N76 12500

(a)

PROCESS-INDUCED DEFECTS IN TERRESTRIAL SOLAR CELLS

(b)-(e)

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.

(f)-(g)

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(i)

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 theoretical 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 tailing, 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 300°K.

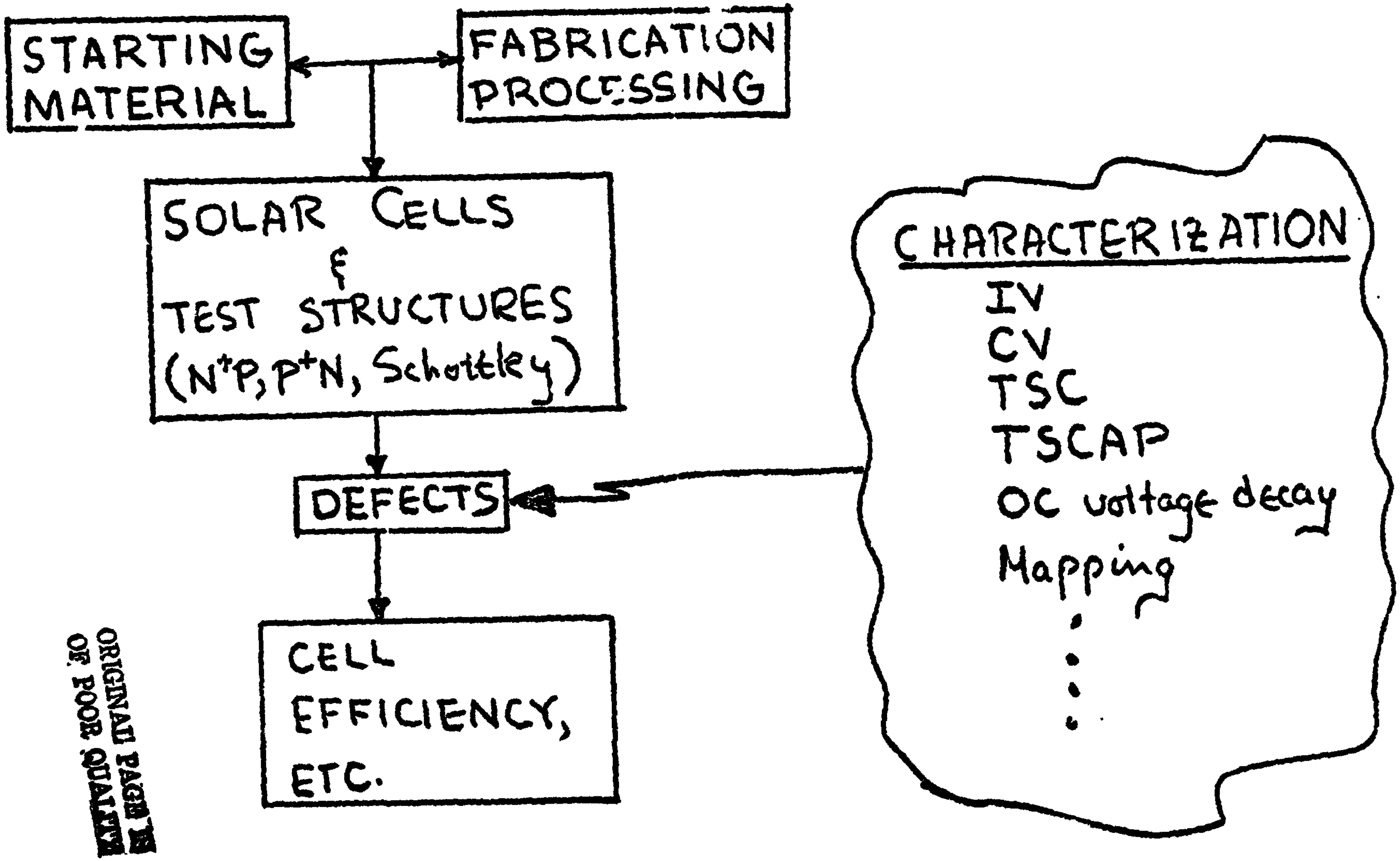
To analyze this device, we have extended the traditional analytical theory of silicon solar cells to enable inclusion of the high doping mechanisms. Of these mechanisms, we have concluded that gap shrinkage, taken alone in a one-dimensional model, falls far short of explaining the measured open-circuit 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 carriers 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
FABRICATION PROCESSING
SOLAR CELLS & TEST STRUCTURES (N^+P, P^+N, Schottky)
DEFECTS
CELL EFFICIENCY, ETC.
CHARACTERIZATION
IV
CV
TSC
TSCAP
OC voltage decay
Mapping
⋮

