

**DEVELOPMENT OF HIGH-EFFICIENCY
SOLAR CELLS ON SILICON WEB**

WESTINGHOUSE ELECTRIC CORP.

A. Rohatgi
D.L. Meier
P.B. Campbell
R.G. Seidensticker
P. Rai-Choudhury

Tasks

- **Perform Model Calculations to Design High Efficiency Web Cells**
- **Investigate the Influence of Twin Planes, Trace Impurities and Heat Treatment to improve Minority Carrier Lifetime in Web**
- **Develop and Optimize Advanced Design Features, Like Passivation, AR Coating and Back Surface Reflector**
- **Fabricate High Efficiency Web Cells With Efficiency Approaching 18%**

HIGH-EFFICIENCY DEVICE RESEARCH

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

A. 4 Ohm-cm ($3.5 \times 10^{15}/\text{cm}^3$) 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	1.6×10^{-12}	32.1×10^{-11}	24.6	.471	.793	9.2	8.3
30	1.6×10^{-12}	9.5×10^{-11}	30.6	.508	.802	12.5	11.2
60	1.6×10^{-12}	5.3×10^{-11}	33.2	.525	.809	14.1	12.7
150	1.6×10^{-12}	2.0×10^{-11}	36.5	.551	.815	16.4	14.8
300	1.6×10^{-12}	1.1×10^{-11}	37.6	.566	.819	17.4	15.7

B. 0.2 Ohm-cm ($1.0 \times 10^{17}/\text{cm}^3$) 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	1.6×10^{-12}	7.5×10^{-12}	24.2	.563	.817	11.1	10.0
30	1.6×10^{-12}	2.5×10^{-12}	30.0	.589	.824	14.6	13.1
60	1.6×10^{-12}	1.2×10^{-12}	33.0	.601	.826	16.4	14.8
150	1.6×10^{-12}	0.6×10^{-12}	35.1	.609	.831	17.8	16.0
300	1.6×10^{-12}	0.5×10^{-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 $8.0 \times 10^{19}/\text{cm}^3$.
4. $S_{\text{front}} = 10^4 \text{ cm/sec}$ (AR On Bare Si); $S_{\text{back}} = 10^6 \text{ cm/sec}$ (Metal on Si)

HIGH-EFFICIENCY DEVICE RESEARCH

Resistivity and Diffusion Length Requirements
for 17.5%-Efficient Web Solar Cells

