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**NASA TM X-71728**

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(NASA-TM-X-71728) EFFECTS OF HIGH DOPING  
LEVELS SILICON SOLAR CELL PERFORMANCE (NASA)  
8 p HC \$3.25 CSCL 10B

**N75-24117**

**Unclas  
G3/44 22208**

**EFFECTS OF HIGH DOPING LEVELS ON  
SILICON SOLAR CELL PERFORMANCE**

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**TECHNICAL PAPER to be presented at  
Eleventh Photovoltaic Specialists Conference  
sponsored by the Institute of Electrical and  
Electronics Engineers  
Phoenix, Arizona, May 6-8, 1975**

## EFFECTS OF HIGH DOPING LEVELS ON SILICON SOLAR CELL PERFORMANCE

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### SUMMARY

Open-circuit voltages measured in silicon solar cells made from 0.01  $\Omega$ -cm material are 150 mV lower than voltages calculated from simple diffusion theory and cannot be explained by poor diffusion lengths or surface leakage currents. An analytical study was made to determine whether high doping effects, which increase the intrinsic carrier concentration, could account for the low observed voltages and to determine the limits on voltage and efficiency imposed by high doping effects. The results indicate that the observed variation of voltage with base resistivity is predicted by these effects. A maximum efficiency of 19% (AMO) and a voltage of .7 volts were calculated for 0.1  $\Omega$ -cm cells assuming an optimum diffused layer impurity profile.

### INTRODUCTION

There has been considerable interest in raising the efficiency of silicon solar cells to near its limit. Analyses (1, 2) have been made to define what gains can be expected and also what areas of research are most likely to yield the necessary improvements (or to identify the principal obstacles that must be overcome).

It has been suggested that the maximum practical silicon solar cell air mass zero efficiency of 18% would occur in 0.1 ohm-cm material. Realization of this efficiency depends heavily on obtaining an open-circuit voltage close to 0.7 volt calculated from simple diffusion theory. The best present-day performance of low resistivity cells, however, falls substantially short of these predictions. Measured efficiency and voltage are typically about 10% and 0.61 volts, respectively. It is believed that improvement of the voltage is the key factor leading to high efficiency. However, the difference between the achieved and predicted voltage performance is one area for which a satisfactory explanation is not available.

It has been widely hypothesized that the low observed performance of the 0.1 ohm-cm cell is a result of undesirable carrier recombination processes occurring in the base and depletion regions. However, measurements show that the short-circuit current and the base diffusion length are not primarily responsible for the low cell performance. A study of low resistivity cells by Soclof and Iles (3) not only support this, but also strongly indicate that other mechanisms which influence junction injection efficiency must be considered. One such mechanism is the narrowing of the silicon bandgap by high dopant concentrations.

The theoretical work of Kane (4) and Morgan (5) demonstrates that donor or acceptor concentrations in excess of  $10^{18}$  atoms/cm<sup>3</sup> alter the conduction band and broaden the impurity band densities of states. This work has been applied to silicon material by several investigators (6-10). Their results suggest that high impurity concentrations can indeed change the bandgap. Additional theoretical and experimental studies are cited in (10).

An important consequence of bandgap narrowing for p-n junction device operation is the increase of the

intrinsic carrier concentration  $N_i$ . Van Overstraeten et al. (11) have incorporated in detail the impurity level-dependent  $N_i$  in the basic semiconductor device transport equations. Similar equations modified to include bandgap narrowing have been used to analyze and reconcile the long-standing discrepancy between the predicted and measured current gain in bipolar transistors (6, 12-16).

The alteration of the bandgap and the intrinsic concentration by high impurity concentration effects, which will be referred to as the Heavy Doping Effect (HDE) in this paper, may also have significant effects on silicon solar cells.