HIGH DOPING (1-DIM'L)
[DEGRADING => LIMITATIONS]

I. GAP SHRINKAGE ΔE_G

$\boxed{Q_E \uparrow}$: $P \propto n_{io}^2 \, \underline{\underline{e^{\Delta E_G / kT}}}$

II. INTERBAND TRANSITIONS

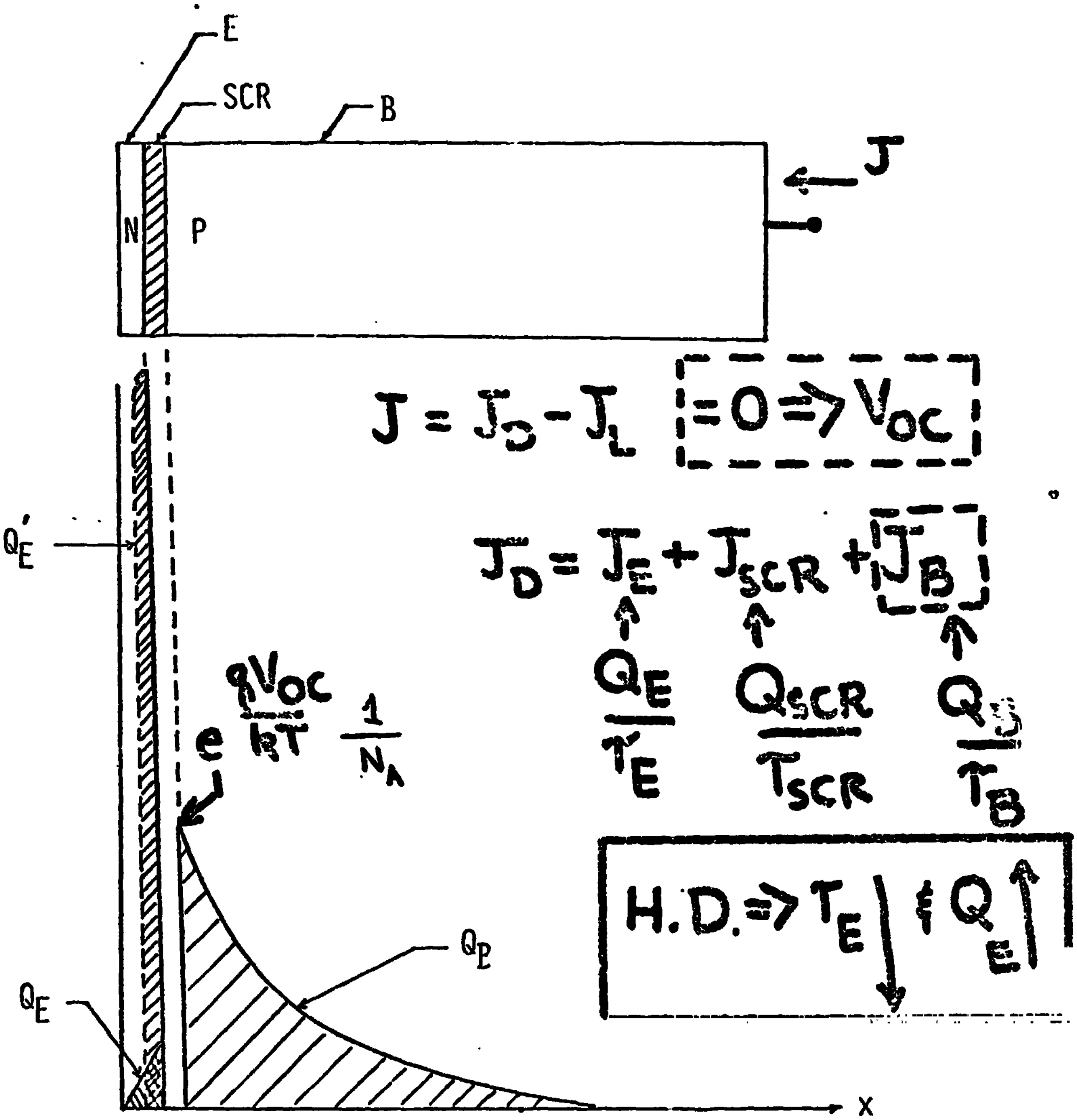
$\boxed{\tau_E \downarrow}$: Auger (high N)