$W = 150 \mu\text{m}$

$S_{0n^+} = 500 \text{ cm/sec}$

$S_{0p^+} = 500 \text{ cm/sec}$

$N_s = 2 \times 10^{20} \text{ cm}^{-3}$

$N_{xj} = 3 \times 10^{17} \text{ cm}^{-3}$

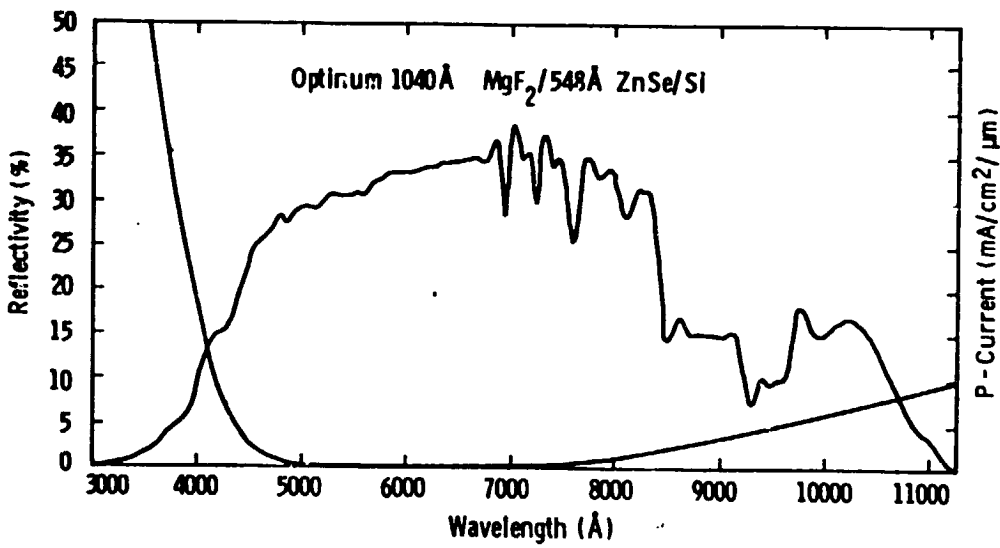
$S_{p-p^+} = 100 \text{ cm/sec}$

ρ $\Omega\text{-cm}$	L μm	J_{sc} ma/cm^2	V_{oc} Volts	η %
4.0	360	35	.589	17.0
4.0	467	35.2	.597	17.5
0.2	360	35.0	.643	18.8
0.2	125	33.2	.634	17.5

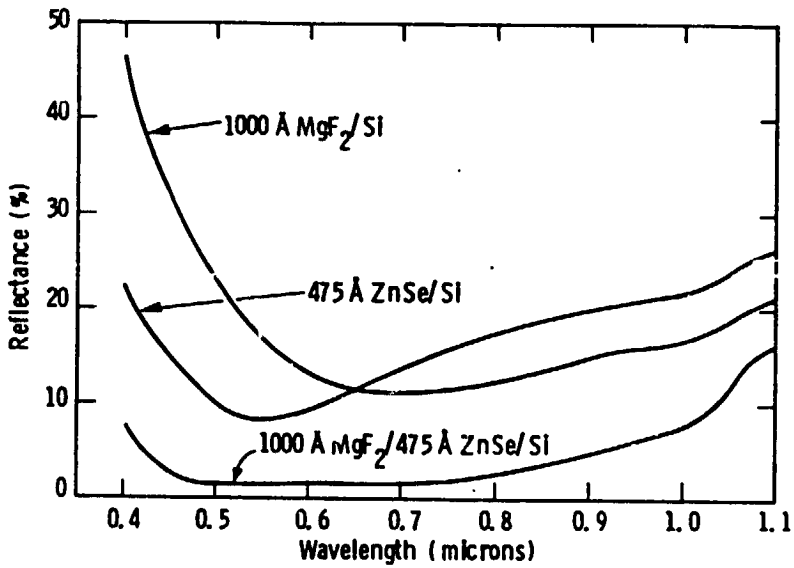
Solar-Cell Data on 4 Ohm-cm Web With
and Without Oxide Passivation

Cell ID	Short-Circuit Current J_{sc} (mA/cm^2)	Open-Circuit Voltage V_{oc} Volts	Fill Factor	Cell Efficiency (%)
<u>Without Passivation</u>				
W6	32.7	0.575	0.732	14.7
W7	33.1	0.577	0.784	15.0
<u>With Oxide Passivation</u>				
W1	34.6	0.584	0.784	15.9
W2	34.5	0.586	0.794	15.8

