N85-32396

SUMMARY OF THE HIGH-EFFICIENCY CRYSTALLINE SOLAR CELL RESEARCH FORUM

UNIVERSITY OF PENNSYLVANIA

M. Wolf

Session I: OVERVIEW

P. Landsberg	Some Aspects of the Minority Carrier Lifetime in Silicon.
C.T. Sah	Review of Recombination Phenomena in High-Efficiency Solar Cells.

Session II: HIGH EFFICIENCY CONCEPTS

M. Wolf	Silicon Solar Cell Efficiency Improvement: Status and Outlook.
A. Lesk	Some Practical Considerations for Economical Back Contact Formation on High-Efficiency Solar Cells.
R. Bell	High-Efficiency Cell Concepts on Low-Cost Silicon Sheet.
R. Swanson	High Lifetime Silicon Processing.
L. Olsen	Silicon MINP Solar Cells.

Session III: SURFACE/INTERFACE EFFECTS

D. Chadi	Atomic Structure of the Annealed Si (111) Surface.
L. Kazmerski	Surface and Interface Characteristics.
S. Lai	Nitridation of SiO_2 for Surface Passivation.
S. Fonash	Surface Passivation and Junction Formation Using Low-Energy Hydrogen Implants.
F. Grunthaner	Chemical Structure of Interfaces.

Session IV: BULK EFFECTS

E. Sirtl	Structural Defects in Crystalline Silicon.
C. Pierce	Oxygen and Carbon Impurities and Related Defects in Silicon.
T. Tan	Current Understanding of Point Defects and Diffusion Processes in Silicon.
G. Schwuttke	Defects in Web Dendrite Silicon Ribbon Crystals and Their Influences on Minority Carrier Lifetime.
J. Hanoka	EBIC Characterization and Hydrogen Passivation in Silicon Sheet.
A. Neugroschel	Measurement of Electrical Parameters and Current Components in the Bulk of Silicon Solar Cells.

Session V: MODELING

R. Schwartz	Current Status of One and Two Dimensional Numerical Models: Successes and Limitations.
M. Lamorte	Application of Closed-Form Solution Using Recursion Relationship in Silicon Solar Cells.
F. Lindholm	Phenomena Simulation for Heavy Doping and Surface Recombination Velocity.

Session VI: HIGH EFFICIENCY DEVICE PROCESSING

S. Johnson	High-Efficiency Large-Area Polysilicon Solar Cells.
P. Iles	High-Efficiency Solar Cell Processing.
A. Rohatgi	Process and Design Considerations for High-Efficiency Silicon Solar Cells.
M. Spitzer	Processing Technology for High-Efficiency Silicon Solar Cells.
L. Dyer	Texture Etching of (100) Silicon for Solar Cells.

Questions Relating to the Attainment of Higher-Efficiency Crystalline Silicon Solar Cells

1. **WHAT ARE THE BEST EFFICIENCIES ATTAINED SO FAR?**

2. **HOW WERE THESE CELLS DESIGNED AND FABRICATED?**

3. **WHAT IS THE NEXT IMPROVEMENT STEP?**

4. **HOW CAN IT BE ACHIEVED?**

5. **WHAT IS THE REALISTICALLY EXPECTABLE "ULTIMATE" EFFICIENCY?**

6. **WHAT IS NEEDED TO GET BEYOND THE NEXT STEP?**

   A. Reduced recombination
   B. Other design parameters
   C. Is heavy doping needed?
   D. Auger recombination as limiter.