The purpose of this paper is to make a preliminary analytical assessment of the significance of the HDE on the open-circuit voltage of silicon solar cells. Voltage calculations based on diffusion theory (such as used in (17)) are modified to include the first order features of the HDE. Comparisons of the open-circuit voltage measured for cells of various base resistivities are made with those calculated using the diffusion model with and without the HDE.

### THEORETICAL BACKGROUND

#### Open-Circuit Voltage

The open-circuit voltage ( $V_{oc}$ ) is calculated using

$$V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc}}{I_0} + 1 \right) \quad (1)$$

where the diode saturation current ( $I_0$ ) with the HDE, given by

$$I_0 = n_{id}^2 \frac{kT}{N_{id}} \frac{\mu_d(N_{id})}{L_d} G_d \left( \frac{W}{L}, s \right) + \quad (2)$$

$$n_{ib}^2 \frac{kT}{N_{ib}} \frac{\mu_b(N_{ib})}{L_b} G_b \left( \frac{W}{L}, s \right)$$

is the sum of the diffused and base region components ( $I_0 = I_{0d} + I_{0b}$ ). The "d" and "b" subscripts refer to the diffused and base regions, respectively. All calculations are made for an n<sup>+</sup>-p device and assume ohmic contacts, uniform n<sup>+</sup> region impurity level, a 0.25  $\mu$ m junction depth, a 300  $\mu$ m cell thickness, and an operating temperature of 300 K. For the purpose of this paper, the effect of bandgap narrowing on the short-circuit current ( $I_{sc}$ ) is neglected. Values of  $I_{sc}$  used in the calculations are typical of the various cell resistivities. The mobilities ( $\mu_d$ ,  $\mu_b$ ) and impurity concentrations ( $N_{id}$ ,  $N_{ib}$ ) corresponding to material resistivities were selected from the literature (18). A diffused region diffusion length ( $L_d$ ) of about 1.0  $\mu$ m is assumed. However, the base region  $L_b$  values are based on typical experimental data. The geometry factors  $G_d$  and  $G_b$  are given in detail in (17). However, for the case considered here they reduce to both W/L (i. e. infinite surface recombination velocity) contacts are assumed.

## RESULTS AND DISCUSSION

### HDE on Impurity Profiles

For those calculations which include the HDE, the values of  $n_{id}$  corresponding to a net impurity concentration are selected from the calculated data of (11). These data are shown in figure 1. It is seen that for net impurity levels below  $10^{18}/\text{cm}^3$ ,  $n_{id}$  has the classical value ( $n_{ic}$ ) of  $1.1 \times 10^{10}/\text{cm}^3$ . More importantly, however,  $n_{id}$  increases rapidly for levels above  $10^{18}$ . Typical solar cells have diffused region impurity concentrations in excess of  $10^{19}/\text{cm}^3$ , thus the variation of  $n_i$  must be taken into account. The implication of figure 1, suggested in (4,5) is that the conduction and valence band edges are no longer well-defined at high impurity levels. Hence the bandgap is narrowed and  $n_i$  increased, compared to a lightly doped, slightly extrinsic crystal.

Calculations which do not include the HDE are referred to as the simple diffusion theory. For this case equations (1) and (2) are also used; however, the intrinsic carrier concentration  $n_i$  is independent of impurity level and equal to the classical value ( $n_{ic}$ ) of  $1.1 \times 10^{10}/\text{cm}^3$ .

### Effective Impurity Profile

An effective impurity concentration is defined by

$$N_{\text{eff}} = \frac{N_{id}(x)}{\left(\frac{n_{id}(N_{id})}{n_{ic}}\right)^2} \quad (3)$$

$N_{id}(x)$  is the actual donor concentration at some location,  $x$  in the material and the ratio,  $n_{id}(N_{id})/n_{ic}$ , is a heavy doping factor based on the data of figure 1. Using equation (3) the diffused region saturation current component ( $I_{od}$ ) can be written in the form given by

$$I_{od} = \frac{n_{ic}^2 (kT)(\mu_d)}{N_{\text{eff}}} \frac{G_d}{L_d} \quad (4)$$

Note that for

- $N_{id} < 10^{18}$ ,  $N_{\text{eff}} = N_{id}$
- $N_{id} > 10^{18}$ ,  $N_{\text{eff}} < N_{id}$

Because  $I_{od}$  becomes large when  $N_{\text{eff}}$  is small, the diffused region properties can dominate the voltages calculated from equation (1).

