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RELATIONSHIP OF DISLOCATION DENSITY OF SILICON TO SOLAR CELL CURRENT LOSS AT LOW TEMPERATURE

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SUMMARY

Large decreases in short circuit current of silicon solar cells have been reported to occur as temperature is decreased below -60° C. The low temperature-large current loss effect was reported as prevalent in crucible-grown, Czochralski, silicon cells but not in low-oxygen-content silicon cells. Consequently, the effect was attributed to the activity of oxygen in silicon. Experimental results are presented which relate high dislocation density of the silicon bulk material of cells to the large current loss effect.

Solar cells were made by the same processes from a variety of silicon materials, namely low-dislocation-density, high-dislocation-density float-zone, and Czochralski silicon. Based upon measurements of low-temperature minority carrier diffusion length and short-circuit current most cells could be categorized as: "poor", having a large decrease in diffusion length and current at low temperature, or "good", having a comparatively low loss of current and diffusion length at low temperature.

All cells were etched in a manner which revealed the dislocation density of the cell bulk silicon. It was found that every cell made from any of the various low-dislocation starting materials obtained from three suppliers still had a low-dislocation bulk after cell processing, and that all such cells belonged to category "good". Cells made from float-zone materials showed high dislocation densities in their bulk and either fell into category "poor", or had intermediate losses of short-circuit current at low temperature. Cells made from Czochralski material had, in most cases, high bulk dislocation density and, in this event, fell into category "poor". However, a few cells from the seed end of Czochralski ingots had low dislocation density and fell into category "good". These results reveal a direct relationship between low bulk dislocation density and low current loss at low temperature. Oxygen content does not appear to play a significant role in the low temperature-large current loss effect, since some Czochralski cells did not suffer from this effect whereas some float-zone cells did. Other float-zone silicon cells had only medium current losses at low temperature despite their high bulk dislocation density. It appears that use of low-dislocation-density silicon can eliminate the current loss problem in low temperature cell operation.

INTRODUCTION

Irregularities in low-temperature behavior of cells were noted several years ago in a study made of thin cells (1). More detailed studies (2, 3) revealed that an abnormally high loss in short-circuit current occurred for many cells as temperature was decreased below -60° C. The low temperature-large current loss effect was attributed to the activity of oxygen in silicon (2) since it was prevelant in crucible-grown Czochralski silicon cells but not in low-oxygen-content silicon cells. However there were a few Czochralski cells that did not suffer current losses greater than those of low-oxygen-content cells (2).

The study reported was undertaken to obtain more information on the cause of the low temperature-large current loss effect. In the prior work, the dislocation density of the silicon bulk of cells was not considered as a possible influence upon cell behavior. However, it is known that Czochralski ingots may contain low-dislocation-density silicon (4) and that dislocations do affect minority carrier lifetime in silicon (5). Bulk dislocation densities were therefore measured for all cells in this study and compared with current losses at low temperatures.

EXPERIMENTAL MEASUREMENTS

Cell Types

A variety of 1 x 2 cm^2 cells were made by similar fabrication processes but from differing silicon materials. Cell surfaces were clean, etch polished, and without antireflective coatings to eliminate coating effects on measured currents.

The various materials used in the study were as follows:

1. Czochralski 10 ohm-cm ingots grown at NASA-LeRC were cut into three sections which were labelled Top (Seed End), Middle, and End. Processed cells were identified in terms of the section and specific ingot from which they were made.

2. Low-dislocation-density ingots from three suppliers of silicon were processed into cells. These cells were designated Lopex (6), Perfex (7) and Monex (8) in accordance with the supplier's tradename.

3. Float-zone ingots from one supplier were

(a) Processed directly into cells labelled D.C.F.Z.

(b) Rezoned at Lewis and processed into cells labelled Lewis F.Z.

Diffusion Length

Low-temperature minority carrier diffusion lengths were measured using the Lewis x-ray diffusion length measurement system (9). The cell under test was mounted on a liquid-nitrogen-cooled baseplate in an evacuated enclosure for the measurement. The method of measurement was identical to that in the reference cited.

Short-Circuit Current

The test cell was mounted on a ceramic plate with provision for making top and bottom contacts to the cell. The plate was placed in a styrofoam dish positioned beneath a bank of tungsten lamps. Liquid nitrogen was poured into the dish to a specific depth. The lamps were operated at low voltage and low intensity so that the cell current was determined primarily by the long-wavelength response of the cell bulk. Intensity was kept at a constant level by monitoring the current of a control cell illuminated by the lamps. The currents so measured are designated $I_{sc}(-196^\circ\ C)$. Each cell was tested to ensure that the I_{sc} measured was not affected by a barrier formed at the back contact at low temperature (2).

Dislocation Density

Upon completion of the electrical measurements, the contacts were removed from the cells by immersion in nitric acid. The cell wafer was then placed in Dash etch (10), 1 part HF, 3 parts HNO_3, 10 parts acetic acid, for 16 hours. After rinsing and drying, the wafers were examined under a low power (10X) microscope and classified according to the following criteria:

(1) LO - Surfaces showing few, if any etch pits. A LO dislocation density is similar to that of nonprocessed 10 ohm-cm wafers cut from dislocation-free material.