SCR ($T < 300°K$)

tunneling ($T << 300°K$)

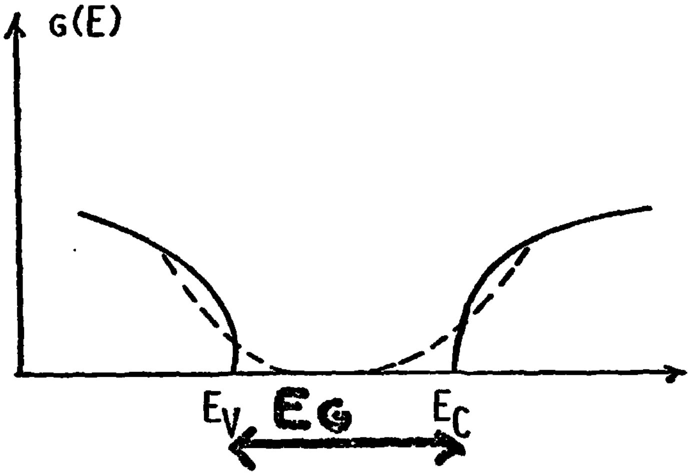
$\tau = \tau[N_D(x)]$ ($T \simeq 300°K$)

WHICH DOMINATES V_{OC} (IN 0.1Ω-CM, 300°K)?

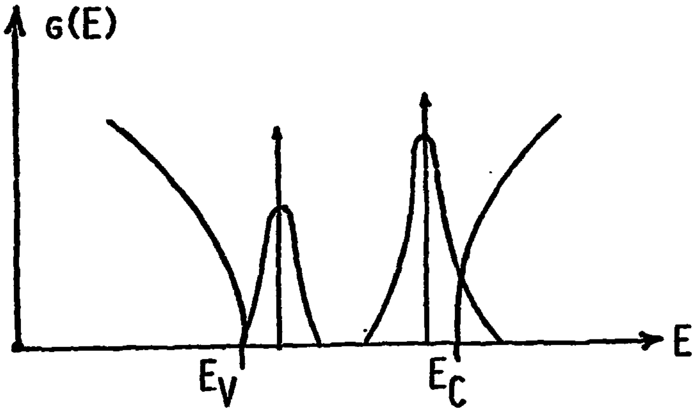

E
SCR
B
N
P
J
$J = J_D - J_L \; \boxed{= 0 \Rightarrow V_{OC}}$
$J_D = J_E + J_{SCR} + \boxed{J_B}$
$\frac{Q_E}{\tau_E}$
$\frac{Q_{SCR}}{\tau_{SCR}}$
$\frac{Q_B}{\tau_B}$
$\boxed{H.D. \Rightarrow \tau_E \downarrow \; \& \; Q_E \uparrow}$
Q_E'
$e^{\frac{qV_{OC}}{kT}} \frac{1}{N_A}$
Q_B
Q_E
x

