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MATERIAL REQUIREMENTS FOR HIGH-EFFICIENCY SILICON SOLAR CELLS

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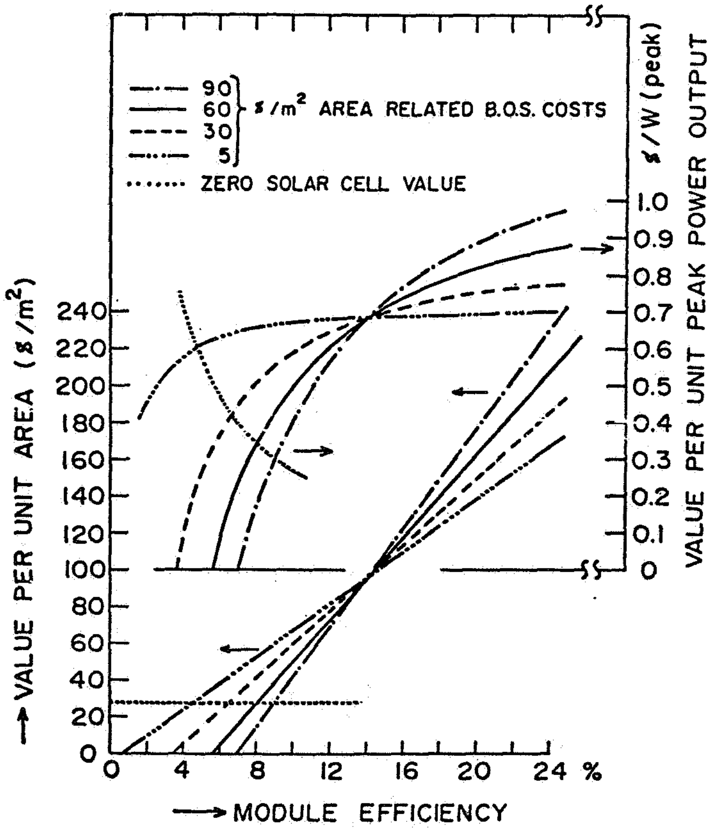


Primary Causes of Losses

1. Light Generated Current:
   - A. Optical Surface Properties (reflection)
   - B. Contact Coverage
   - C. Incomplete Absorption (thickness)
   - D. Recombination Outside Depletion Region (bulk and surface, including contacts)
   - E. ("Dead Layers")
2. Open Circuit Voltage:
   - A. Recombination Outside Depletion Region (bulk and surface, including contacts)
   - B. Bandgap Narrowing
   - C. "Current Leakage"
3. Fill Factor:
   - A.
   - B. } Same as Open Circuit Voltage
   - C.
   - D. Recombination In Depletion Region
   - E. Series Resistance

PRIMARY CAUSES OF LOSSES	SYMBOL	DESIGN PARAM	1970 COM'L CELL	"VIOLET CELL"	"BLACK CELL"	1978 SPACE CELL	1984 EXPER'L CELLS			GOALS	
							SPIRE	WESTINGH	M.A.GREEN	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^+}	—	—	—	?		(0.1 μs)	(0.1 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
		$\tau_{p,n}$	?	?	?	?			1ns ~15 μs	0.1 μs	10 μs
		S	?	?	?	?	~10⁴ cm s⁻¹	~10⁴ cm s⁻¹	10³ cm s⁻¹	10³ cm s⁻¹	10² cm s⁻¹
		TREATM.	SiO	Ta₂O₅ + GLASS	TEXT'D + Ta₂O₅ + GLASS	TEXT'D + Ta₂O₅	TEXT'D + SiO₂ + TiO₂	TiO₂/SiO₂	ZnS/MgF₂	DUAL AR	DUAL AR
1. LIGHT GENERATED CURRENT:											
FUNDAMENTAL LIMIT (AM1)	$j_{L,id}$		44 mA cm⁻²								
A. OPTICAL SURFACE PROPERTIES (REFLECTION)	(1−R)		0.905	0.90	0.97	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	0.96	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 } = 0.90	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)	$j_L = \gamma \cdot j_{L,id}$ (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 ($j_0 = 4.2 \cdot 10^{-16}$ A cm^{-2})								
A. RECOMBINATION OUTSIDE DEPLETION REGION (BULK AND SURFACE, INCLUDING CONTACTS) B. BANDGAP NARROWING	} $(VF) = (VF)_{techn} \cdot (VF)_{fund}$		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	} $(CF) = (CF)_{techn} \cdot (CF)_{fund}$		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