(2) LO-MED - Large surface areas free of etch pits but one or more small areas where the etch pit density was so high that the pits merged into one another. LO-MED represents densities observed on 1 ohm-cm dislocation-free wafers.

(3) HIGH - Etch pits covering most of the surface with pits merging into one another. HIGH is a representative designation for float-zone silicon dislocation densities.

RESULTS AND DISCUSSION

The effect of decreasing temperature on minority carrier diffusion length is shown in figure 1. "Good" cell behavior is characterized by small decreases in diffusion length over the +25° C to -196° C temperature range. "Poor" cell behavior is manifested by rapidly decreasing diffusion lengths as temperature is decreased below -60° C. "Fair" cell behavior designates intermediate diffusion length decreases. Figure 2 shows the spread of short circuit currents at -196° C for "good" and "poor" cells. Also shown is the current spread for all cells measured at room temperature. It is seen that at low temperature, "poor" cells suffer a large loss in current as well as in diffusion length. The short circuit currents at 25° C of all cells used in this study were within 5 percent of each other indicating that similar diffusion lengths existed in all cells at this temperature.

Numerical values of current and diffusion length of cells at low temperature are compared in Table I. The data show that the cells can be validly sorted into categories of "good" or "poor" based upon the rapid and simple current measurement described. Normally, cell currents and diffusion lengths are not simply related because cell current is determined by antireflective coatings and junction depths in addition to diffusion length. However, in this investigation, emphasis was placed upon making all cells by the same processes and making current measurements on clean bare cells so that differences in cell currents could be validly considered as representing differences in their diffusion lengths. Also, the light source provided a long wavelength spectrum fostering strong dependency of cell current on cell diffusion length.

Table II presents $I_{sc}(-196^\circ\ C)$ measurements for a number of cells made from different sections of a Czochralski ingot. As shown "good" (low current loss) cells were made only from the top part of the Czochralski ingot. These results held true for cells made from several Czochralski ingots.

Dislocation densities were measured on cells from each ingot section. The results are shown in Table III. These data indicate that those Czochralski seed-end cells which had low current losses also had lower bulk dislocation densities.

A study was also made of cells fabricated from low-dislocation (e.g., Lopex, Monex, Perfex) and high-dislocation (e.g., float-zone) silicon material. These materials are generally accepted to be low in oxygen content. Table IV compares the $I_{sc}(-196^\circ\ C)$ for these types of cells. It is seen that cells made from low-dislocation silicon are clearly superior, having the lowest current loss at low temperature. Furthermore, numerous cells (not shown in Table IV) made from other Lopex ingots including resistivities in the 0.5 - 1.0 ohm-cm range were also free of the current loss effect.

Comparison of I_{sc}(-196° C) in Tables III and IV shows that oxygen content does not appear to play a vital role in determining the low-temperature current loss. As shown, some low oxygen content F.Z. cells have large current losses whereas some high oxygen content Czochralski cells have low current losses at low temperature. A similar conclusion was reached from the measurement of oxygen content in a wide range of silicon cell bulk materials using an infrared absorption technique (11). The results (12) showed that no correlations existed between oxygen content and low temperature diffusion length decrease.

The data of Table IV for float-zone cells shows that wide variation in low temperature current loss can occur for cells made from various float-zone materials having high dislocation density. In the case of Czochralski cells which had high dislocation densities, all cells had large losses in current at low temperature. This difference may be due to the higher impurity content of Czochralski materials.

CONCLUSION

A direct correlation between bulk dislocation density and low-temperature current loss was found in this study. Every cell made from low-dislocation-density silicon exhibited a minimum current loss. Cells made from high-oxygen-content Czochralski material can have low current loss at low temperature if the dislocation density of their bulk is low. Silicon material taken from the top of these ingots was found to have low dislocation density and to yield low current loss cells. Current loss at low temperature for float-zone material appears to be variable and possibly influenced by impurity content as well as by dislocation density. This would not be surprising in view of the considerable background literature on impurities interacting with dislocations and thereby changing properties of semiconductor materials.

The important practical information derived from this study is that, apparently, the most reliable way of making high efficiency cells for low temperature application is to use low-dislocation-density silicon material.