7. **HOW CAN RECOMBINATION BE REDUCED?**

   A. Bulk recombination
   B. Surface recombination.

8. **DO WE UNDERSTAND THE DEVICE PHYSICS ADEQUATELY?**

   A. Band-Gap narrowing
   B. Auger recombination
   C. High level injection
   D. 2- and 3- dimensional interactions.

9. **DO WE UNDERSTAND THE ORIGINS OF RECOMBINATION CENTERS?**

10. **HOW CAN ONE PROCESS TO ACHIEVE REDUCED RECOMBINATION?**

11. **ARE OTHER NEEDED TOOLS ADEQUATE?**

    A. Modeling
    B. Analysis

12. **WHAT ARE THE INHERENT PERFORMANCE LIMITATIONS IN "LOW COST" CRYSTALLINE SI?**

ORIGINAL PAGE IS
OF POOR QUALITY

PRIMARY CAUSES OF LOSSES	SYMBOL	DESIGN PARAM	1970 COM'L CELL	"VIOLET CELL"	"BLACK CELL"	1978 SPACE CELL	1984 EXPER'L CELLS SPIRE	STINGH	M.A.GREEN	GOALS 20%	22.6%
		BASE: WIDTH	?	300μm	300 μm	300μm(A)	380 μm	375 μm	280 μm	200μm	200μm
		$\tau_{n,p}$	3μs	?	?	?	~40 μm	~23 μm	~25 μm	95μs	950μs
		τ_{n,p^+}	—	—	—	?		(0.1 μs)	(0.1 μs)	0.26μs	2.6 μs
		FRONT: WIDTH	0.4 μm	~0.15 μm	~ 0.2μm	~0.2 μm	~0.2μm	~0.3 μm	~0.3 μm	2 μm	2 μm
		$\tau_{p,n}$	?	?	?	?			ns -15μs	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)	$j_{L,fd}$		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 } 0.90	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)	$j_L = \gamma \cdot j_{L,fd}$ (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_o = 4.2·10^{-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. C. } 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
	(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. THOUROUGH DEVICE ANALYSIS COUPLED WITH MODELING:

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

b. GLOBAL DESIGN VIEW 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:

SQUEEZE A LITTLE MORE PERFORMANCE OUT,
WHEREVER CURRENT TECHNOLOGY PERMITS.

Status of 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.