The Recent Approach

a. <u>THOUROUGH</u> DEVICE <u>ANALYSIS</u> COUPLED WITH <u>MODELING</u>:

- TO DETERMINE ALL LOSS CONTRIBUTIONS
- TO IDENTIFY POSSIBILITIES FOR IMPROVED DEVICE DESIGN.

b. <u>GLOBAL DESIGN VIEW</u> OF DEVICE:

- OPTIMIZED CONTACT DESIGN
- DUAL AR OR TEXTURED FRONT SURFACE
- FRONT SURFACE PASSIVATION (AT LEAST PARTIAL)
- BSF AND/OR BSR DESIGN (LIMITED EFFECT)
- SELECTION OF LOW RESISTIVITY FZ Si
- PROCESSING TO MAINTAIN HIGHER FRACTION OF ORIGINAL L_b
- OPTIMIZATION OF EMITTER IMPURITY CONCENTRATION FOR PRESENT DESIGN

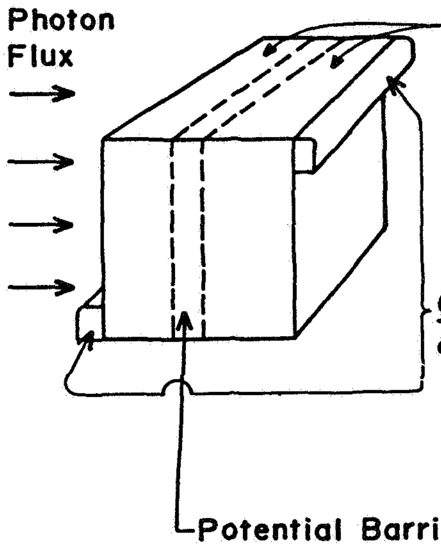
IN SUMMARY:

<u>SQUEEZE A LITTLE MORE PERFORMANCE OUT,</u>
<u>WHEREVER CURRENT TECHNOLOGY PERMITS.</u>

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.

The Basic Solar Cell



Volume for
- Photon Absorption

Contacts to
- Extract Current

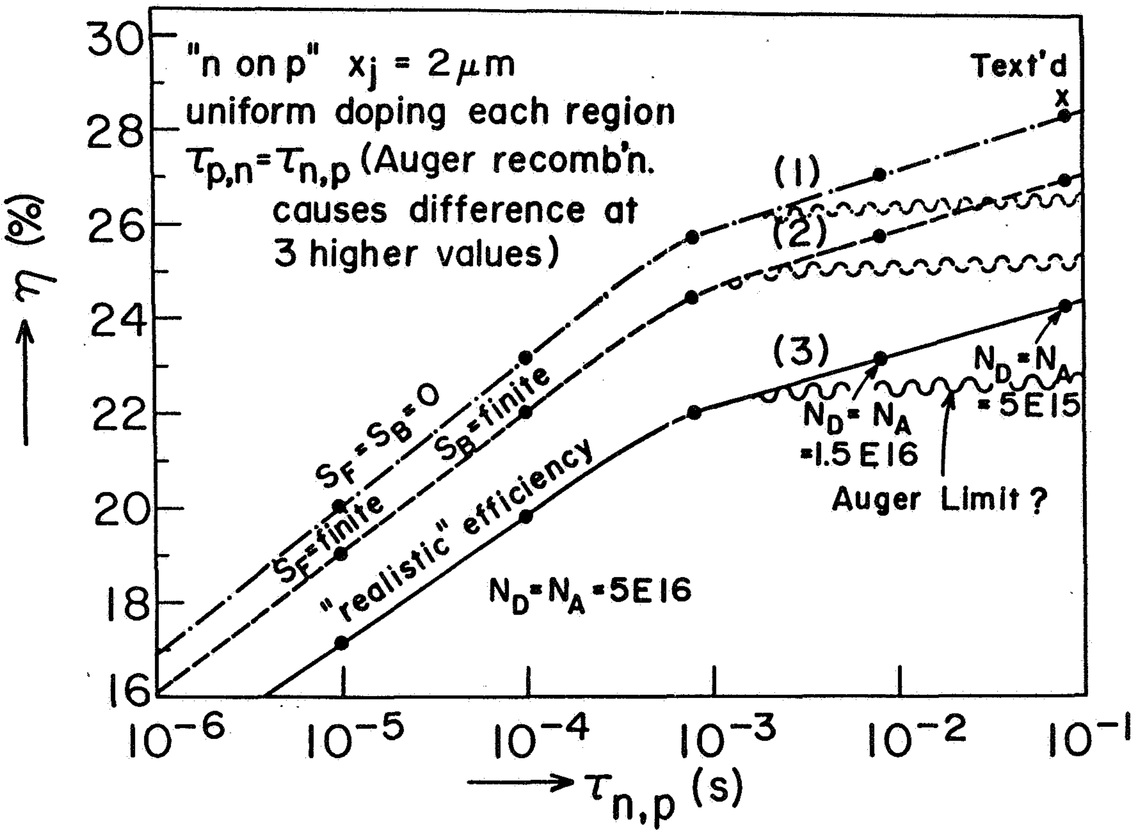
Potential Barrier for
- Collection of Light-Gen'd Carriers
- Generation of Voltage

