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DEVELOPMENT OF HIGH-EFFICIENCY SOLAR CELLS ON SILICON WEB

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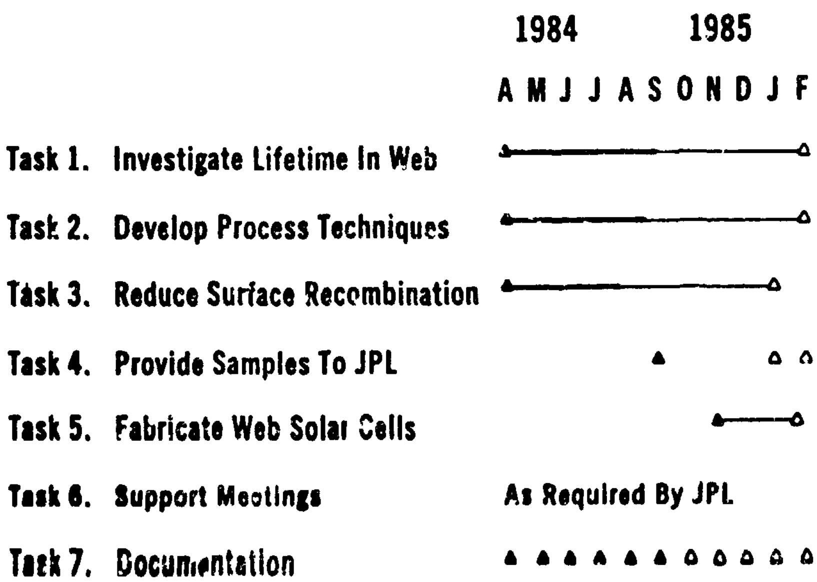
Specific Tasks

- **Investigate The Heat Treatment Effects On Web Quality**
- **Investigate The Influence Of Twin Plane Lamellae, Trace Impurities And Stress On Minority Carrier Lifetime**
- **Fabricate High Efficiency Web Solar Cells**

Milestone Chart



Calculated AM1 Performance of Standard Web Cells With Base Diffusion Length as a Parameter

Cell Base: 4 Ohm-cm (3.5e15/cm^3) P-Type, 150 Microns Thick

Ln (Microns)	J_{oe} (A/cm^3)	J_{ob} (A/cm^3)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff (%)	Eff' (%)
10	1.6e-12	32.1e-11	24.6	.471	.793	9.2	8.3
30	1.6e-12	9.5e-11	30.6	.508	.802	12.5	11.2
60	1.6e-12	5.3e-11	33.2	.525	.809	14.1	12.7
150	1.6e-12	2.0e-11	36.5	.551	.815	16.4	14.8
300	1.6e-12	1.1e-11	37.6	.566	.819	17.4	15.7

Note:

1. Calculations Were Made Using Martin Wolf's Program SPCOLAY.BAS
2. Calculated Values Do Not Account For Grid Shadowing, Light Reflection, Or Resistive Losses. In Order To Estimate These Effect, The Calculated Efficiency (Eff) Was Multiplied By 90% To Give A More Realistic Efficiency (Eff').
3. The Model Accounts For Variation In Doping Density In The Emitter And In The Back Region. For Both The n+p And p+p Regions The Junction Depth Was Taken To Be 0.3 Microns With A Surface Concentration Of 8.0E19/cm^3.
4. The Surface Recombination Velocity Was Taken As 10,000 cm/sec On The Front (AR Coating On Bare Silicon) And 1,000,000 cm/sec On The Back (Metal On Silicon).