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

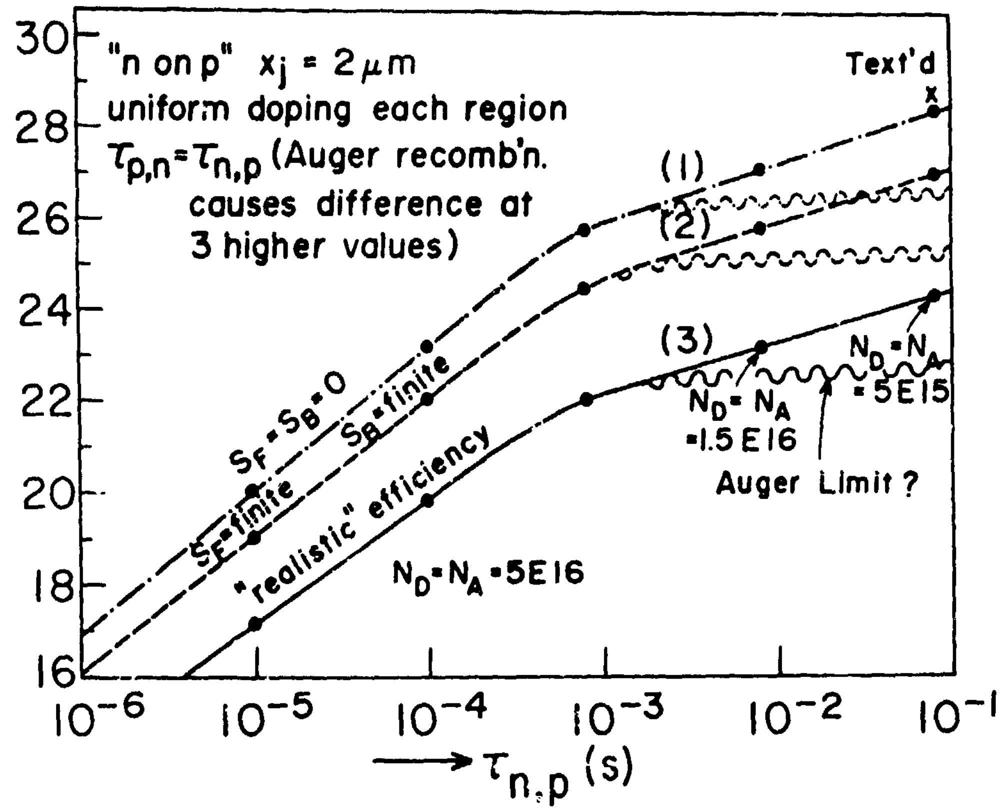
The Next Step

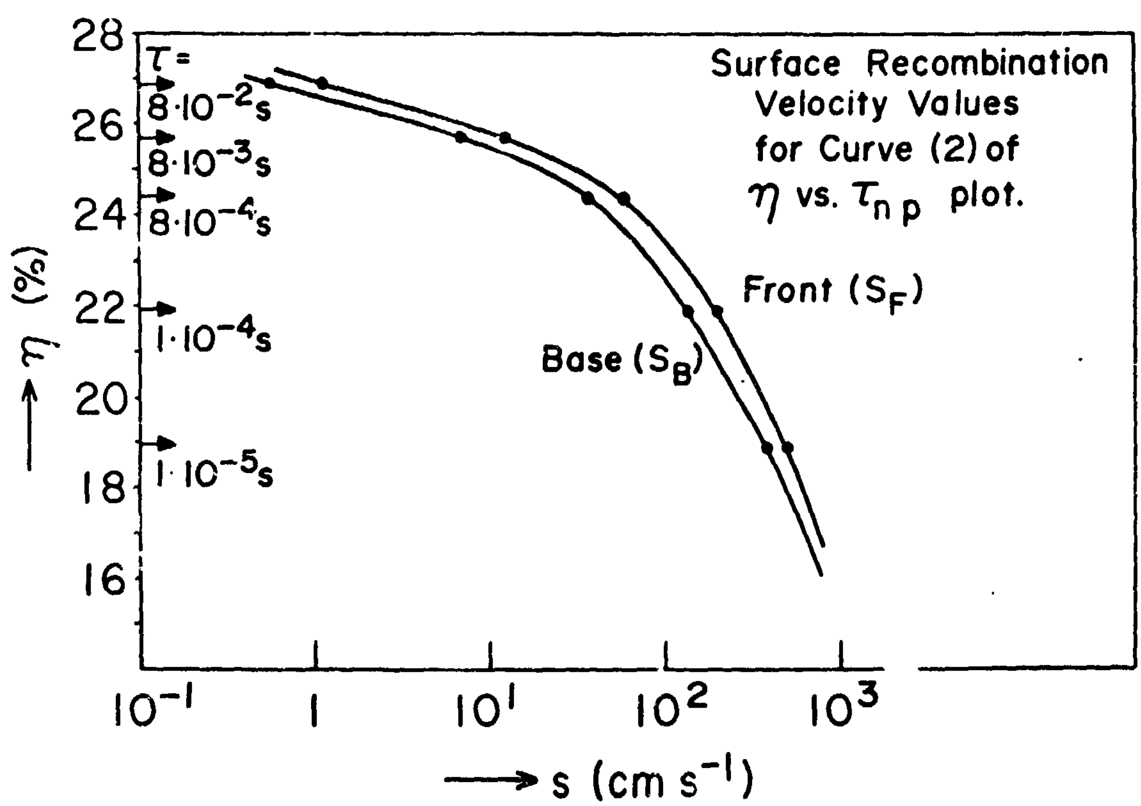
EACH OF THE GROUPS ACTIVE IN EFFICIENCY IMPROVEMENT FEELS THAT THEY HAVE:

a. NOT EXHAUSTED THE PRESENT APPROACH

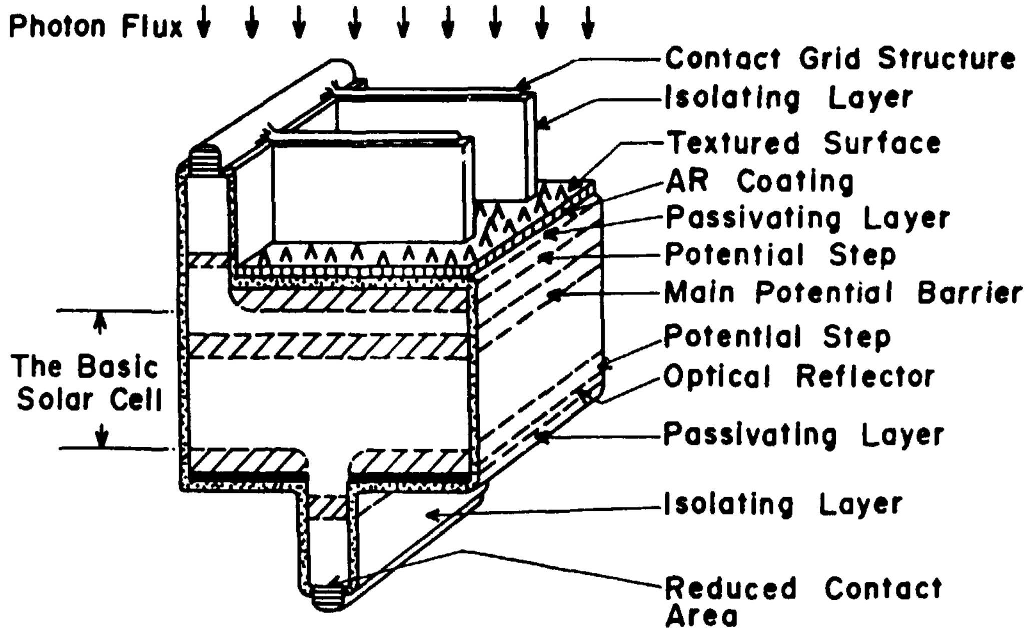
b. IDENTIFIED POSSIBILITIES FOR FURTHER OPTIMIZATION IN THEIR PARTICULAR DESIGNS.

c. REASON TO BE CONFIDET OF REACHING 20% (AM 1.5) EFFICIENCY SOON.