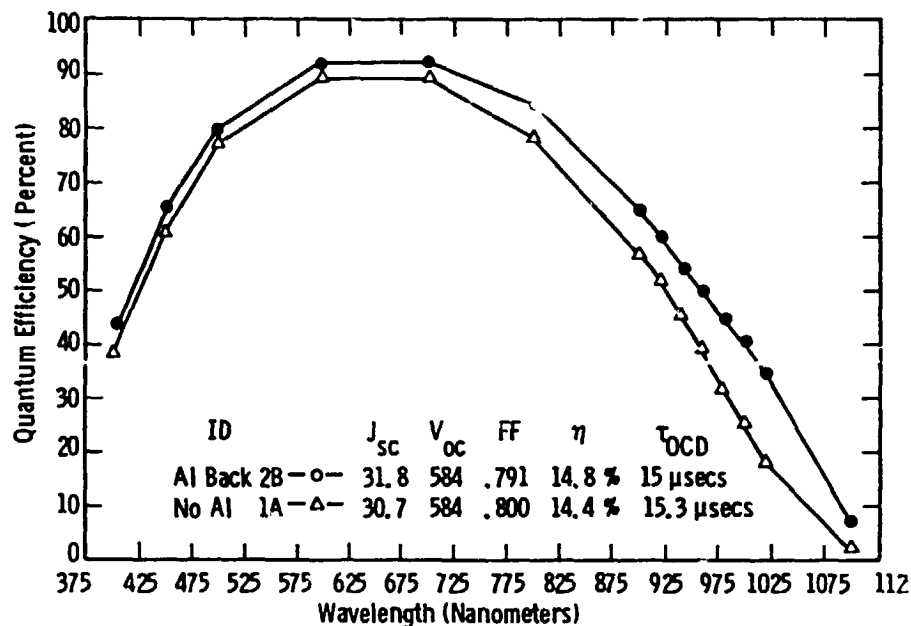
HIGH-EFFICIENCY DEVICE RESEARCH



Experimentally Determined Reflectance Curves for
 (a) 1000 Å MgF₂/Si; (b) 475 Å ZnSe/Si, and
 (c) 1000 Å MgF₂/475 Å ZnSe/Si



Effect of Aluminum Back-Surface Reflector
on Web Cell Performance



Baseline Web Solar Cells on 0.37 Ohm-cm Web
(Crystal No. 4-275) Without AR Coating,
Back-Surface Reflector, and Oxide Passivation

Cell ID	J_{sc} mA/cm ²	V_{oc} mV	FF	Efficiency %
6-1-2	21.3	579	.790	9.7
6-2-6	21.6	575	.803	10.0
6-3-6	22.1	574	.778	9.9

Hiefy 20, Qual.

Crystal #6

AM1, 100 mW/cm² Illumination

HIGH-EFFICIENCY DEVICE RESEARCH

Low-Resistivity (0.37 Ohm-cm) High-Efficiency Web Solar Cells With Surface Passivation, BSR and Evaporated Double-Layer AR Coating

Cell ID	Area cm ²	J _{sc} mA/cm ²	V _{oc} mV	FF	η %
1-1	1.0	35.2	600	0.800	16.9
1-2	1.0	35.2	600	0.800	16.9
1-3	1.0	35.0	598	0.802	16.8
1-4	1.0	34.9	598	0.800	16.7
1-5	1.0	35.2	596	0.793	16.7
1-6	1.0	35.1	596	0.792	16.6