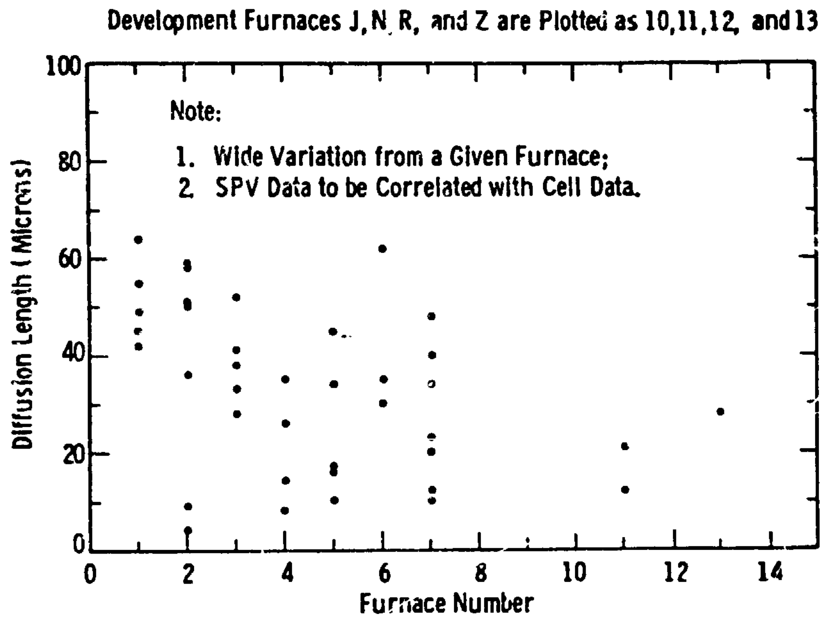
15% Baseline Web and Float-Zone Silicon Cell

n^+-p-p^+ With Single Layer AR And NO Oxide Passivation

Cell ID	J_{sc}	V_{oc}	FF	η	τ_{OCD}
4412-49W Cell 63A, 4 Ω-cm	31.8	0.588	0.80	15.0%	40 μs
FZ, 4 Ω-cm	33 4	0.584	0.78	15.2%	45 μs

τ_{OCD} Of 40 μsecs = 360 μm Diffusion Length In 4 Ω-cm Base

Scatter Plot for As-Grown Web

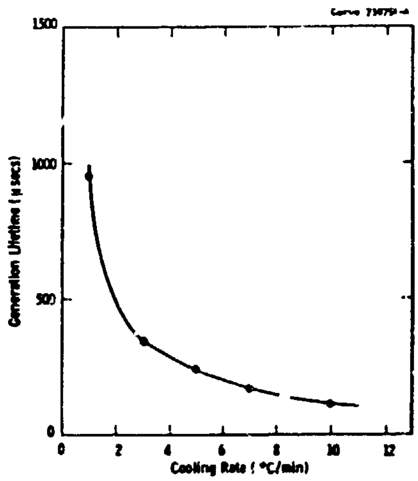


Effect of Quench Temperature and Cooling Rate on Generation Lifetime

Table 4 — Effect Of Quench Temperature Of Lifetime And Defects In FZ Silicon[a]

Quench Temperature, °C	Lifetime, μs
500	2012
600	2000
700	850
800	73
900	40

[a]Oxidation Was Performed At 1100°C With 1% HCl By Using Back-Surface Damaged Wafers And A Cooling Rate Of 1°C/Min.