GAP SHRINKAGE

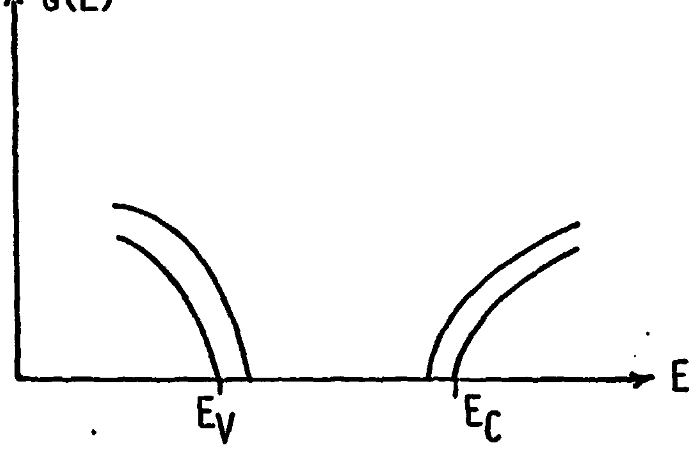
BAND TAILS
(RANDOMNESS)

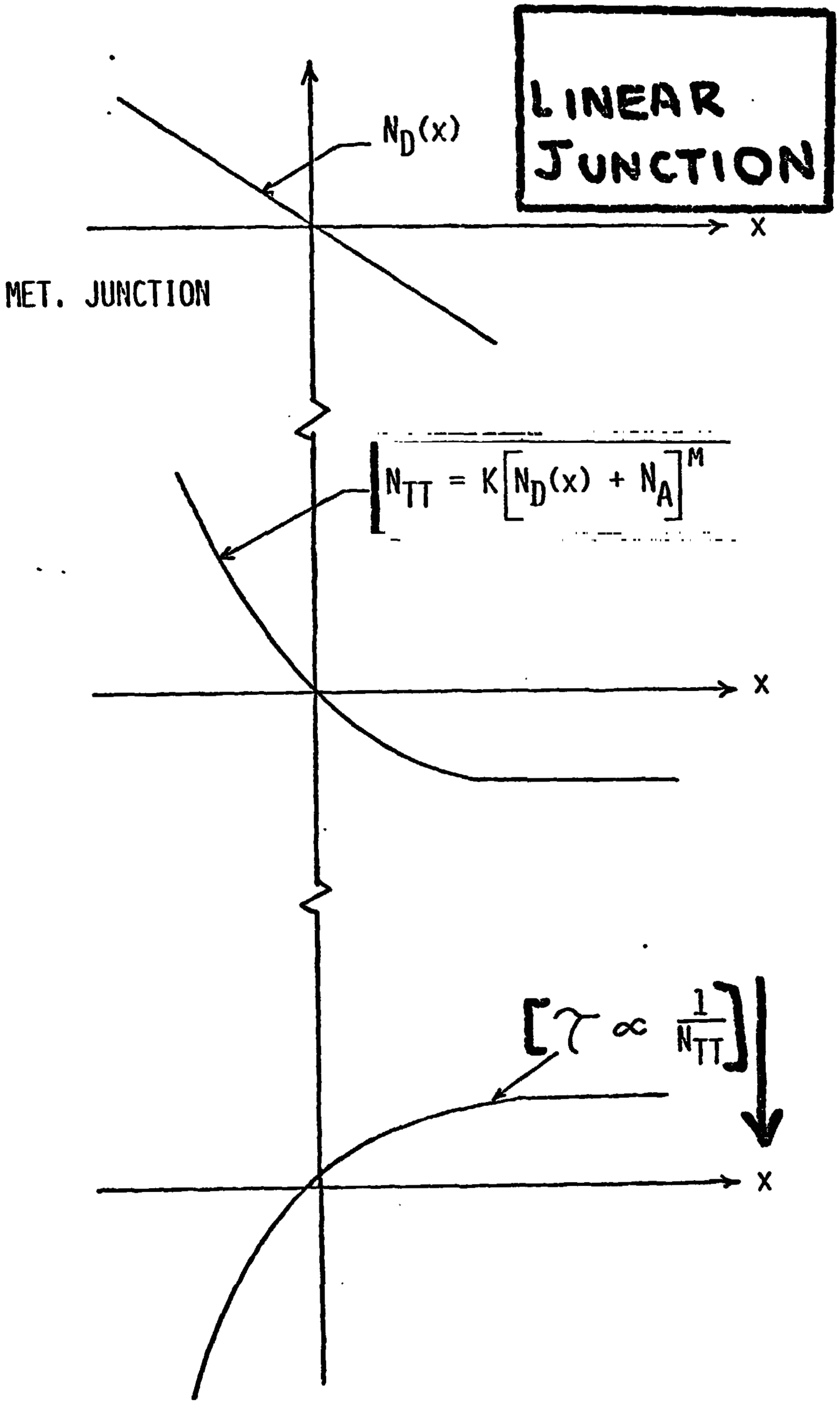


IMPURITY BAND
(OVERLAP)