*Run # Hiefy 20, Web #1

*AM1, 100 mW/cm² illumination

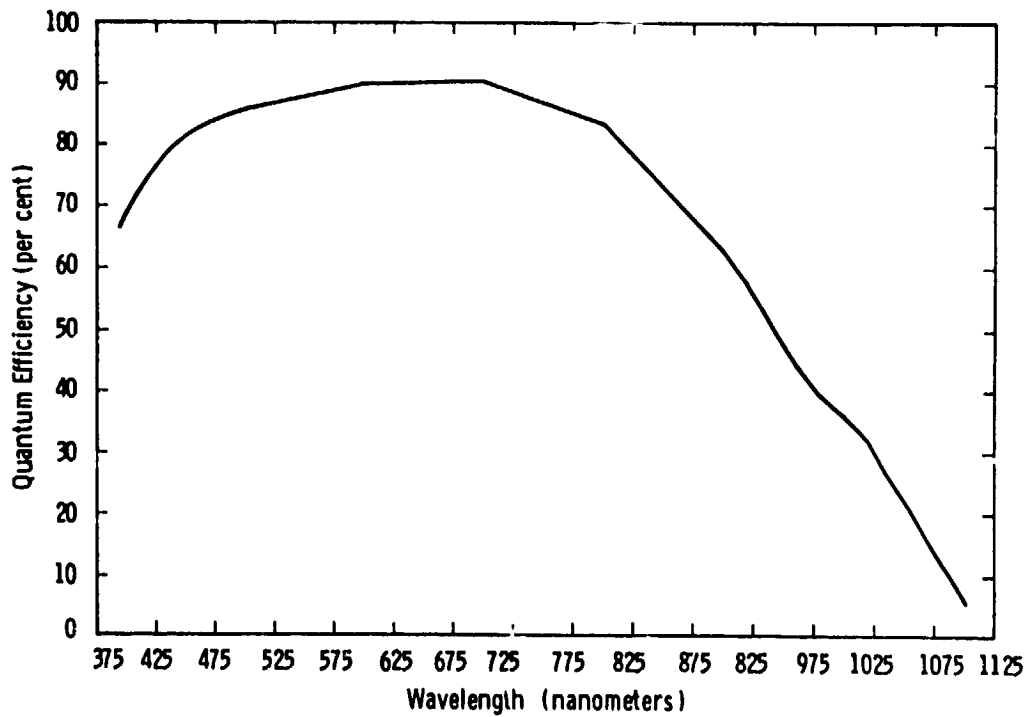


Fig. 6 - Internal quantum efficiency versus wavelength plot for 16.9% efficient web solar cell with oxide passivation, evaporated double-layer AR coating and aluminum back-surface reflector (hiefy 20, web 1-4)

HIGH-EFFICIENCY DEVICE RESEARCH

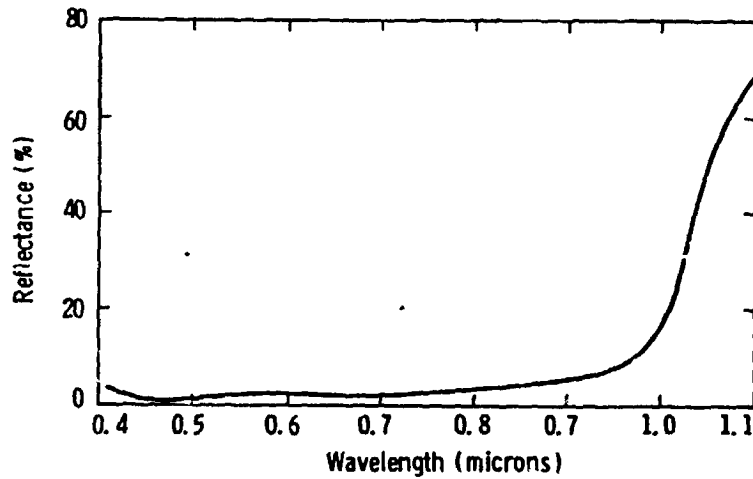


Fig. 8 -- Reflectance as a function of wavelength for 16.9% efficient wet cell with oxide passivation, evaporated Zn Se + MgF₂ double-layer antireflective coating, and aluminum back-surface reflector