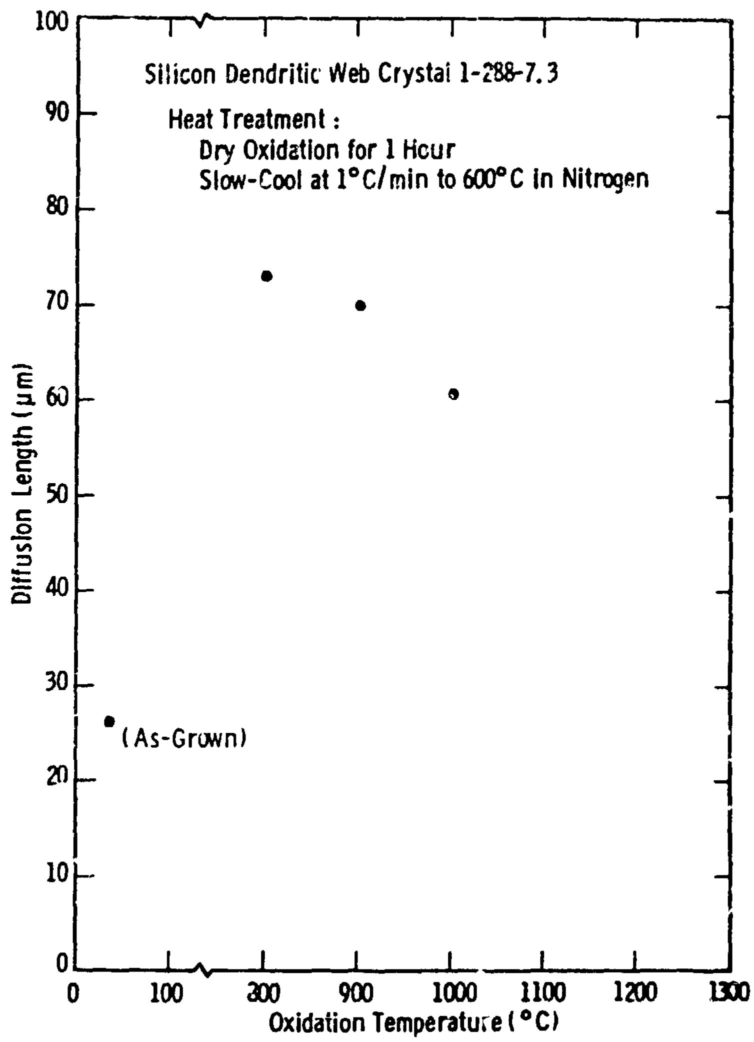


Effect of Process Sequence on Lifetime in FZ Silicon

Process	Lifetime (us)
1% HCl Oxidation At 1100°C Slow Cooled ↓	2115
1 Hr Anneal in N_2 At 1100°C Quenched ↓	50
1 Hr Anneal in N_2 At 1100°C Slow Cooled	1400
1% HCl Oxidation At 1100°C Quenched ↓	60
1 Hr Anneal In N_2 At 1100°C Slow Cooled ↓	1650
1 Hr Anneal In N_2 At 1100°C Quenched	40

Back Surface Of The Samples Was Damaged

Effect of Dry Oxidation Temperature on SPV Diffusion Length for a Dendritic-Web Silicon Crystal



Diffusion-Length Map of Web Crystals as a Function of Cell Processing

Sample ID	Crystal ID	As Grown L (μm)	After BSF L (μm)	After $POCl_3$ L (μm)	After Passivation L (μm)
#2	4.229 – 4.2 (0.5 Ω-cm)	27	51	41	30
#3	4.227 – 2.4 (1.0 Ω-cm)	27	51	22	26
#5	4.225 – 3.2 (1.5 Ω-cm)	23	–	9	40
#25	1.288 – 5.5 (4 Ω-cm)	24	–	52	76
#26	1.288 – 5.6 (4 Ω-cm)	28	–	124	60
#90	1.288 – 7.4 (4 Ω-cm)	26	–	110	88
#26	2.244 – 6.4 (4 Ω-cm)	25	40	71	63
#28	2.244 – 7.3 (4 Ω-cm)	22	74	76	80
#76	3.155 – 11.7 (4 Ω-cm)	19	151	124	73
#77	3.155 – 15.5 (4 Ω-cm)	23	50	78	–
#79	3.155 – 15.3 (4 Ω-cm)	16	–	91	103
FZ	Wacker 0.25 Ω-cm	216	220	220	225

Note: On 4 Ω-cm Web Crystals AESD Made Baseline Cells (n^+–p–p^+ With 14.5 – 15% Efficiencies

Effect of Residual Stress on Diffusion Length in Web Silicon Before and After 960°C Boron Diffusion

Crystal	Residual Stress $Mdyne/cm^2$	Diffusion Length As-Grown Microns	Diffusion Length After BBr_3 Microns
Z-025-3.4	14	19	16
Z-025-3.10	40	16	23
Z-025-3.15	42	16	12
Z-028-12.4	< 5	25	27
Z-028-12.10	< 5	40	-
Z-025-12.16	< 5	33	116
R-461-5.3	< 5	17	39
R-461-5.8	< 5	9	-
R-461-5.13	< 5	10	83