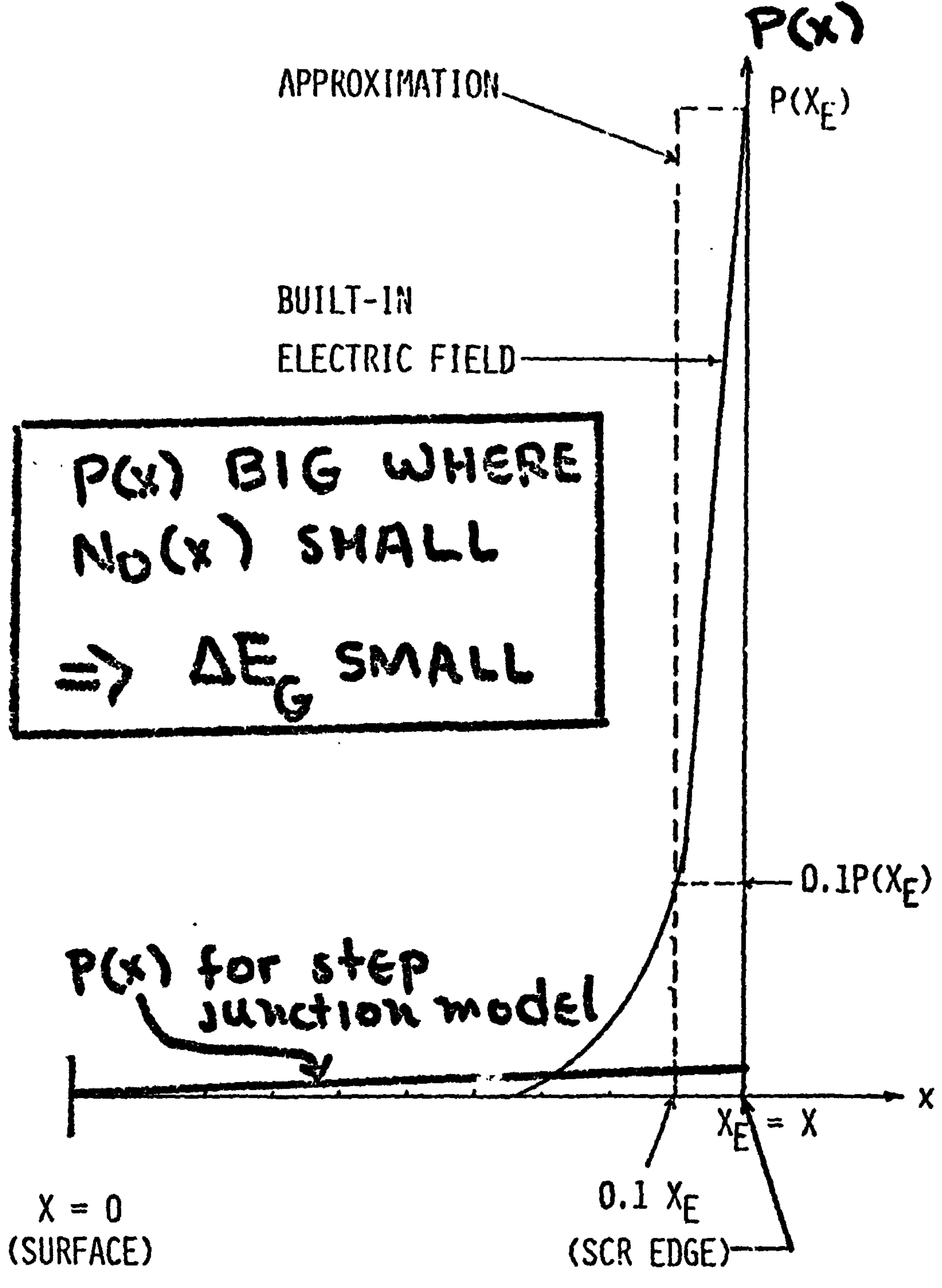


STRAIN
(MISFIT)