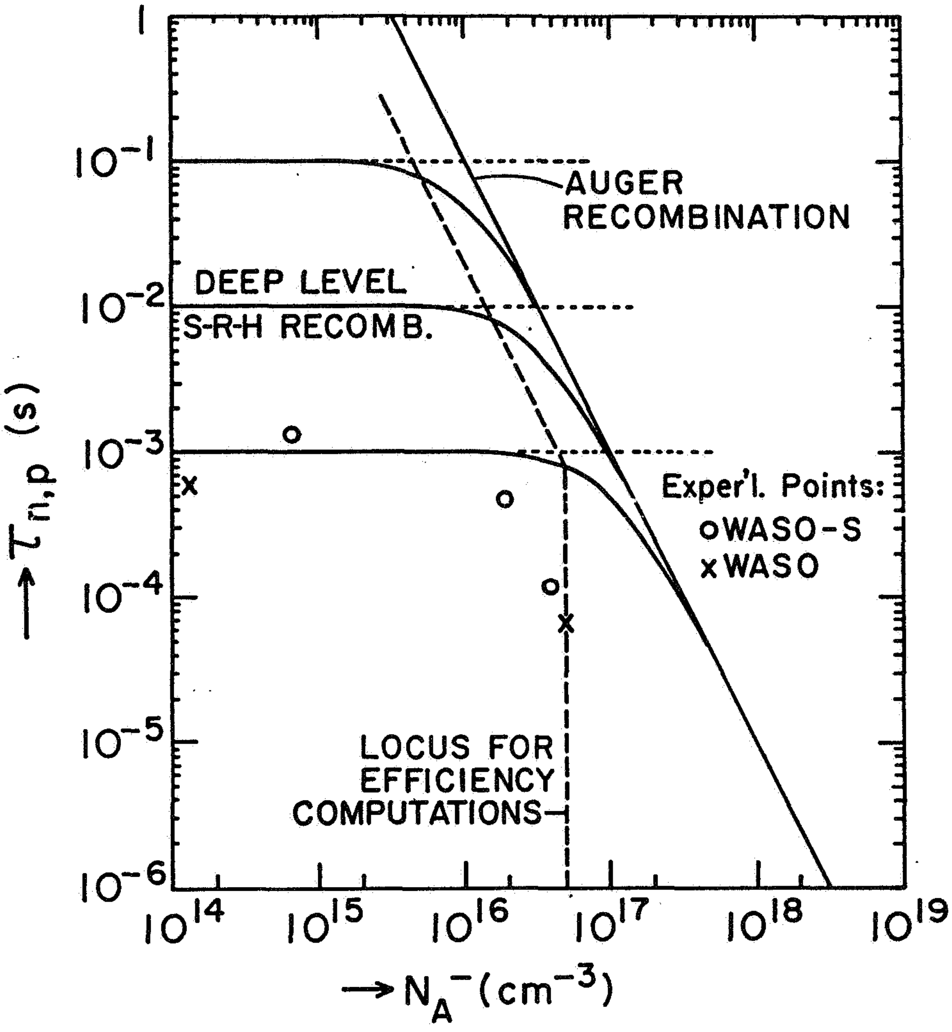
Everything Else

(AR coatings, Hi/Lo Junctions, extra Layers, etc)