"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
(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)


Surface Recombination Velocity Values for Curve (2) of η vs. $\tau_{n\,p}$ plot.
τ =
$8 \cdot 10^{-2}$s
$8 \cdot 10^{-3}$s
$8 \cdot 10^{-4}$s
$1 \cdot 10^{-4}$s
$1 \cdot 10^{-5}$s
Front (S_F)
Base (S_B)
η (%)
s (cm s^{-1})

Schematic View of the Solar Cell That Has Everything



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.

The Three Principal Paths to Reduced Recombination

DECREASE

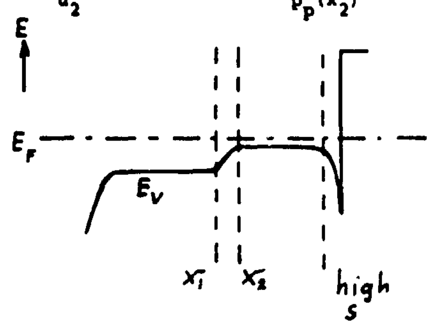
1. DENSITY OF RECOMBINATION CENTERS
   - IN BULK N_t $[cm^{-3}]$ ⟶ HIGHER τ
   - AT SURFACES $N_{s,t}$ $[cm^{-2}]$ ⟶ LOWER s
2. VOLUME OR AREA CONTAINING RECOMBINATION CENTERS:
   - "THIN" LAYERS
   - "DOT CONTACTS"
3. DENSITY OF EXCESS MINORITY CARRIERS
   - FAST REMOVAL TO OUTSIDE
   - "SHIELDING" WITH POTENTIAL STEPS
   - "ISOLATING" FROM HIGHER RECOMBINATION RATE
   - HIGH DOPANT CONCENTRATION

   (first three:) FOR η_{coll} } FOR V_{oc} (all four)

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)



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

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

<u>FORMS OF POTENTIAL "STEPS"</u>:

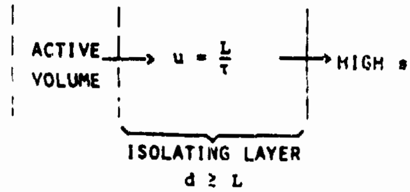
- DRIFT FIELD REGIONS
- HIGH/LOW JUNCTIONS
- ACCUMULATION LAYERS (USUALLY UNDER INSULATORS, INCLUDING "TUNNEL CONTACTS").
- "FLOATING" pn JUNCTIONS (OR INVERSION LAYERS).
- BANDGAP CHANGES (USUALLY ΔE_G WITH HIGH/LOW JUNCTION, "WINDOW LAYER").

<u>LIMITS</u>:

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

Isolating With Thick Layers

PRINCIPLE:



LIMITS:

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

Effective Bulk Recombination Mechanisms

INTRINSIC (INTERBAND) RECOMBINATION:

RADIATIVE	ULTIMATELY LIMITS EFFICIENCY
AUGER?	

EXTRINSIC (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

- 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.
- 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

- 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?)
  - 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"?

Swanson's Prescription for Processing for Reduced Recombination

a. NEVER USE METAL TWEEZERS ON WAFERS
b. ALWAYS PERFORM RCA CLEANING BEFORE HIGH TEMPERATURE PROCESS STEPS.
c. PROCESS IN A CLASS 100 CLEAN AREA
d. PERIODICALLY CLEAN FURNACE TUBES WITH HCl.