### Four Layer Model

Calculations of the voltage, current, and efficiency were made for several p-base resistivities using the four layer model (17,19). These calculations include those features that are currently believed necessary to optimize cell performance, e.g.,  $X_g = 0.1 \mu\text{m}$ , 3% reflection losses, a p<sup>+</sup> back contact, and the optimum n<sup>+</sup> impurity profile (an actual gaussian profile with a  $1 \times 10^{19}/\text{cm}^3$  surface concentration). Diffused layer and p-base lifetimes were based on experimental data (3). A diffused layer lifetime of  $3 \times 10^{-9}$  sec corresponds to an impurity level of  $1 \times 10^{19}/\text{cm}^3$ . The p-base diffusion lengths are 303, 206, 201, 100, and 39  $\mu\text{m}$  for 10, 1, 0.5, 0.1, and 0.01  $\Omega\text{-cm}$  resistivities, respectively. The rear surface recombination velocity (SRV) is  $10^7$  cm/sec. Data are calculated for two values of front SRV,  $10^3$  and  $10^7$  cm/sec.

It is clear from equation (3) that as the actual doping level increases, the effective doping concentration, as modified by the HDE, will decrease. Thus substantial alterations to observed diffusion profiles would be expected. Figure 2 indicates the influence of the HDE on a gaussian profile having several different surface concentrations. For concentrations above about  $10^{20}/\text{cm}^3$ , the effective impurity profile is retrograde. The slope of the retrograde portion increases as the surface carrier concentration increases. Thus it would appear that in these cases, an opposing drift field is set up which prevents flow of minority carriers to the junction. This explanation is an alternative to the 'dead layer' model of the cell. The retrograde profile can be eliminated by reducing the surface concentration to about  $10^{19}/\text{cm}^3$ . A gaussian profile results with an effective surface concentration of  $3 \times 10^{19}/\text{cm}^3$ . Gaussian profiles are obtained for surface concentration less than or equal to  $10^{19}/\text{cm}^3$ . The electric field (11) associated with this gaussian effective profile is such that the minority carriers throughout the region are directed toward the collecting junction, thus aiding carrier collections. It appears that optimum cell performance will result for the maximum doping concentration at which the effective profile has no retrograde sections.

### HDE on Open-Circuit Voltage

Results of two types of calculations are to be presented. First, those of voltage using equations (1) and (2) assuming a uniformly doped n<sup>+</sup> diffused layer. Second, an overall cell performance calculation using the four layer model with the gaussian profile and other parameters described above.

Figure 3 summarizes the highest measured voltages for 10, 1.0, 0.1 and 0.01 ohm-cm silicon cells. Also shown as the solid line are the "simple theory" voltages calculated with no HDE and where  $I_{od}$  is insignificant compared to  $I_{ob}$  for all base resistivities. As seen, a discrepancy exists between the calculated and measured voltages which becomes more severe with decreasing base resistivity. The discrepancies are about 75 mV and 200 mV for 0.1 and 0.01 ohm-cm cells, respectively.

**Uniform Doping Calculations.** Using the values for  $n_{id}$  in figure 1 and equations (1) and (2), the voltages are recalculated for the 0.1 and 0.01 ohm-cm cases for various values of uniform diffused region impurity level. Since the p-base properties for each resistivity were not varied, the changes in the total  $I_o$  and the voltage were due only to the different diffused layer impurity levels. These calculated data are shown in figure 4. For comparison, the simple theory results are also shown for a 0.1 ohm-cm cell. It is seen that the simple-theory  $V_{oc}$  rises, then saturates with increasing impurity level. This result is expected since it reflects the diminishing influence of  $I_d$ .