to overcome

- Secondary Effects
  caused by material, process, or
  design limitations


"n on p" x_j = 2 μm
uniform doping each region
$\tau_{p,n} = \tau_{n,p}$ (Auger recomb'n. causes difference at 3 higher values)
Text'd
x
(1)
(2)
(3)
$S_F = S_B = 0$
S_B = finite
S_F = finite
"realistic" efficiency
$N_D = N_A = 5E16$
$N_D = N_A = 1.5E16$
$N_D = N_A = 5E15$
Auger Limit ?
η (%)
$\tau_{n,p}$ (s)
30
28
26
24
22
20
18
16
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}



1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\longrightarrow \tau_{n,p}$ (s)
AUGER RECOMBINATION
DEEP LEVEL S-R-H RECOMB.
Exper'l. Points:
o WASO-S
x WASO
LOCUS FOR EFFICIENCY COMPUTATIONS
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
$\longrightarrow N_A^-$ (cm^{-3})

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 V_{oc}
● "ISOLATING" FROM HIGHER RECOMBINATION RATE		
● HIGH DOPANT CONCENTRATION		

High Dopant Concentration

PRINCIPLE:

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

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

LIMITS:

- HEAVY DOPING EFFECTS.

Is Heavy Doping Needed?

ITS PERFORMANCE-INCREASING APPLICATIONS:

- **REDUCE SHEET RESISTANCE**
- **OBTAIN LARGER HIGH/LOW JUNCTION POTENTIAL STEP, OR HIGHER DRIFT FIELD.**

ITS PERFORMANCE DECREASING ATTRIBUTES:

- **AUGER RECOMBINATION**
- **BAND-GAP NARROWING.**

Effective Bulk Recombination Mechanisms

<u>INTRINSIC</u> (INTERBAND) RECOMBINATION:

RADIATIVE	**ULTIMATELY**
	LIMITS
AUGER?	**EFFICIENCY**

<u>EXTRINSIC</u> (BAND-TO-BOUND STATE) RECOMBINATION:

THERMAL (PHONON ASSISTED) SRH
(AUGER?)

EXTRINSIC RECOMBINATION CAN BE DECREASED BY REDUCING THE NUMBER OF BOUND STATES (RECOMBINATION CENTERS, "DEFECTS").

Knowledge of Defects

a. **ARE SOME DEFECTS "INTRINSIC"?**

(NEUTRAL DEFECT WITH ACTIVATION ENERGY E_a AT PROCESS TEMPERATURE "FROZEN IN." IONIZED FRACTION AT DEVICE OPERATION TEMPERATURE FORMS RECOMBINATION CENTER, PARTICULARLY IN N-TYPE).

b. **TRUELY EXTRINSIC (PROCESS-INDUCED) DEFECTS**

- o **IMPURITIES (O, C, Au, Ti, Mo, Fe, ...)**
  - **BIG PROGRESS MADE IN DETECTING PRESENCE, DETERMINING CONCENTRATION. OPEN QUESTION OFTEN IS: INTERSTITIAL, SUBSTITUTIONAL, COMPLEXED, OR PRECIPATED?**
  - **O: PRIMARY SOURCE: CRUCIBLE IN Cz PROCESS. TECHNIQUES KNOWN TO REDUCE O-CONTENT TO 0.1 OF STANDARD LARGE-CRUCIBLE Cz PROCESS. O-CONTENT INCREASES WITH C- OR B-CONTENT.**
- o **CRYSTAL GROWTH DEFECTS.**
  - **BIG PROGRESS MADE IN DETECTION, IDENTIFYING CRYSTAL GROWTH DEFECTS.**
  - **STRONGLY CONNECTED WITH THE CRYSTAL GROWTH TECHNOLOGY APPLIED; TECHNOLOGY APPLIED SEEMS PRIMARILY DETERMINED BY THROUGTHPUT, PRICE, AND WHAT THE MAJORITY OF USERS ARE WILLING TO ACCEPT.**

