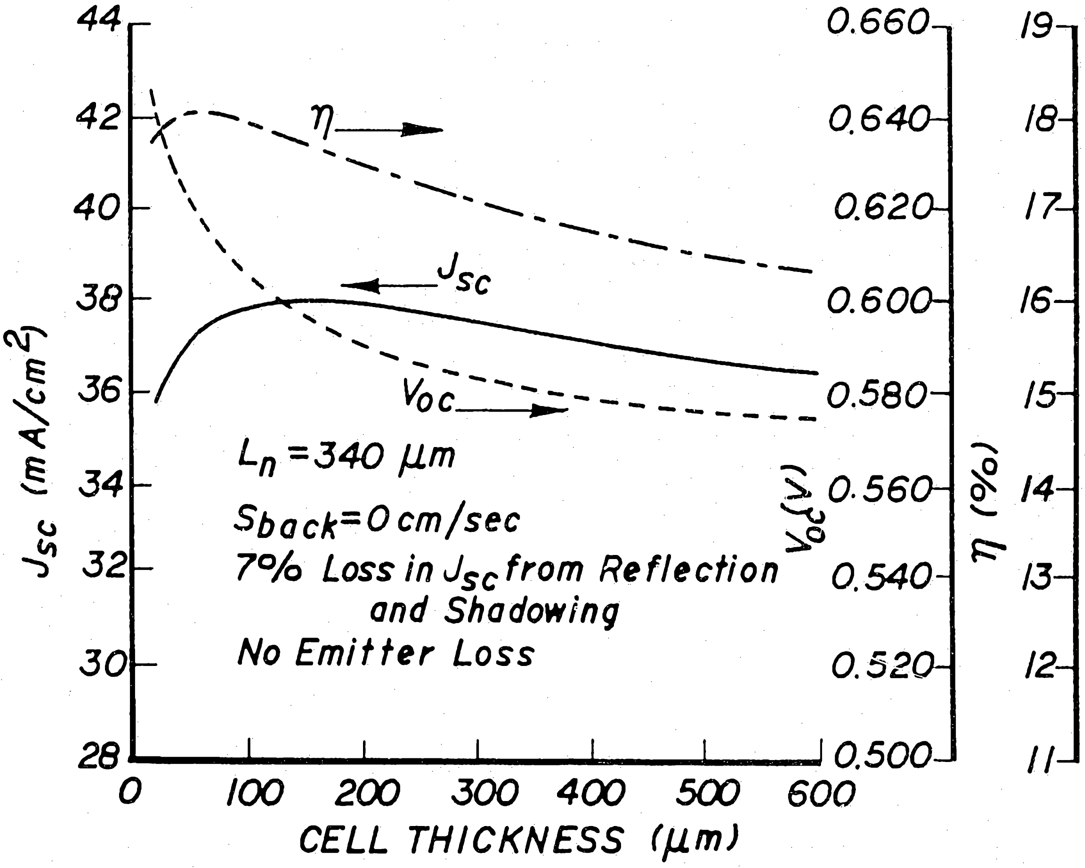

44
42
40
38
36
34
32
30
28
0.660
0.640
0.620
0.600
0.580
0.560
0.540
0.520
0.500
19
18
17
16
15
14
13
12
11
η
Jsc
Voc
Ln =340 μm
Sback=0 cm/sec
7% Loss in Jsc from Reflection and Shadowing
No Emitter Loss
Jsc (mA/cm2)
Voc (V)
η (%)
0
100
200
300
400
500
600
CELL THICKNESS (μm)

FIG. 11