Calculations which include the HDE contrast sharply with the simple theory. The voltage is seen to rise initially but, rather than saturate, peaks at about 0.66 volts, for a concentration of  $1 \times 10^{19}$  atoms/cm<sup>3</sup>. The  $V_{oc}$  then decreases reflecting the influence of large  $n_i$  values i.e., the HDE. Note, that at  $2 \times 10^{20}/\text{cm}^3$ , which corresponds to the present day diffused layer impurity level, the calculated voltage of nearly 60 volts is in agreement with the experimental data of figure 3.

A trend, similar to the 0.1 ohm-cm case, occurs for the 0.01 ohm-cm cell. Although the voltage again peaks at an impurity level of about  $1 \times 10^{19}$  atoms/cm<sup>3</sup>,

its magnitude is only 0.60 volts. Interestingly, a voltage of 0.36 volts is predicted for an impurity level of  $2 \times 10^{20}$ . This voltage also compares well with the measured value shown in figure 3.

A summary of the experimental and peak calculated voltages is shown in figure 5. The open circles and the solid line are the data of figure 3. The dotted line represents the peak voltages calculated with the HDE for the uniform diffused layer impurity concentrations. The significance here is that in addition to predicting the experimentally observed trend of  $V_{oc}$  with base resistivity, the HDE theory also suggests that voltage improvements appear possible by reducing the doping level in the diffused region.

Four Layer Model Calculations. A more detailed analysis of cell performance was made using the four layer model. Calculations of efficiency, voltage and current as a function of base resistivity are shown in figure 6. It is seen that for the  $10^3$  SRV case a peak efficiency of nearly 19% AMO and a  $V_{oc}$  of 0.7 V occurs for 0.1  $\Omega$ -cm material. These values are in agreement with previous estimates (1). They also suggest that HDE need not reduce cell performance provided that the optimum diffused layer doping profile can be achieved.

For the  $10^5$  SRV case, these calculations yield a lower peak efficiency of 16.2% and a lower voltage of about 0.6 V. The base resistivity for peak efficiency shifts to 1  $\Omega$ -cm material. This decrease in performance is most probably related to the value of lifetime chosen for the diffused layer. Use of bulk material lifetime values would have improved the performance in this case. There is a strong sensitivity of these calculations to the shape of the profile, the value of SRV and the lifetime in the layer. Of these parameters, least is known about the lifetime in the diffused layer. This parameter is critical to separation of the various models for predicting solar cell performance. Thus a research effort should be undertaken to determine this lifetime and thus provide necessary input data for theoretical calculations.

#### SUMMARY AND CONCLUSIONS

This paper describes a preliminary analytical assessment of the influence of heavy doping on the open-circuit voltage performance of silicon solar cells. The modification of simple diffusion theory, guided by published calculations of the intrinsic carrier concentration as a function of impurity concentration, can explain the experimental voltage trends in low resistivity cells. Furthermore, the calculations suggest that voltage improvements can be expected, provided that the diffused layer impurity concentration and profile are optimized.