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Table I. - CORRELATION OF DIFFUSION LENGTH AND I_{sc} AT LOW TEMPERATURE

Cell	Category	I_{sc}(-196°C)[a] (μA)	L(-183°C)[b] (microns)
261-9	Poor	600	38
272-1	Poor	550	34
242-10	Poor	500	38
275-10	Fair	840	82
242-5	Fair	860	87
242-15	Fair	990	97
261-3	Good	1100	140
252-14	Good	1150	155
242-3	Good	1250	160

[a] I_{sc} under long wavelength low intensity illumination at -196°C

[b] L, minority carrier diffusion length at -183°C

Table II. - COMPARISON OF CELLS FROM DIFFERENT SECTIONS OF A CZOCHRALSKI INGOT

Category (I_{sc}(-196° C) Range)	Number of Wafers		
	Top Section	Middle Section	End Section
Good (1000-1200 μA)	5	-	-
Fair (800-950 μA)	7	-	-
Poor (500-600 μA)	-	11	7
Total Wafers	12	11	7

Table III. - TYPICAL CHARACTERISTICS OF HIGH OXYGEN CONTENT CZOCHRALSKI CELLS

Cell	Section[a]	Category	I_{sc}(-196° C) (μA)	Dislocation Density
260-14	T	Good	1150	LO
250-5	T	Good[b]	1000	LO-MED
264-16	M	Poor	500	HIGH
266-3	M	Poor	500	HIGH
260-1	E	Poor	425	HIGH

[a] Section of ingot, T-Top, M-Middle, E-End

[b] Borderline

Table IV. - COMPARISON OF DISLOCATION-FREE AND FLOAT-ZONE LOW OXYGEN CONTENT SILICON CELLS

[All cells are 10 Ω-cm except where noted]

No. of Cells	Ingot	Category	I_{sc}(-196° C) (μA)	Dislocation Density
9	Lopex[a]	Good	1180-1220	LO
2	Monex[b]	Good	1100-1150	LO
4	Perfex[c]	Good	1100-1140	LO
4	D.C. FZ[d]	Fair	860-1000	HIGH
6	Lewis FZ[e]	Poor	540-680	HIGH

[a] Lopex, Texas Instruments Inc. (10-20 Ω-cm)

[b] Monex, Monsanto Co.

[c] Perfex, Dow Corning

[d] D.C. FZ, Dow Corning Float-Zone Silicon

[e] Lewis FZ, Dow Corning Float-Zone Silicon Rezoned at NASA-Lewis Research Center

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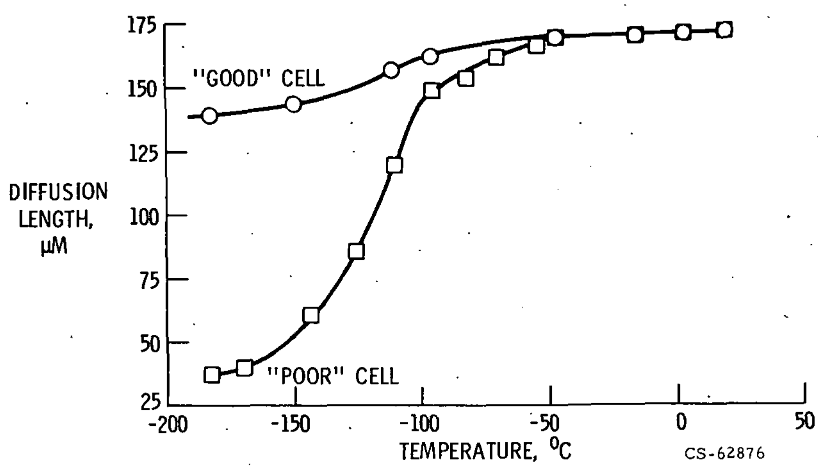

Figure 1. - Variation of diffusion length with temperature for two categories of cells.

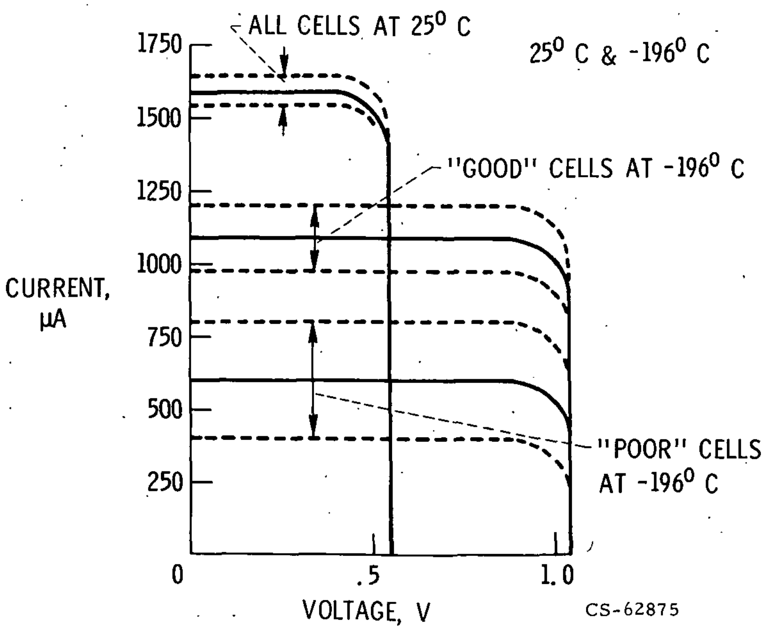

Figure 2. - Current-voltage characteristics of silicon solar cells.