**Diffusion Length in Low-Resistivity Web Crystal
No. 4-275, Which Gave 16.9%-Efficient Web Cells**

As Grown Crystal - 30 μ m - SPV

Processed Cell - 90 μ m - SPV

150 μ m - OCVD

HIGH-EFFICIENCY DEVICE RESEARCH

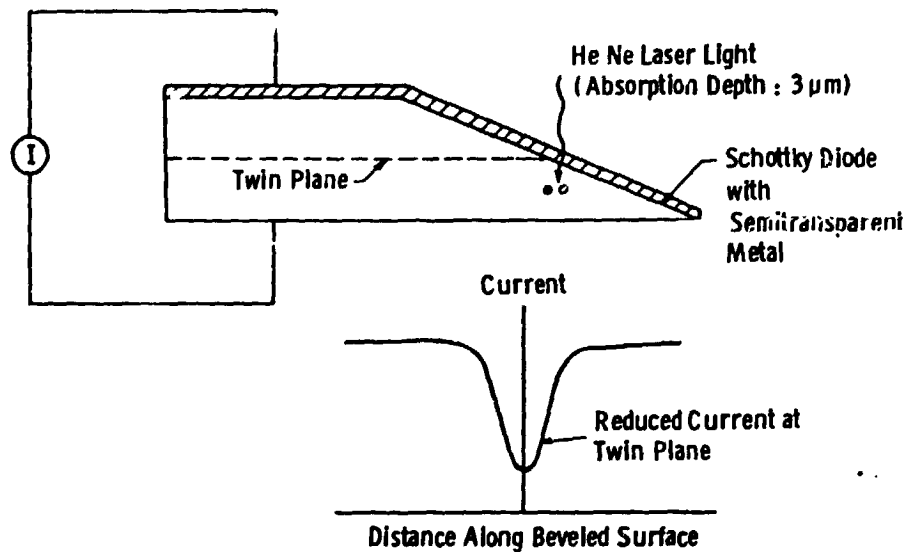


Fig. 6--Sensing the electrical activity of the twin plane with light-beam-induced current (LBIC)

Examples of Large-Area Web Cells With Ratio of Twin Plane Depth to Minority Carrier Diffusion Length as a Parameter

Twin Plane Depth Diffusion Length	Diffusion Length μm	Twin Plane Depth μm	Cell Thickness μm	J_{sc} mA/cm^2	V_{oc} V	FF	Eff %
0.33	78	26	153	31.4	0.591	0.81	15.1
0.50	116	58	164	31.6	0.591	0.81	15.3
0.72	86	62	133	30.8	0.591	0.81	14.9
0.84	61	51	130	30.9	0.590	0.80	14.6
1.14	50	57	132	30.8	0.589	0.80	14.5
1.52	65	99	165	31.1	0.589	0.81	14.9

Notes: 1. Cell Size is 9.8×2.5 cm, and Base is Boron-Doped to 4 Ohm-cm.

2. Cell Data Acquired Using AM1 Spectrum, $100 \text{ mW}/\text{cm}^2$ Intensity at Room Temperature.

3. Diffusion Length Measured by Surface Photovoltage Technique.

Observations: For Cells Where Twin Plane Depth \ll Diffusion Length, the Carrier Recombination at the Twin Planes is Not Significant Compared to Recombination in the Bulk.

HIGH-EFFICIENCY DEVICE RESEARCH

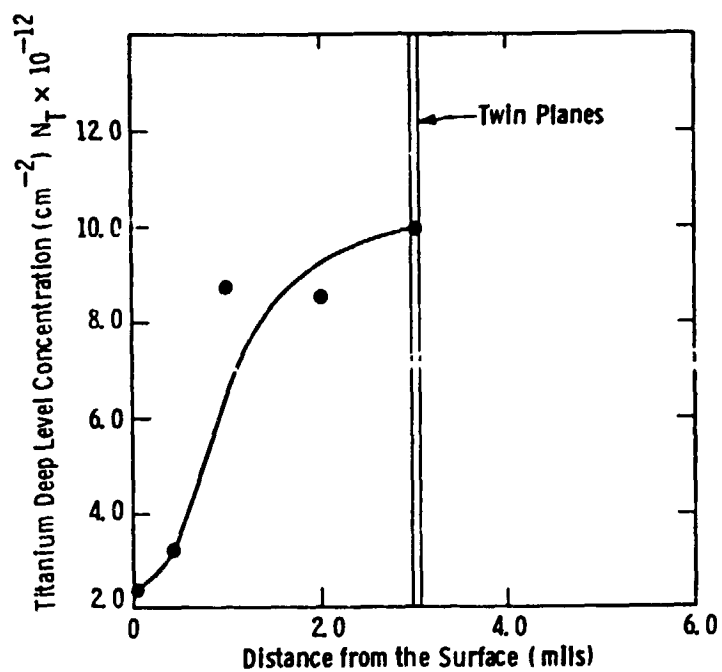
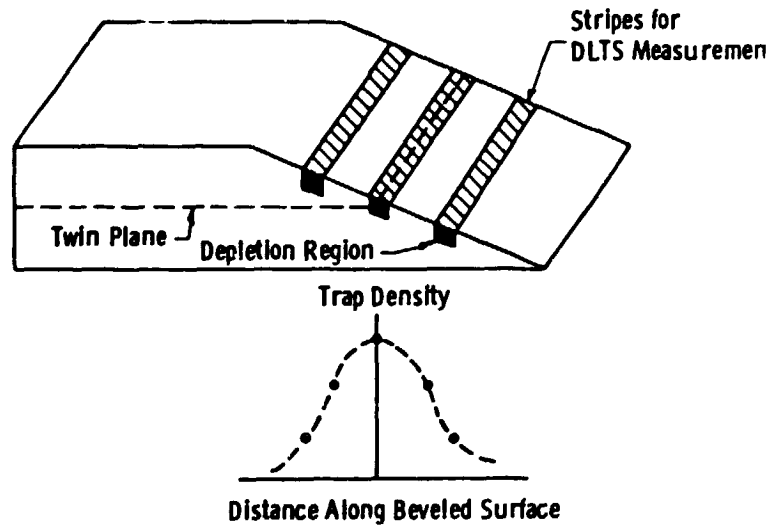