Reduce Volume Recombination Center Density

- ● <u>ORIGINAL MATERIAL PROCESSING:</u>
  - FEWER IMPURITIES
  - ROLES OF OXYGEN, CARBON?
  - FEWER CRYSTAL DEFECTS (THERMAL ENVIRONMENT IN X-TAL GROWTH?)
  - ROLES OF DEFECT COMPLEXES
- ● <u>DEVICE PROCESSING:</u>
  - NO NEW IMPURITY INTRODUCTION
  - REMOVE EXISTING DEFECTS (GETTERING)
  - AVOID TRANSFORMATION OF DEFECTS TO RECOMBINATION CENTERS (EFFECTS OF THERMAL PROCESSES?)
  - FOSTER TRANSFORMATION OF RECOMBINATION CENTERS TO HARMLESS DEFECTS (PASSIVATION; CHANGES OF COMPLEXES?; ROLE OF HYDROGEN?)

Steps Toward Reduced Number of Recombination Centers

1. IDENTIFY "DEFECT(S)" WHICH FORM RECOMBINATION CENTER(S)
    - BROAD RANGE OF DEFECTS AND OF ENERGY LEVELS IDENTIFIED
    - INTERCONNECTION AND RELATIONSHIP TO RECOMBINATION CENTERS MADE IN ONLY A FEW CASES.
2. IDENTIFY SOURCE(S) OF DEFECT(S)
    - USUALLY NOT KNOWN.
3. FIND WAYS FOR ELIMINATING SOURCE(S) OF DEFECT(S)
    - STILL MOSTLY "BLACK ART."
4. PASSIVATE EXISTING DEFECTS
    - LITTLE KNOWN. IS H^+ THE BROAD SPECTRUM ANTIBIOTIC"?

Passivation with Hydrogen

- IT CAN NEUTRALIZE RECOMBINATION CENTERS, APPARENTLY EVEN DEEP IN THE BULK, PARTICULARLY AT GRAIN BOUNDARIES.
- HYDROGEN IMPLANTS PASSIVATE DANGLING BONDS, WHEREVER HYDROGEN IONS REACH THEM.
- HYDROGEN IMPLANTS MAY POSSIBLY ALSO PASSIVATE DEEP LEVELS (IMPURITIES) in Si.
- THE "IMPLANTATION" OF HYDROGEN IONS, EVEN AT LOW ENERGIES CAUSES SPUTTER ETCHING, LATTICE DAMAGE (200 Å DEEP AT 400eV).
- HYDROGEN CAUSES MORE LATTICE DAMAGE THAN ARGON, EVEN AMORPHIZES SURFACE LAYER, BUT FEWER DANGLING BONDS ("PASSIVATES ITS OWN DAMAGE")
- WHETHER PASSIVATION DOMINATES OVER INTRODUCED DAMAGE DEPENDS ON IMPLANTATION ENERGY, PRIOR PROCESS HISTORY.
- HYDROGEN IS ALSO KNOWN TO NEUTRALIZE B AS AN ACCEPTOR.

Low-Cost Crystalline Si Is Primarily:

- "CAST" INGOT MATERIAL (SEMIX, SILSO, HEM, etc.)
- NOT-SINGLE CRYSTALLINE RIBBON (EFG, LASS, etc.)

EFFORTS TO INCREASE GRAIN SIZE, REDUCE DEFECTS, PASSIVATE REMAINING ONES, ALL SHOW PROGRESS.

BUT: IT SEEMS IMPOSSIBLE TO COMPLETELY PASSIVATE ALL THE DEFECTS ASSOCIATED WITH GRAIN BOUNDARIES

ALSO: FASTER, LESS CONTROLLED GROWTH MAY ALWAYS RESULT IN INCREASED NUMBERS OF IMPURITIES, CRYSTAL DEFECTS.

CONSEQUENTLY: THE ULTIMATELY ACHIEVABLE PERFORMANCE MARGIN RELATIVE TO THAT OF SINGLE CRYSTAL DEVICES IS NOT KNOWN.