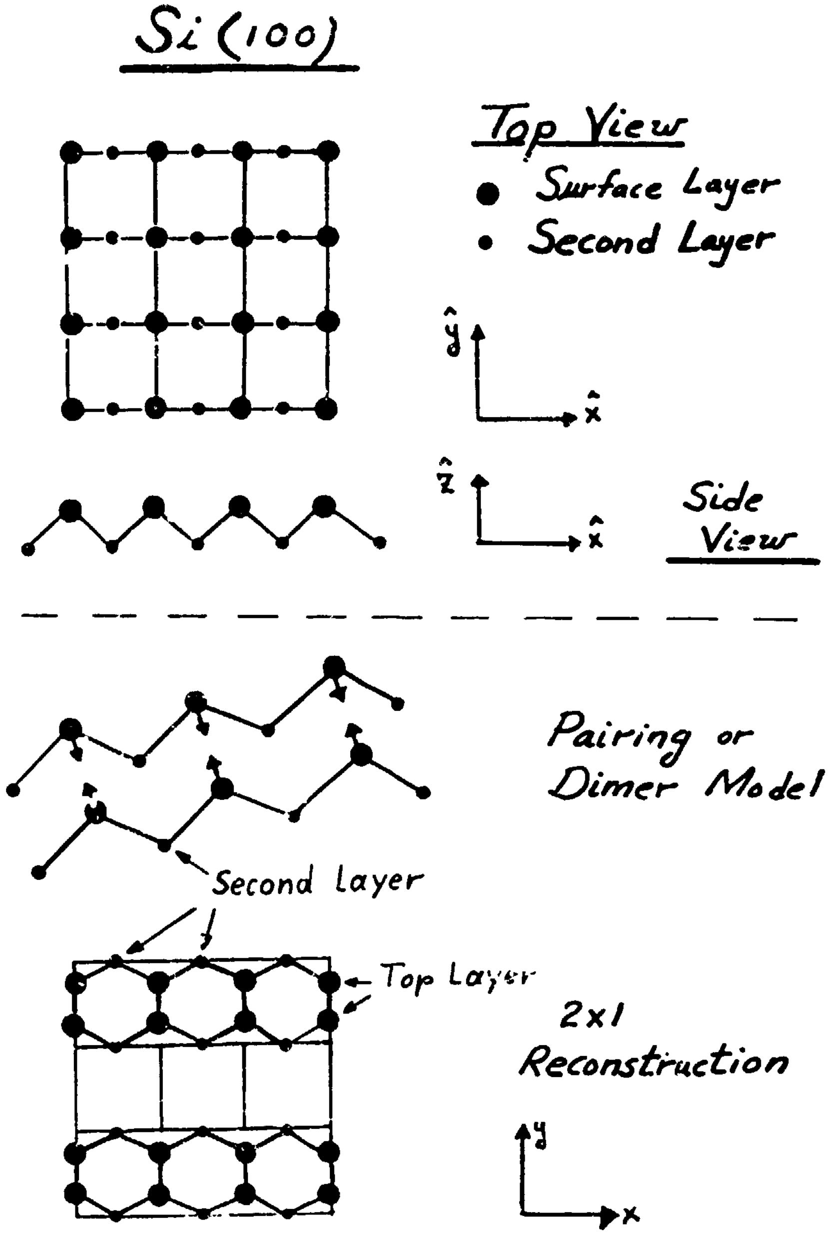
Passivation With Hydrogen

- 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 A 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.