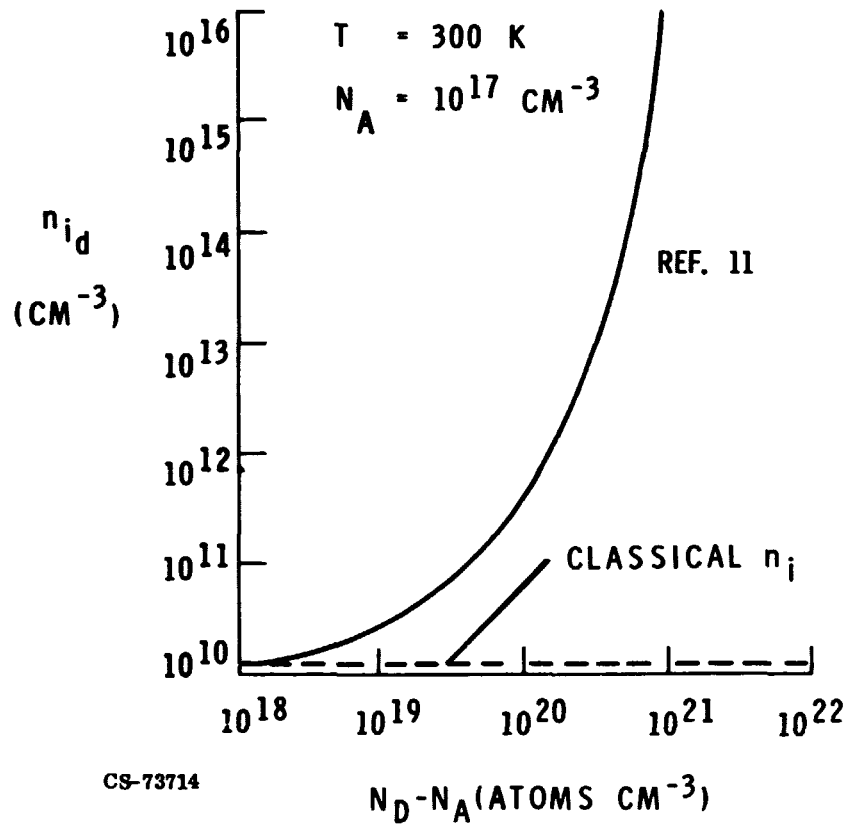
An assessment of the maximum practical efficiency for 300  $\mu$ m thick cells in the 0.01 to 10  $\Omega$ -cm range was also made using the four-layer model. These calculations assume a  $p^+$  back, 0.1  $\mu$ m junction depth, 3% reflection losses, front surface recombination velocities of  $10^3$  or  $10^7$ , and the optimized diffused layer profile. A maximum AMO efficiency of about 19% occurs for 0.1  $\Omega$ -cm material. This supports earlier predictions and suggests that heavy doping effects should not be deleterious to cell efficiency providing the

diffused layer impurity profile is optimized. For the lifetime values used, cell efficiency was sensitive to surface recombination velocity, decreasing to 16% for SRV =  $10^7$ . Cell performance is critically dependent on the profile, the value of SRV and the lifetime. Because lifetime is the least well known, a research effort to obtain the necessary data is required.

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Figure 1. - Effect of dopant concentration on intrinsic concentration.

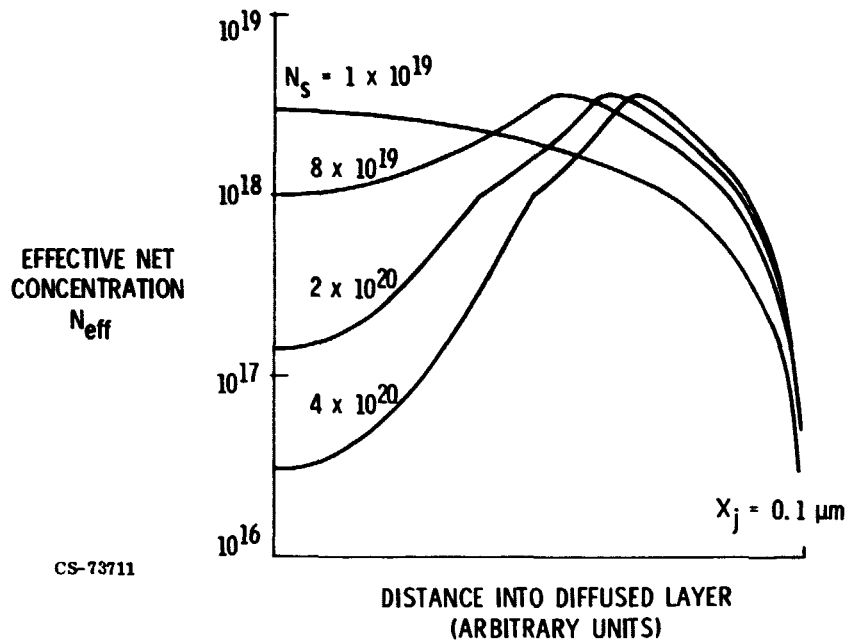


Figure 2. - Effective net impurity profile in diffused layer of 0.1  $\Omega$ -cm solar cell (for actual Gaussian profiles of various surface concentration).