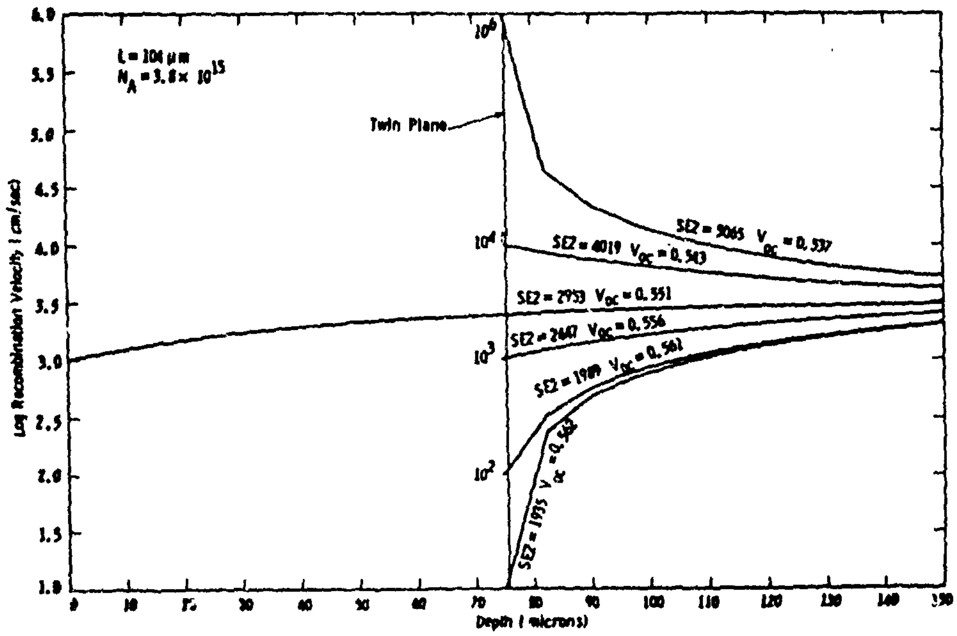
Note:

1. Crystal Z-025 Was Grown With J435 Configuration And Crystals Z-028 And R-461 Were Grown With J460L Configuration;
2. Web Was 4 Ohm-cm, P-type

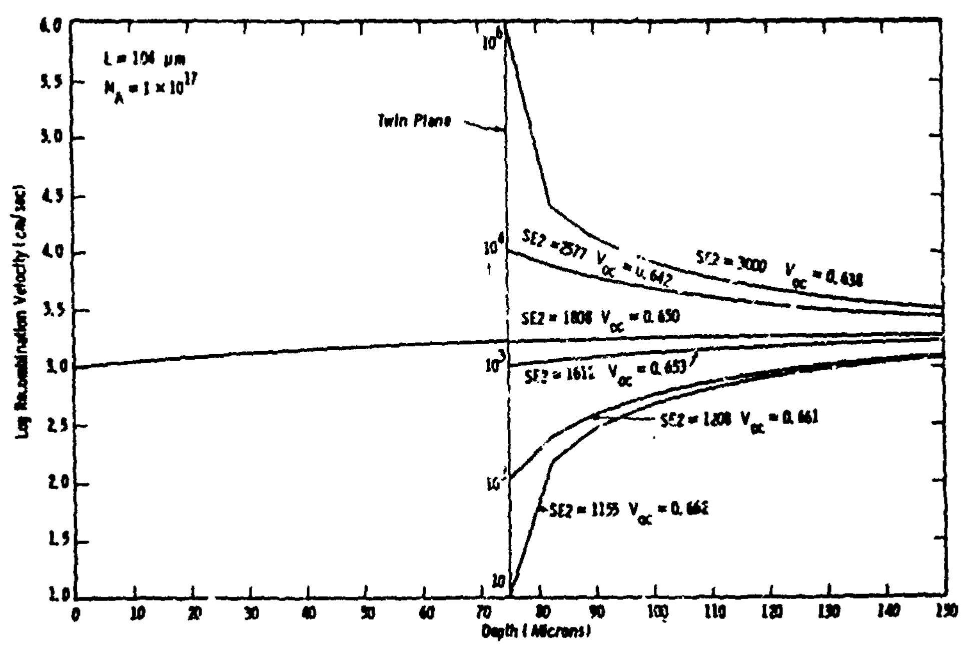
Observations:

1. Diffusion Length For Web Crystal With High stress (Z-025) Did Not Improve After Boron Diffusion;
2. In Three Of Four Samples With Low Stress, The Diffusion Length Improved Appreciably After Boron Diffusion

Model Calculations for the Effect of Electrical Activity of the Twin Plane on V_{OC} in 4 ohm-cm Web Cells



Cell Model Calculations



Calculated AM1 Performance of Standard and Low-Resistivity Web Cells With Base Diffusion Length as a Parameter

A. 4 Ohm-cm (3.5e15/cm^3) P-Type, 150 Microns Thick

Ln (Microns)	J_{oe} (A/cm^3)	J_{ob} (A/cm^3)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff (%)	Eff' (%)
10	1.6e-12	32.1e-11	24.6	.471	.793	9.2	8.3
30	1.6e-12	9.5e-11	30.6	.508	.802	12.5	11.2
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150	1.6e-12	2.0e-11	36.5	.551	.815	16.4	14.8
300	1.6e-12	1.1e-11	37.6	.566	.819	17.4	15.7

B. 0.2 Ohm-cm (1.0e17/cm^3) P-Type, 150 Microns Thick

Ln (Microns)	J_{oe} (A/cm^3)	J_{ob} (A/cm^3)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff (%)	Eff' (%)
10	1.6e-12	7.5e-12	24.2	.563	.817	11.1	10.0
30	1.6e-12	2.5e-12	30.0	.589	.824	14.6	13.1
60	1.6e-12	1.2e-12	33.0	.601	.826	16.4	14.8
150	1.6e-12	0.6e-12	35.1	.609	.831	17.8	16.0
300	1.6e-12	0.5e-12	35.7	.611	.832	18.1	16.3

Note:

1. Calculations Were Made Using Martin Wolf's Program SPCOLAY.BAS
2. Calculated Values Do Not Account For Grid Shadowing, Light Reflection, Or Resistive Losses. In Order To Estimate These Effect, The Calculated Efficiency (Eff) Was Multiplied By 90% To Give A More Realistic Efficiency (Eff').
3. The Model Accounts For Variation In Doping Density In The Emitter And In The Back Region. For Both The n+p And p+p Regions The Junction Depth Was Taken To Be 0.3 Microns With A Surface Concentration Of 8.0e19/cm^3.
4. S_{front} = 10^4 cm/sec (AR On Bare Si); S_{back} = 10^6 cm/sec (Metal on Si)

Effect of Oxide Passivation on 4 ohm-cm FZ Silicon

Table 1 - Baseline Unpassivated Solar Cells (n^+-p-p^+) Fabricated On 4 Ohm-cm Float Zone Silicon

Cell ID	Short Circuit Current J_{sc} mA/cm^2	Open Circuit Voltage V_{oc} Volts	Fill Factor	Cell Efficiency %
1	33.3	0.582	0.767	14.8
4	32.9	0.581	0.772	14.7
6	33.4	0.583	0.780	15.2

Table 2 - Oxide-Passivated Solar Cells On Boron-Doped 4 Ohm cm Float-Zone Silicon

Cell ID	J_{sc} (mA/cm^2)	V_{oc} (Volts)	FF	η (%)
HIEFY 4-4	36.1	0.599	0.794	17.1
-5	36.2	0.600	0.793	17.2
-7	36.2	0.599	0.791	17.2

• Improvements: $\Delta J_{SC} \sim 3\ mA/cm^2$, $\Delta V_{OC} \sim 20\ mV$, $\Delta\eta \sim 2\%$

$\Delta J_o \sim$ Factor Of Two

Solar-Cell Data on 4 ohm-cm Web With and Without Oxide Passivation

Cell ID	Short-Circuit Current J_{sc} (mA/cm^2)	Open-Circuit Voltage V_{oc} Volts	Fill Factor	Cell Efficiency (%)
		Without Passivation		
W6	32.7	0.575	0.782	14.7
W7	33.1	0.577	0.784	15.0
		With Oxide Passivation		
W1	34.6	0.584	0.784	15.9
W2	34.5	0.586	0.794	15.8