LINEAR JUNCTION
$N_D(x)$
x
MET. JUNCTION
$N_{TT} = K\left[N_D(x) + N_A\right]^M$
x
$\left[\tau \propto \frac{1}{N_{TT}}\right]$
x

HOLES IN EMITTER



P(x) BIG WHERE $N_D(x)$ SMALL

$\Rightarrow \Delta E_G$ SMALL

WHICH DOMINATES? MATCH TO EXPT.

0.1Ω-CM, 300°K, $n^{+}p$

MEASURED $V_{OC} = 610\,mV$

$$J_D = J_E + \cancel{J_{SC}} + J_B$$

$$\boxed{J_E = 11.1\,J_B}$$

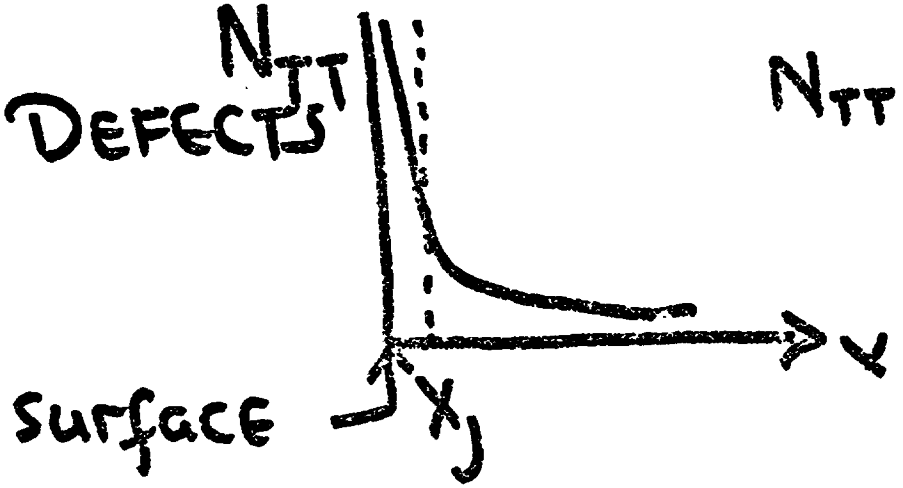
$$J_E = J_{ET}\left[F \quad G \quad S\right]$$

field: 0.1

ΔE_G: <15

$\boxed{T(x): 466}$

CONCLUSION : DOMINANT <u>1-DIM'L</u> H.D. MECHANISM IS

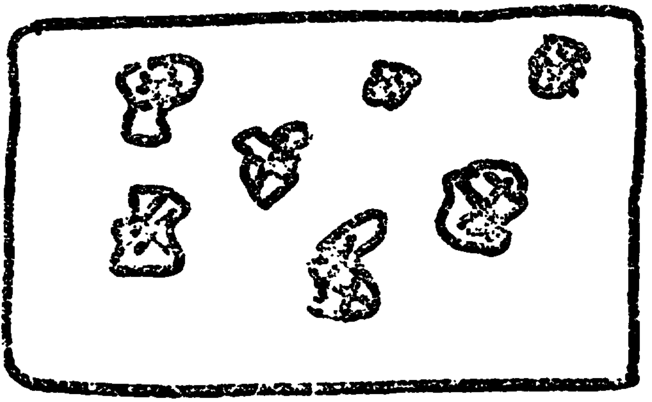


$$N_{TT} = K[N_D(x) + N_A]^m$$

- $m \cong 4$ OR $m \simeq 2$
- VACANCY COMPLEXES
- INCONCLUSIVE

3-DIM'L H.D MODEL:

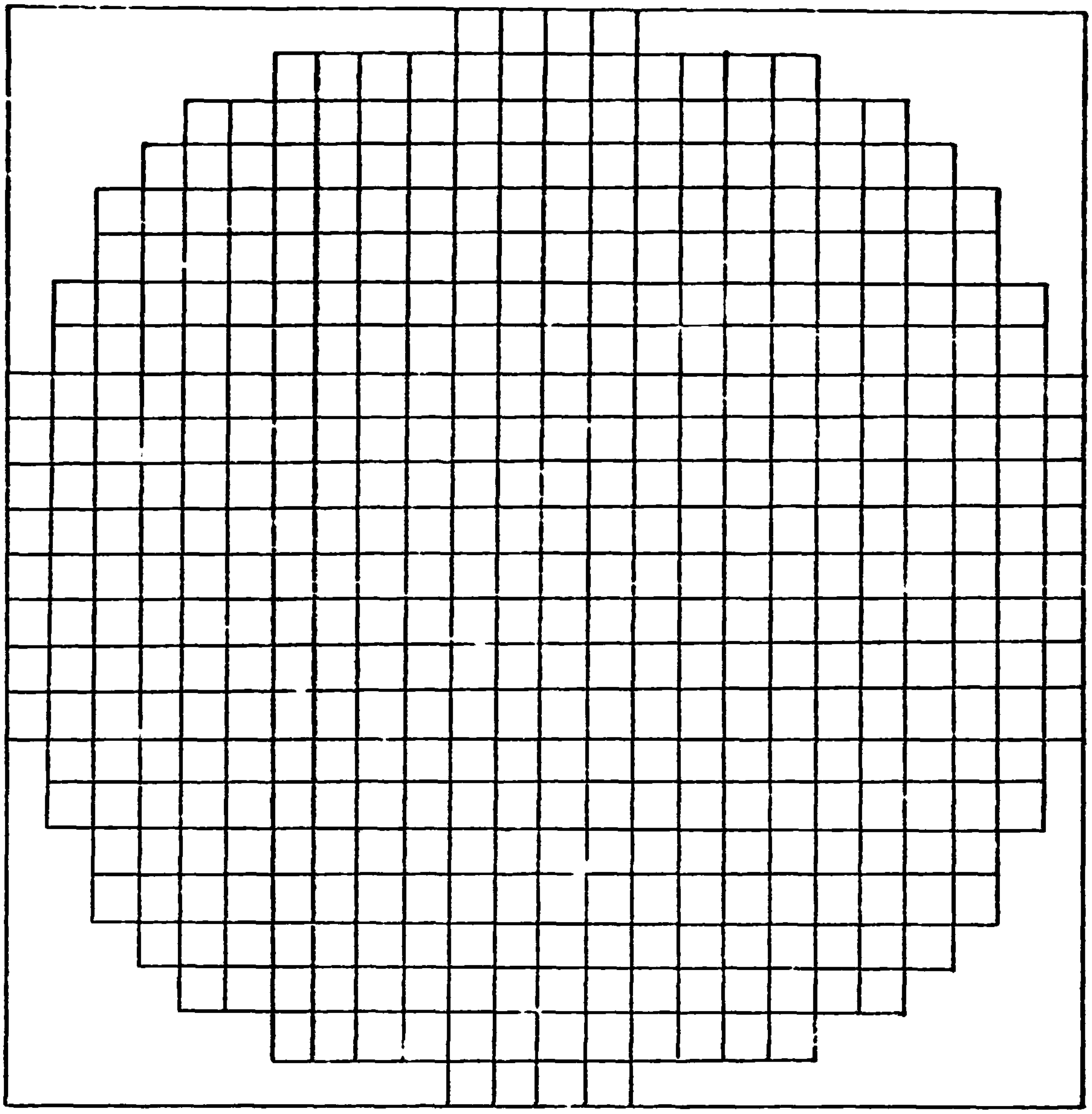
IMPURITY CLUSTERS IN LARGE AREA DEVICE



SOME 1-D MECHANISMS SENSITIVE:

