PROCESS-INDUCED DEFECTS IN TERRESTRIAL SOLAR CELLS

We are not now a grantee or contractor in either ERDA or NSF sponsored solar photovoltaic research. The results we report have derived from research sponsored by NASA (Grant NSG-3018) beginning June 23, 1974 and still in force at $60,000 per year.

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Part of this paper was presented at the 1975 PSC Conference in May in Phoenix; part has never been presented before.
The expectation of good performance has prompted interest in low-
resistivity, shallow-junction solar cells for space applications. Such
devices contain, however, regions of high doping and high impurity gradients.
Hence the physics underlying their operation is complex; many different
mechanisms, traditionally ignored, compete to determine cell behavior.

Thus a major problem in understanding the operation of such cells lies
in determining which of these mechanisms are dominant and which may be
neglected. A second problem, relating to design, lies in controlling both
the dominance and the magnitude of the phenomena via controlling the device
structure and the steps used in fabrication.

These problems are the main undertakings of our research sponsored by
NASA Grant NSG-3018. Our program includes collateral experimental and
theoretical efforts. At present, the experimental effort concentrates on
the fabrication of solar cells and related test devices, and on a detailed
characterization of the current-voltage properties and of the defects that
contribute to them. The experimental tools employed in our study include:
current-voltage measurement and transient-capacitance, thermally-stimulated-
capacitance and thermally-stimulated-current measurements made on pn
junction or Schottky-barrier test vehicles. The theoretical effort anticipates
the dominant contributors to the behavior that need experimental study, provides
a careful interpretation of the experimental data, and seeks full utilization
of the data in calculating its inferences on solar-cell behavior. The theore-
tical and experimental efforts interplay, each guiding the direction of the
other.

Although aimed toward very high-efficiency, low resistivity silicon
solar cells for space applications, the results of our studies reached
thus far have considerable implications for cells of materials, such as
solar-grade silicon, currently being advanced for terrestrial application.
A review of our main findings will help clarify these implications.

To examine the issue of dominance among the high-doping mechanisms, we
have divided them into two broad categories:

1. Gap shrinkage, as produced, for example, by band tilting, impurity-band widening and impurity misfit; and
2. Altered interband transition rates, arising from Auger-impact or SRH processes or from electronic tunneling via defects.

Which of these mechanisms predominates depends, in general, on the physical
make-up of the device, on environmental conditions such as temperature, and
on the aspect of cell performance of interest.

To provide a quantitative illustration, we have taken a concrete example:
a phosphorous diffused n+p cell, junction depth 0.25 microns, impurity grade
constant 10^{23} atoms/cm^4, substrate resistivity 0.1 ohm-cm. Further our
attention has centered on the measured open-circuit voltage at 300K.

To analyze this device, we have extended the traditional analytical
theory of silicon solar cells to enable inclusion of the high doping mechanisms.
Of these mechanisms, we have concluded that gap shrinkage, taken alone in a
one-dimensional model, fails far short of explaining the measured open-circuit
voltage. To fit the data, a gap shrinkage of 0.23 eV would be required for
impurity concentrations only slightly higher than 10^{18} cm^{-3}, which compares
to our upper-bound estimate of 0.07 eV for such concentrations. From a
physical standpoint, we predict gap shrinkage to be small because minority
charges can exist in sizable numbers in the dark cell only where the doping
is relatively small.

...
Of all the other mechanisms described until now in this paper, we have proposed the sharp increase in the defect density near the highly-doped surface to be the most likely candidate to explain the data. This result indicates the desirability of additional experiments concerning the properties of the defects near the surface and their relationship to processing, particularly to the processing now used in the solar-cell technology.

To this point in our review, we have considered a one-dimensional model of the cell, the only coordinate of interest having been that measuring the distance from the surface. But the solar cell is a large area device, and inhomogeneities across this area could play a significant role in governing the performance. In particular, we note the existence of a statistical distribution of impurity clusters, thermodynamically stable, occurring in the diffused layer.