Fig. 5—DLTS study of the interaction between grown-in Titanium impurity and the twin planes in dendritic web silicon

HIGH-EFFICIENCY DEVICE RESEARCH



- Use a Grown-In Impurity (TI, V) as an Internal Tracer
- Observe Trap Density as a Function of Distance from Twin Plane, Both As-Grown and After Processing (Including Gettering)
- Compare Web Having High Diffusion Length with Web Having Low Diffusion Length (As Determined by SPV) Using this Technique

Fig. 1—Detecting and Identifying Impurities piled up at the twin plane by DLTS

HIGH-EFFICIENCY DEVICE RESEARCH

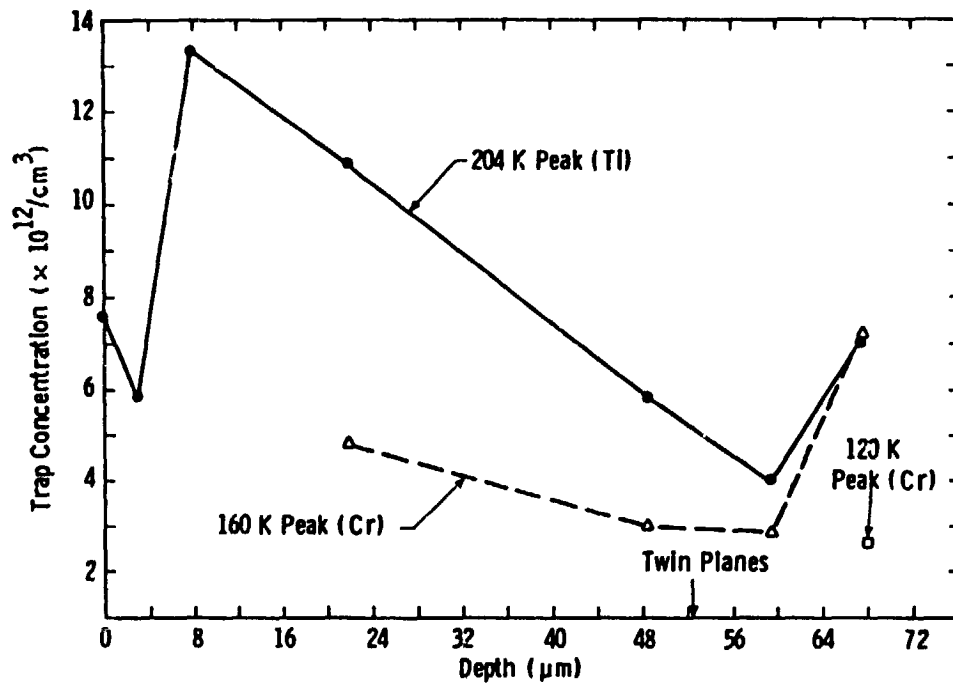


Fig. 3—Depth profile of traps detected by DLTS for TI-doped dendritic web silicon crystal J167-1.1, as-grown. (Sample #T4 from Run TP-4). Web crystal is 4 ohm-cm, p-type