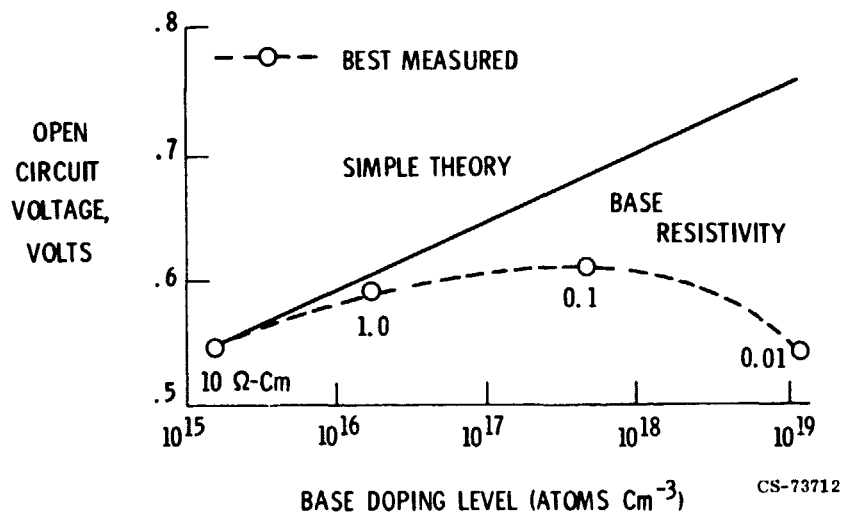


Figure 3. - Experimental and predicted open-circuit voltage dependence on base doping levels.