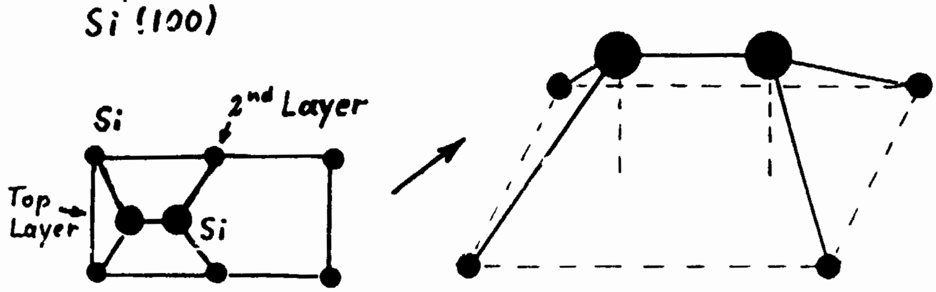
Reducing Surface Defects

1. OXIDATION

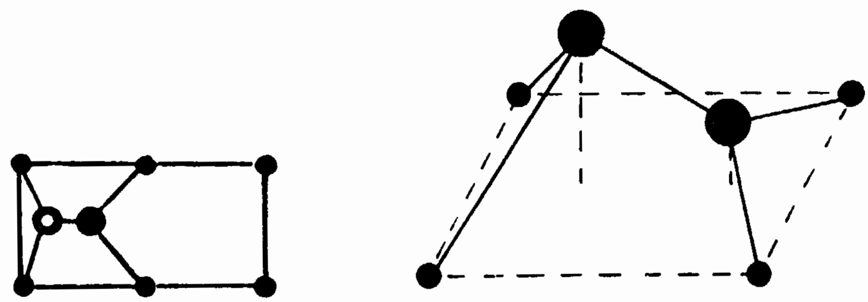
- MOST HIGH EFFICIENCY CELLS NOW USE SOME FORM OF OXYDE PASSIVATION.
- REMAINING SURFACE RECOMBINATION VELOCITY IS FUNCTION OF PREPARATION PROCEDURE FOR FORMING OXIDE LAYER.
- DRY THERMAL OXIDE FOLLOWED BY LOW TEMPERATURE HYDROGENATION CAN YIELD MID-GAP STATE DENSITIES NEAR $1.10^{10}/(CM^2\ eV)$, BUT OXIDATION FOLLOWED BY AN INERT ATMOSPHERE ANNEAL CAN YIELD $1.10^9/(CM^2\ eV)$, 1.e = 2 - 5 cm/s IN HIGH LEVEL INJECTION.
- NITRIDING OXIDE LAYERS MAY IMPORVE STABILITY, RADIATION RESISTANCE OF PASSIVATION LAYERS.


Si (100)
Top View
Surface Layer
Second Layer
Side View
Pairing or Dimer Model
Second layer
Top Layer
2x1 Reconstruction

Top View
Si (100)

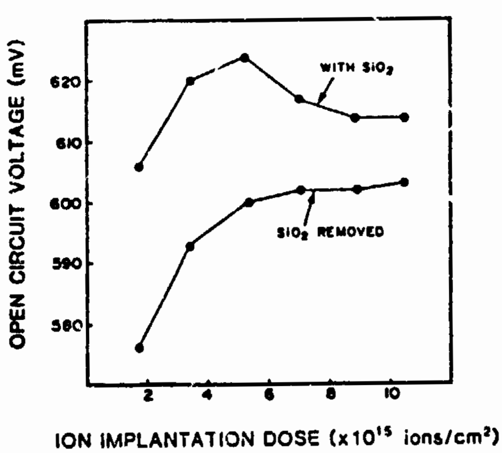


Symmetric Dimer   Unstable



Asymmetric Dimer   Stable

Buckling of symmetric dimer lowers energy by 0.16 eV/dimer



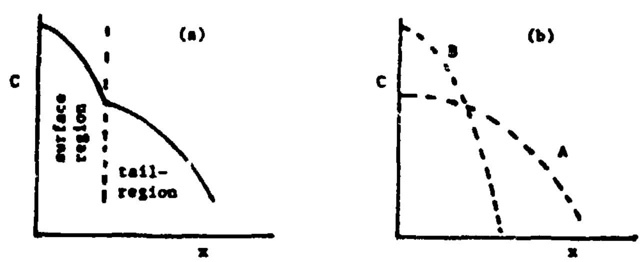
PLENARY SESSIONS

Modeling

- THE "MODELERS" CAN ONLY INCORPORATE THE PHYSICS AS PRESENTLY UNDERSTOOD.
- DIFFUSION PROFILES CAN BE "ANOMALOUS," DEPEND ON MATERIAL PERFECTION.
- THE ACHIEVEMENT OF THE ULTIMATE EFFICIENCIES WILL REQUIRE THE DETAILED SIMULATION OF ALL EFFECTS. THIS NEEDS 2- AND 3-DIMENSIONAL CAPABILITIES.
- SUCH SIMULATION CANNOT BE ANALYTICAL, BUT MAY, FOR SPEED AND COST-SAVINGS, BE QUASI-NUMERICAL.

<u>ANALYSIS</u>

- MATERIAL ANALYSIS HAS REACHED IMPRESSIVE CAPABILITIES.
- IN DEVICE ANALYSIS, THE SEPARATION OF BASE AND EMITTER CONTRIBUTIONS TO SATURATION CURRENT IS STILL TENUOUS, OFTEN LEADING TO CONFLICTING RESULTS.
- PROGRESS IS BEING MADE IN DEVELOPING METHODS TO PERMIT DETERMINATION OF RECOMBINATION RATES IN DIFFERENT PARTS OF THE DEVICE, BUT FURTHER ADVANCES ARE NEEDED.



(a) Schematic drawing of the kink-tail structure of P profile, which, hypothetically, may be obtained by adding (b) profiles of physically distinguishable A and B atoms diffusing independently.

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.

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?