Viewing the overall solar cell as a collection of sub-cells roughly in parallel one with another, we propose that those sub-cells with relatively high doping and defect density can severely degrade the performance of the overall device. Hence the area-inhomogeneity mechanism accompanying high doping could play a dominant role and establish a basic limitation on the performance obtainable. We give experimental indications on devices of our fabrication that suggest the importance of area inhomogeneity.

Our work on low-resistivity, high-efficiency cells has suggested the dominant role that defects take in determining performance. For materials being put forward for terrestrial use (EFG, WEB, polysilicon, etc.), the characterization of the defects and their relation to the fabrication processes used will be even more significant. Research similar to ours, conducted presently with NASA, but extended in scope and aimed toward terrestrial solar cells, could thus provide valuable information to the nation's solar photovoltaic program.
STARTING MATERIAL \rightarrow FABRICATION PROCESSING

SOLAR CELLS & TEST STRUCTURES (N^P, P^N, Schottley)

\rightarrow DEFECTS

\rightarrow CELL EFFICIENCY, ETC.

\rightarrow CHARACTERIZATION

IV
CV
TSC
TSCAP
OC voltage decay
Mapping
HIGH DOPING (1-DIM'L)
[DEGRADING => LIMITATIONS]

I. GAP SHRINKAGE $\Delta E_G$

$Q_{\text{e}^\uparrow} : p \propto n_i^2 e^{\Delta E_G/kT}$

II. INTERBAND TRANSITIONS

$T_{\text{e}^\downarrow} :$
- Auger (high $N$)
- SCR ($T < 300^\circ K$)
- tunneling ($T << 300^\circ K$)

$\tau = \tau [N_D(x)] (T \approx 300^\circ K)$

WHICH DOMINATES $V_{OC}$ (IN 0.1$\Omega$-CM, 300$^\circ$K)?
\[ J = J_D - J_L = 0 \Rightarrow V_{OC} \]

\[ J_D = J_E + J_{SCR} + J_B \]

\[ \frac{qV_{OC}}{kT} \frac{1}{N_A} \]

\[ Q_E \quad Q_{SCR} \quad Q_B \]

H.D. \Rightarrow T_E \downarrow \& Q_E \uparrow
GAP SHRINKAGE

BAND TAILS
(RANDOMNESS)

IMPURITY BAND
(OVERLAP)

STRAIN
(MISFIT)
\[ N_{TT} = K \left( N_D(x) + N_A \right)^M \]

\[ \gamma \to \infty \frac{1}{N_{TT}} \]
Holes in Emitter

$P(x)$ for step junction model

$P(x)$ big where $N_0(x)$ small

$\Rightarrow \Delta E_g$ small

$X = 0$
(SURFACE)

$0.1X_E$
(SCR EDGE)
WHICH DOMINATES? MATCH TO EXPT.

0.1-ohm-cm, 300 K, n^+ p

MEASURED \( V_{OC} = 610 \text{ mV} \)

\[
J_D = J_E + J_{SC} + J_B
\]

\[
J_E = 14.1 J_B
\]

\[
J_E = J_{ET} \begin{pmatrix} F & G & S \end{pmatrix}
\]

field: 0.1 \( \Delta E_G < 15 \)

\( T(x) : 466 \)
CONCLUSION: DOMINANT 1-DIM'L
H.D. MECHANISM IS

\[ N_{TT} = K [N_D(x) + N_A] \]

\[ m = 4 \text{ OR } m = 2 \]

VACANCY COMPLEX OR INCONCLUSIVE

3-DIM'L H.D. MODEL:

IMPURITY CLUSTERS IN LARGE AREA DEVICE

SOME 1-D MECHANISMS SENSITIVE:

\[ \Delta E_G / kT, \quad e^{-m}, \quad T \propto N_D^{-m} \]
Figure 4.4 Experimental I-V curves for the 0.1 Ω-cm N⁺P test cells obtained randomly from wafers C-101 and C-102 respectively.