$e^{\Delta E_G/kT}$,

$\tau \propto N_D^{-m}$



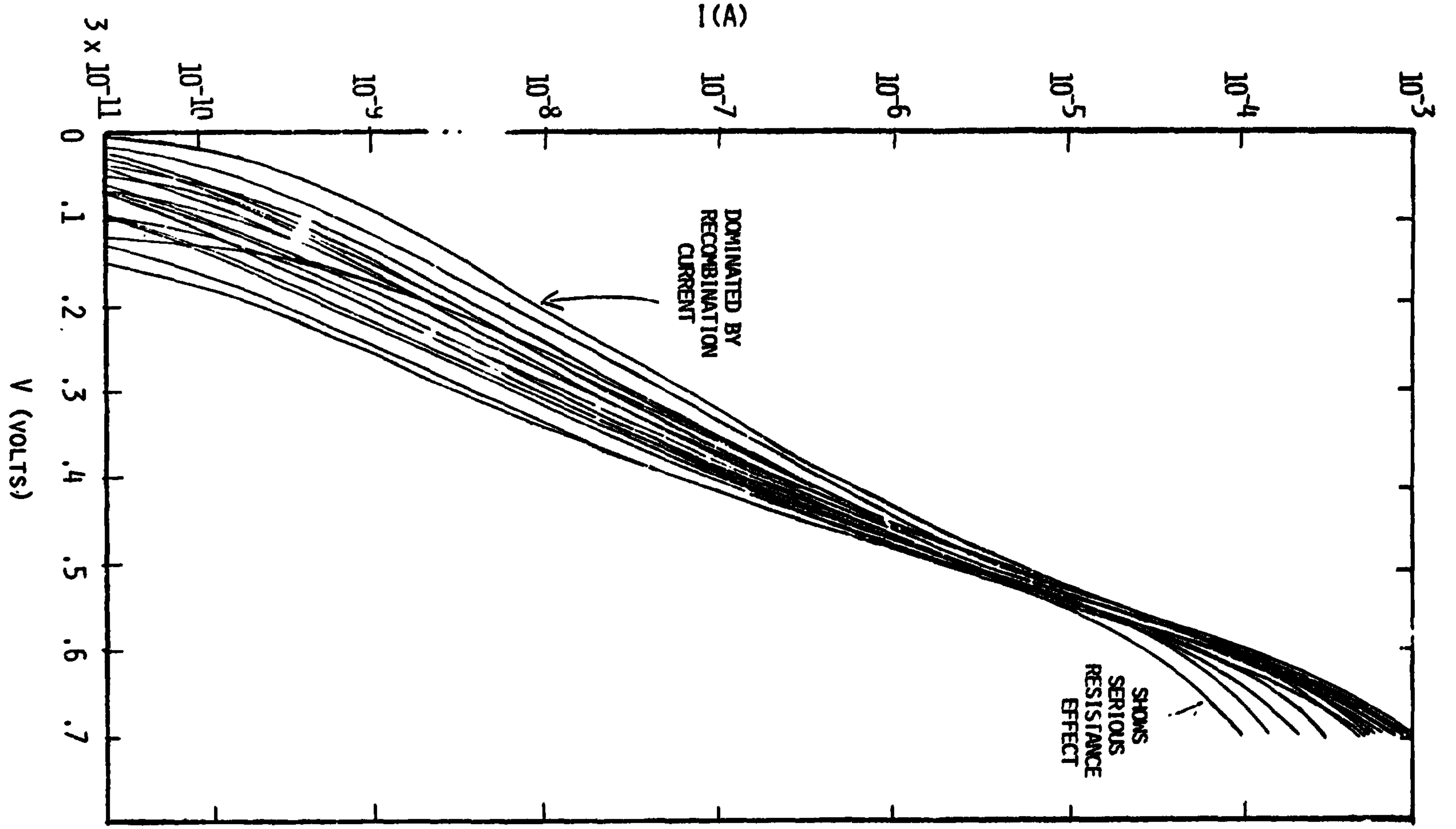


Figure 4.4 Experimental I-V curves for the 0.1 Ω-cm N^+P test cells obtained randomly from wafers C-101 and C-102 respectively.