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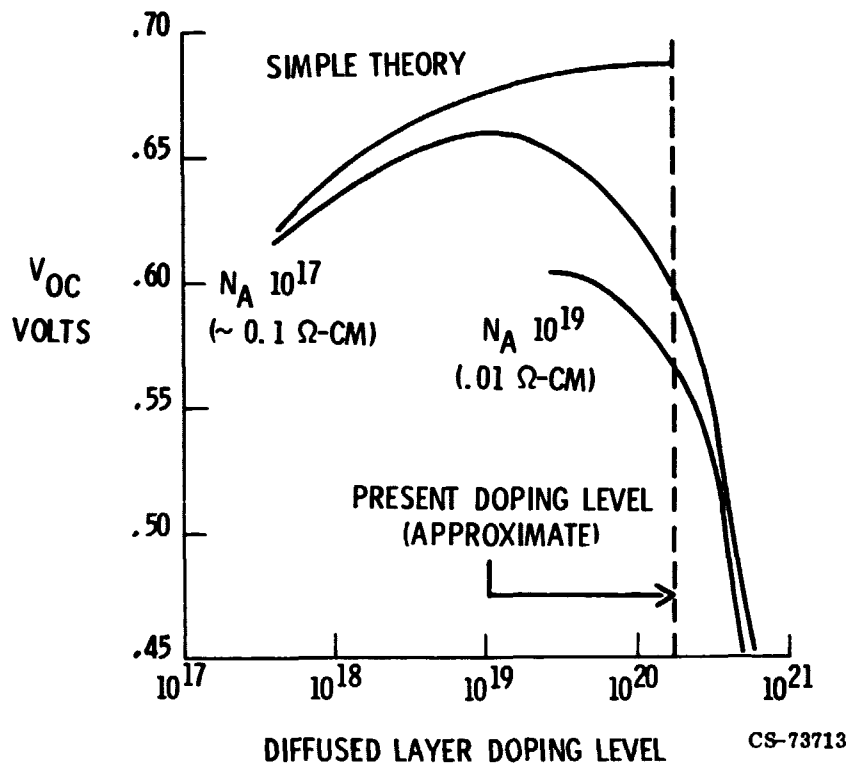
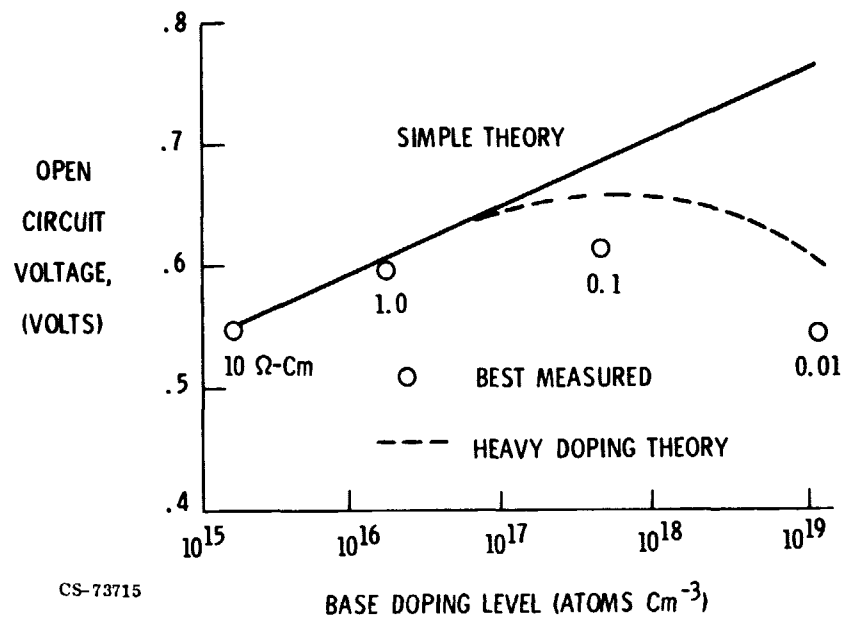
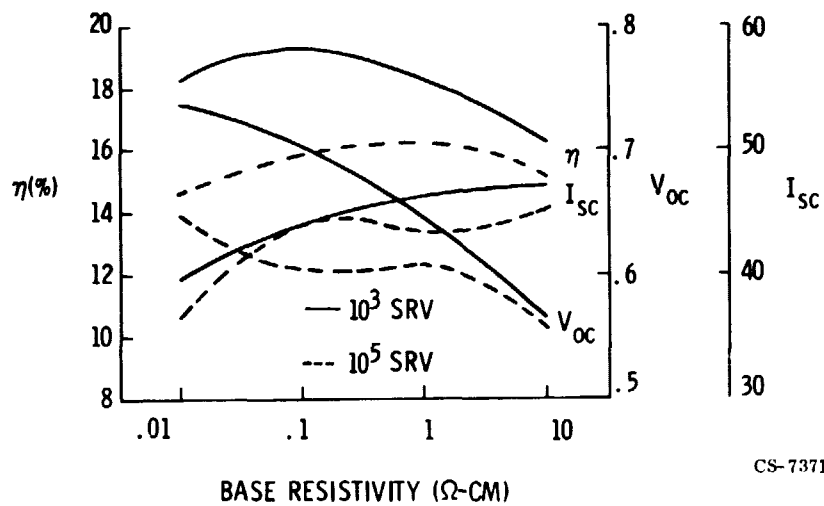


Figure 4. - Influence of diffused layer heavy doping effects on open-circuit voltage.



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Figure 5. - Experimental and predicted open-circuit voltage dependence on base doping level.



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Figure 6. - Calculated cell performance as a function of base resistivity (using the four layer model and two values of front surface recombination velocity).