- WEB-DENDRITE RIBBON IS IN A CLASS BY ITSELF.
  MAY HAVE POSSIBILITY, WITH INTERNAL GETTERING AT TWIN PLANES, TO SURPASS THE QUALITY OF SINGLE CRYSTAL WAFERS.

IN ALL METHODS, THE CONTROL OF THE THERMAL ENVIRONMENT DURING AND SHORTLY AFTER GROWTH APPEARS IMPORTANT.

The Device Engineer's Wish List to the Materials Engineer

1. SILICON OF LONG MINORITY CARRIER LIFETIME
   (e.g., 0.2 Ω cm p-type with $\tau > 500\ \mu s$)

2. SILICON OF REPEATEDLY UNIFORM LIFETIME
   (not 50-1000 μs)

3. SILICON WHOSE LIFETIME DOES NOT DECREASE DURING NORMAL DEVICE PROCESSING
   (a repeatable, uniform increase is o.k.)

4. SILICON SHEET (WAFER) WHICH IS FLAT, AND STAYS FLAT THROUGHOUT NORMAL DEVICE PROCESSING

5. SILICON WHICH UNIFORMLY HAS REASONABLE MECHANICAL STRENGTH

6. SILICON SHEET OF LOW COST
   ($<\$50/m^2$)

Final Discussion

- FOR HIGHER EFFICIENCIES (AT LEAST > 20%), BETTER SINGLE CRYSTAL Si IS NEEDED.
- IT SHOULD BE POSSIBLE TO BRING Cz Si TO THE SAME LOW-RECOMBINATION LEVEL AS FZ Si.
- HOW CAN DEVICES BE FABRICATED FROM THIS Si WITHOUT GREATLY INCREASING THE RECOMBINATION CENTER DENSITY?
- ARE SPECIAL Si QUALITIES NEEDED TO PERMIT SUCH PROCESSING?
- HOW CAN THE PROGRESS MADE IN MATERIAL SCIENCE BE TRANSLATED INTO BETTER PROCESSING METHODS?
- IF SOLAR CELL FABRICATORS WOULD SPECIFY THE QUALITY OF Si THEY NEED, WOULD Si MANUFACTURERS DELIVER TO THESE SPECIFICATIONS?
- DO SOLAR CELL FABRICATORS KNOW WHAT SPECIFICATIONS TO WRITE?

DISCUSSION

STORTI: How much of a sacrifice in efficiency and lifetime do you see by going down to very low values of resistivity?

WOLF: Calculations of intrinsic defect levels of recombination center densities indicate that the lifetime goes down with one over the impurity concentration. This means that you still would gain by going to a lower resistivity until you reach Auger recombination.

RAO: Regarding hydrogen passivation: are there data that verify if we are passivating the dangling bonds and/or the impurities?

CORBETT: No, it has not been verified. It does passivate sometimes, including the substitutional impurities, and sometimes it doesn't. We have speculations as to why it doesn't but we don't know for sure.

LANE: You've been talking about the defects and their effect on the cell. There is a lot of effort going on in industry today to improve the uniformity of the crystal, the uniformity of the distribution of defects, the uniformity of the impurities, striations, etc. If we get a perfectly uniform crystal and it's still full of impurities or defects, are we no farther ahead or is this effort on uniformity truly important?

WOLF: The device fabricator would like to see ingots all of nearly uniform lifetime from which to make a device.

SCHWUTTKE: If you want high-efficiency solar cells, you must have a uniform minority carrier lifetime over the whole device area. This means the minority carrier lifetime is not allowed to go below a certain limit. It is welcome to go over that limit if you average over the total area.

LESK: Regarding uniformity: I don't think that the material we get today is uniform either, but if making the material uniform drives the cost up too high, then we may still have to accept something that is not uniform but is still pretty good.

JASTRZEBSKI: How far away from the junction do you need a good lifetime?

WOLF: Silicon is an indirect bandgap semiconductor, so some of the photons of the solar spectrum penetrate up to a millimeter. To make devices with high voltage, we make the layers thinner than the diffusion lengths. The lifetime determines how thick we make the layers, therefore, a long lifetime would use a thicker wafer. For a lifetime of 100 µs, a 10-µm-thick wafer would be optimal, while a millisecond lifetime would require 300 to 500-µm-thick wafers.